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EXTENSION OF KNOWLEDGE BASE
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TOWARDS SUSTAINABLE CROP POLLINATION SERVICES
MEASURES AT FIELD, FARM AND LANDSCAPE SCALES

POLLINATION SERVICES FOR SUSTAINABLE AGRICULTURE

TOWARDS SUSTAINABLE CROP POLLINATION SERVICES
MEASURES AT FIELD, FARM AND LANDSCAPE SCALES

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Preface

Globally, agricultural production systems are under pressure to meet multiple challenges: to sustain or increase production from the same area of land and reduce negative impacts on the environment amid uncertainties resulting from climate change. As farming systems adapt to meet these challenges, there is a growing awareness that one of agriculture's greatest assets in meeting them is nature itself: many of the ecosystem services provide by nature – such as nutrient cycling, pest regulation and pollination – directly contribute to agricultural production, and by extension, human well-being. The healthy functioning of these ecosystem services ensures the sustainability of agriculture as it intensifies to meet growing demands for food production.

In this context, managing agricultural landscapes – which encompass field, farm and landscape levels – to optimize the use of ecosystem services will contribute to agricultural production while maintaining and encouraging biodiversity. In agro-ecosystems, pollinators are essential for orchard, oilseed crop, horticultural and forage production, as well as the production of seed for many root and fibre crops.

As the discipline of pollination ecology moves from describing the extent of a pollinator crisis, to identifying what can be done about it, there is a need to share and highlight very practical measures that will support sustainable crop pollination services. Identifying these practices will require a mix of farmer, local and natural historian knowledge plus scientific research.

Within the context of its lead role in the implementation of the International Pollinator Initiative (2002-2016), the Food and Agriculture Organization of the United Nations (FAO) established a Global Action on Pollination Services for Sustainable Agriculture. FAO also developed a global project, supported by the Global Environment Facility (GEF) through the United Nations Environment Programme (UNEP), titled "Conservation and management of pollinators for sustainable agriculture, through an ecosystem approach". Seven countries (Brazil, Ghana, India, Kenya, Nepal, Pakistan and South Africa) worked together with FAO to identify and carry out targeted activities that address, among other things, the management of pollinators in agricultural landscapes.

This publication, prepared through the GEF/UNEP/FAO Global Pollination Project and in collaboration with international experts, outlines a number of practices that have been so far identified, and what experiences may contribute to the effectiveness of these measures under different circumstances. It is our hope that it jump-starts practical action to conserve and sustainably manage pollinators as outlined in the International Pollinators Initiative 2.0 (2018-2030).

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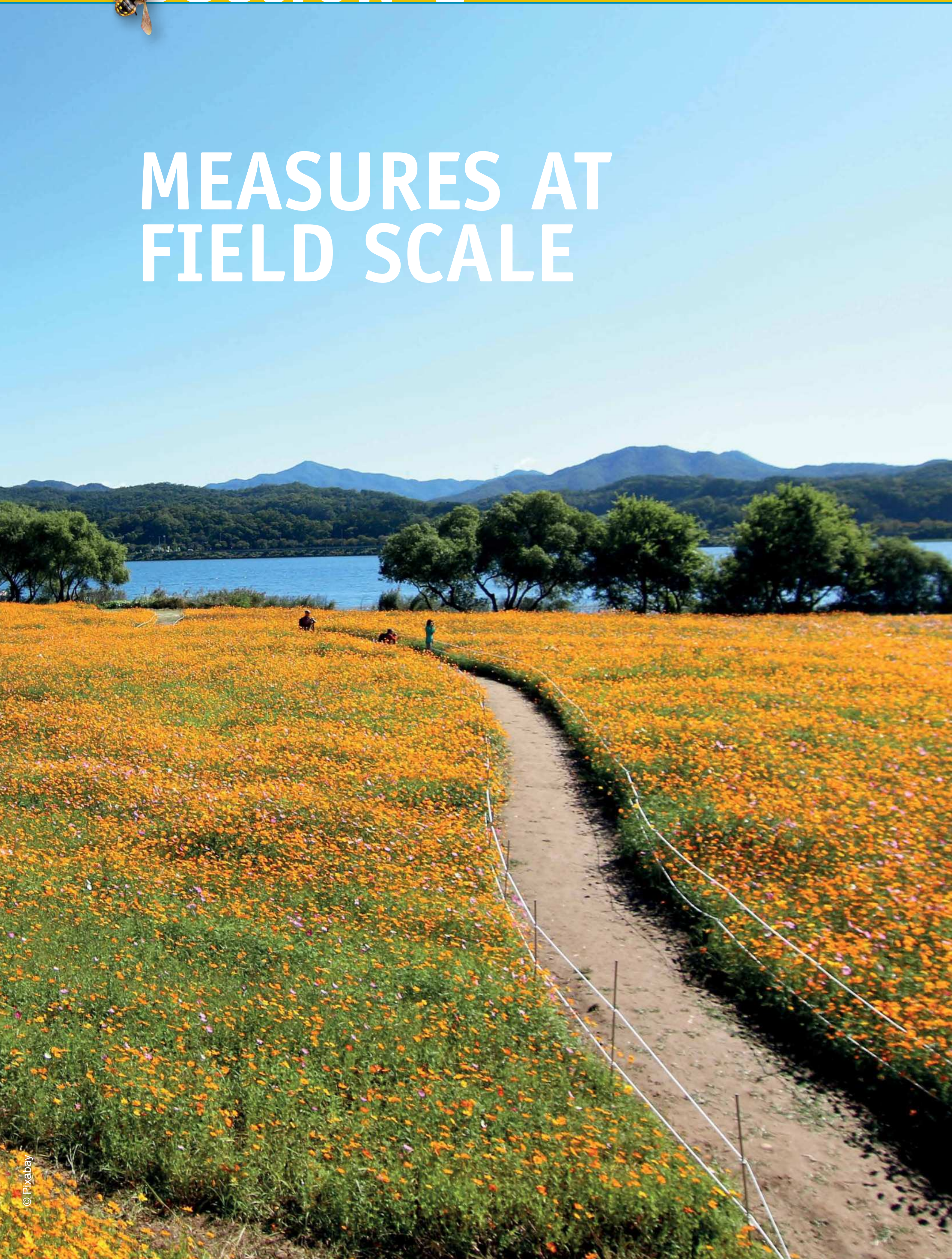
Section 1

MEASURES AT FIELD SCALE



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Chapter 1

Measuring diversity in the field

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REASON FOR THE PRACTICE

Wild bees provide under-appreciated pollination services to many crops (Breeze *et al.*, 2011) though often crop systems are managed in such a way that the habitat becomes unsuitable for them. Finding ways to conserve and/or increase the abundance, diversity and ultimately the pollination services provided by wild bees involves being able to reliably assess their diversity and abundance within crop systems, and draw comparisons to crop systems under different management regimes, or to more naturalized habitats. Such comparisons can improve our understanding of the responses of wild bees to habitat characteristics, and ultimately to improve crops management systems with respect to natural pollination services (e.g. Watson *et al.*, 2011; Morandin and Kremen, 2013; Sheffield *et al.*, 2013a).

This chapter will focus on methods of collecting pollinators for assessing diversity and abundance, with the main focus on bees based on summaries of collecting methods which can be standardized for diversity analysis. What this chapter does not provide are guidelines for setting up experimental designs for sampling bees, nor ways to analyse the resulting data sets. These methods will vary from study to study, based on different crop or plant community systems and the nature of the specific study (e.g. what questions are being asked?). For some of these topics, readers are referred to Magurran (1988, 2004), Magurran and McGill (2011), Krebs (1999), Hayek and Buzas (1997), Gotelli and Colwell (2001), and other related works. There are many excellent and recent examples of scientific studies that present different ways of analysing bee/pollinator diversity. However, the methods reviewed here are those most commonly used in pollinator community assessments. The discussion below offers a framework for standardising pollinator sampling methods across sites and studies, and summarizes the pros and cons of each method to facilitate adoption within pollinator assessment projects.

For more general accounts of collecting methods used for insects, readers are referred to Martin (1977), Schauff (1986), and Gibb and Oseto (2006). Other useful information on surveys, collecting techniques, etc. can be found in several publications of the Biological Survey of Canada (e.g. Danks, 1996; Danks and Winchester, 2000; Danks *et al.*, 1987; Marshall *et al.*, 1994) and for bees specifically, readers are advised to see Droege's *Handy Bee Manual* (2015). The importance of retaining voucher material from every study is stressed by Francoeur (1976), Knutson (1984), Huber (1998), and Wheeler *et al.* (2001), and is recommended for pollinator studies.

HOW TO IMPLEMENT IT

Crop systems differ remarkably with respect to their size, age, structure (e.g. plant height, arrangement, row orientation versus uniformly covered crops, density of planting) and proximity to natural habitats, all of which may influence bee diversity. As such, no single method is ideal to assess bee diversity in all crop systems, and a range of methods should be explored to address specific diversity-related questions (e.g. Monsevièius, 2004; Toler *et al.*, 2005; Roulston *et al.*, 2007; Westphal *et al.*, 2008; Wilson *et al.*, 2008; Nielsen *et al.*, 2011; Spafford and Lortie, 2013). Below, a summary of some of the most common sampling methods used for collecting bees and other pollinators is provided, with discussion on the utility of each under various cropping systems.

Researchers interested in exploring bee diversity in any landscape should have a detailed experimental plan prior to conducting surveys in order to address specific questions related to the study. Each method discussed below has advantages and disadvantages, and some may not be appropriate for certain crop systems or plant communities (Westphal *et al.*, 2008). For instance, only net-collecting from flowers provides specific information on flower visitors, though pollen analysis from bees collected by other methods may provide additional information on floral use. In planning any survey, there are many things to consider with respect to sampling methods, experimental designs, and the time requirements to sort, prepare and identify material for identification, and create voucher specimen repositories.

Net collecting from flowers

One of the most effective ways to determine which bee species are important crop pollinators is to collect them directly from the flowers using a net. This technique provides direct information on the specific visitors of the crop(s) of interest (i.e. the pollinators), and also facilitates the study of other components of pollination biology, including foraging behavior, and examination of pollen loads for constancy (Popic *et al.*, 2013) (see Kearns and Inouye (1993) and Dafni *et al.* (2005) for various techniques). In some systems, net collecting may outperform other methods of collecting pollinators (e.g. Morandin and Kremen, 2013; Popic *et al.*, 2013), while in other systems, it may not (e.g. Westphal *et al.*, 2008; Wilson *et al.*, 2008).

However, net collecting has several limitations which may affect its full utility as a single sampling method for pollinators. First, collectors may differ greatly with respect to their skill and experience with a net, which can greatly bias the resulting capture efficiency if comparisons are required (Roulston *et al.*, 2007). Depending on the nature of the study, collector bias can sometimes be accounted for with careful consideration within the experimental design (e.g. rotating collectors across sites, etc.). In other cases, standardized sampling may not be possible with net collecting.

Second, the structure of the crop system may be conducive to collecting with a net, or may be very prohibitive. For instance, net collecting on low, evenly dispersed crops (e.g. lowbush blueberry, alfalfa) or uniform rows (e.g. strawberry) (Figure 1a) is relatively easy, and one can use sight-and-capture methods and/or net collecting to survey pollinators; the latter method is preferred for standardized sampling (e.g. walking and sweeping a 30 m transect with a full 180° pendulum sweep). In contrast, brambles and other crops arranged as orchards (in particular, tree fruit crops) (Figures 1b and c) are much harder from which to net collect, as the fast, sweeping motion required to catch fast-flying insects often causes the net to become caught on branches, greatly reducing capture efficiency. In addition, in crop systems with tall trees, bees that prefer to forage on higher limbs would be under-sampled. Practice and experience greatly enhance capture efficiency in these crop settings, though standardized methods are much harder to develop.

GENERAL DO's AND DON'Ts

- Use a net with a handle of appropriate length for the crop of interest.
- Sweep nets with a flexible rim are less destructive to the crop than solid rimmed nets, and are recommended.
- Practice techniques for the target crop(s), and develop standardized methods (e.g. techniques, duration) for comparisons to different fields and/or studies.
- Wet vegetation greatly reduces capture efficiency, and can cause damage to the insect specimens; avoid collecting just after rainfall.
- Net collect in weather conditions that are suitable for all pollinators, so temperature, wind speed, and light levels need to be considered.

Figure 1.

Crop structure of a) a lowbush blueberry field, with low plants evenly spread over the ground, b) a Haskap orchard, with the shrubs arranged in rows, and c) an apple orchard, consisting of trees arranged in rows

- Pollinators may show different daily patterns of activity, so sampling should be timed to coincide to capture all pollinators, or be standardized for consistency with a specific timed period (e.g. morning versus afternoon).
- Be considerate of the farmer's crop; net collecting and walking through a field can be destructive to the crop, and intensive netting may cause significant crop losses.

Pan-trapping

Pan-trapping basics

Pan-trapping, or the use of coloured "bowls" (Figure 2) to passively collect flower-visiting insects is one of the most inexpensive, widely used and effective methods for surveying bees and other flying insects (e.g. Toler *et al.*, 2005; Westphal *et al.*, 2008; Droege *et al.*, 2010; Sheffield *et al.*, 2013a and b). The pan-traps act as proxies for flowers, and bees and other flower visiting insects are drawn to them while seeking pollen, nectar, oil, or other floral resources. Pan-traps typically use water (with dish soap as a surfactant) as a killing agent; the insects land on the surface of the water, break through via the reduced surface tension, and drown. The insects can later be collected from the pan-trap and transferred to alcohol in vials (see Droege, 2015 for an excellent account of preparation methods). Typically, this can be done on a daily basis (i.e. the pans can be left in the field for a day). If longer durations are required, different killing/preservation agents should be used. Durations of a few days to up to a week can use the water/soap in combination with a rock salt tablet, which retards the decomposition of the captured insects (see Sheffield *et al.*, 2013a). However, evaporation becomes a large problem in some settings, and propylene glycol should be used as a killing/preservative agent if pans are left out for more than a few days.

Bees and other pollinators respond differently to pan-traps of various colours (Leong and Thorp, 1999; Toler *et al.*, 2005; Campbell and Hanula, 2007; Gollan *et al.*, 2011; Grundel *et al.*, 2011) as naturally, many bees show floral preferences. For general surveys or pilot studies, multiple colours (mainly yellow, blue, and white) should be used to initially assess efficiency of each pan-trap's colour within the habitat of interest. Ultimately, it may turn out that one colour works best, but standardized sampling facilitates comparisons to other habitats. Droege (2015) provides a detailed account of all methodologies associated with conducting pan-trap surveys.

Placement of pan-traps is also a consideration. Pan-traps placed in shaded areas typically will catch fewer bees than those placed in direct sunlight, although for longer periods of capture, sunlight will also increase the rate of evaporation. In open habitats with low lying vegetation, pan-traps can be placed directly on the ground, while areas with a plant canopy where flowers are above ground-level may require that pans be supported and raised to the canopy level. Sheffield *et al.* (2013a), in a study where pan-traps were left out continuously, supported using pan-traps at ground level within a base that provided uniform surroundings to reduce blockage by vegetation and reduced capture of non-target crawling arthropods (Figure 2).

Floral resource density (e.g. number of flowers per plant, or number of plants/shrubs per sampling plot) may affect pan trap effectiveness, therefore, it will be important to keep floral resource density as consistent as possible among all plots when using pan traps. In some studies, pan trap effectiveness decreases with an increase in floral resource availability explained by the shorter distances and time needed to reach flowers/floral patches corresponding to the lower probability of landing in a pan trap (Cane *et al.*, 2000; Roulston *et al.*, 2007; Wilson *et al.*, 2008, Baum and Wallen, 2011). Both bee species richness and abundance may be underrepresented in pan trap catches when floral resources are abundant (Baum and Wallen, 2011).

Figure 2.

A typical yellow pan-trap used for collecting bees and other flying flower visitors

GENERAL DO's AND DON'Ts

- Fluorescent painted bowls may be more effective than non-fluorescent or pre-coloured bowls with respect to capturing bees, though paints may vary significantly across brands, and vary in availability in different countries.
- Pan-traps fade rapidly in direct sunlight, and may lose effectiveness over time, so frequent replacement is recommended.
- Positioning of pan-traps is important; bowls should be placed in more open habitats and areas within the crop system to increase visibility.
- Pan-traps should be collected frequently enough to prevent drying out.
- One should be aware of farm vehicle traffic, and set pan-traps in safe areas.
- Pan-traps should be placed at a height matching that of the flowers of interest, and should be visible to pollinators (i.e. in aisle ways in orchard systems).
- Be aware that shade from canopies from tree-fruit crops or adjacent woodlands reduces capture efficiency of pan-traps.
- Pan-traps do not work well in windy conditions.

Vane traps

In some habitats, and for some groups of bees, yellow (Figure 3a) and blue (Figure 3b) vane traps offer many advantages over net collecting and pan-traps (see Stephen and Rao, 2005, 2007; Rao and Stephen, 2010; Broussard *et al.*, 2011; Hall, 2018), though are not necessarily a replacement (Gibbs *et al.*, 2017). For instance, in plant communities where the flowers form part of the canopy above ground level, and/or for crops grown in rows (e.g. orchards), vane traps can be easily hung at canopy level. In other cases, they can be partially buried (Figure 3).

Vane traps serve as a combination visual attractant and flight intercept trap for pollinators. They work especially well at capturing larger pollinators (i.e. bumble bees) and can be left in habitats for months at a time with the appropriate preservation agent. Although there are only a few published studies using this method (Stephen and Rao, 2005, 2007; Rao and Stephen, 2010; Brossard *et al.*, 2011; Kimoto *et al.*, 2012; Hall, 2018), vane traps provide a good additional method for sampling bee communities. Kimoto *et al.* (2012) suggest that for bee surveys, vane traps offer the ability to capture a lot of bees with few traps, and thus, may provide an economic and temporal advantage to other methods.

GENERAL DO's AND DON'Ts

- Experiment with trap height, placement, and position within plant communities.
- Use killing agents and preservatives that are appropriate for the duration of trapping.
- Vane traps can capture a lot of bumbles bees in a short period of time, a situation that potentially should be avoided if rare species are present.

Figure 3.

A vane trap; a combination of a flight intercept and colour attractant

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Trap-nests

As discussed in other chapters, bees nest in a variety of locations, including in the soil and in pre-existing cavities. For bees in the latter category, artificial nesting sites called trap-nests may be used to assess the diversity and relative abundance of these bees in agricultural settings (e.g. Sheffield *et al.*, 2008). Unlike the other methods suggested in this chapter, trap-nests are not traps *per se*, but instead are nesting sites for bees (and wasps). However, they are excellent for assessing the diversity of cavity-nesting bees in a range of habitats, providing knowledge of nesting behavior and preferences, and can be used to determine pollen-use patterns (e.g. MacIvor *et al.*, 2013), nesting associates (e.g. Krombein, 1967; Sheffield *et al.*, 2008; Barthélémy, 2012), etc. They can also be the basis of developing management strategies for pollinators.

There are several styles of trap-nests which can be built to address specific questions. If only diversity, fecundity, and nesting associates are of interest, wooden blocks with drilled holes or with paper tube inserts are adequate (Figure 4a and c). Bundles of open-ended hollow reeds are also suitable for this type of work (e.g. Barthélémy, 2012). If one wishes to examine the nesting contents to look at nesting biology or to sample pollen, using laminate nests (Figure 4b) – which can be taken apart – could be used, though reeds are also easily split to examine nest contents (see Barthélémy, 2012).

As trap-nests are typically placed in the field for the entire season, one has to consider the potential negative impact of weather conditions on the nests and nest occupants. For paper nesting tubes, it is particularly important that the nests stay dry, as moisture promotes mould growth, which can become an issue for nest occupants. Trap-nests should be constructed in such a way as to minimize rain getting into the nesting tubes (e.g., designed with roofs or angled to have water flow away from nest entrances). Trap-nests should be cleaned each year to prevent mould build-up, and to prevent the likelihood of pathogen build-up. When appropriate, fresh paper tubes should be used each year.

As many types of organisms (e.g., ants, parasites, etc.) will also be interested in the nests, care must be taken to prevent loss of bees. For crawling insects such as ants, it is recommended that Tanglefoot® insect barrier or something similar be applied on the support for the trap-nest, well below the area where the nest is placed (Sheffield *et al.*, 2008).

Bees in trap-nests must also be wintered properly, as exceptionally cold conditions during the winter may cause high mortality in bees within artificial nests. Unheated, sheltered sheds provide warmer, and – more importantly – less fluctuating temperatures which are best for bees.

Figure 4.

Trap-nests used for cavity-nesting aculeate Hymenoptera

a) a nest consisting of individual paper tubes, b) a nest constructed of wooden laminates which can be separated to examine nest contents, and c) a nest consisting of individual paper tubes

GENERAL DO's AND DON'Ts

- Become familiar with the local cavity-nesting bee fauna and their specific nesting requirements.
- Conserve and encourage natural nesting sites for cavity-nesting bees.
- Use a range of nesting tube diameters and nesting materials to sample broadly from the cavity-nesting bee community.
- Have trap-nests oriented so that they face the sun (i.e., south-facing in the Northern Hemisphere), and properly shielded from water exposure.
- Provide a range of artificial substrates for cavity-nesting bees, which encourage them in habitats lacking natural nesting sites.

Malaise traps

Malaise traps (Malaise, 1937), resembling a tent with open sides, are a type of flight intercept trap that collects flying insects (Figure 5). Typically, they are placed along corridors used by flying insects to maximise capture rates, though it is often worthwhile to experiment with trap placement, especially in homogeneous habitats. Insects entering the trap are intercepted at the central mesh wall(s), and typically fly upwards towards a collecting vessel. Malaise traps are very effective for some groups of flying insects, including flies, bees and wasps (e.g. Juillet, 1963; Bartholomew and Prowell, 2006; Ngo *et al.*, 2013), and often capture insects that are not collected easily by other methods. Malaise traps are also sensitive to trap placement; how the trap is positioned and placed can drastically affect the efficiency of the Malaise trap. In addition, because they are large and quite visible, they can be an easy target for vandals, and even large animals. They are also expensive, so one has to consider the cost of replication for experimental design.

Figure 5.
A typical Malaise trap

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Malaise traps with coarser mesh work better for bees and other aculeate Hymenoptera (Darling and Packer, 1988). For monitoring bees, placing pan-traps on the ground within the Malaise trap often increases the capture efficiency, and is recommended (Darling and Packer, 1988; Campbell and Hanula, 2007). Variants of Malaise traps often incorporate both flight intercept and pan-trapping (e.g. Russo *et al.* 2011).

Although the Townes style (Townes, 1972) Malaise trap is the most commonly used style, many other designs are available, and some may be more suitable than others in different habitats (see Campos *et al.*, 2000; van Achterberg, 2009).

GENERAL DO's AND DON'Ts

- Place Malaise traps along corridors or vegetation edges used by flying insects for most effective trap capture.
- Malaise trap central panels need to be taut when erected for effective insect capture.
- Use a collecting/killing agent that is appropriate for the duration of collection.
- Check traps frequently, as they may need to be cleared of vegetation to maintain effectiveness.
- Use a large collecting tray or pan-traps at the base of the Malaise trap to increase overall capture, as some insects may not fly up into the collecting jar.
- Avoid setting up Malaise traps close to pathways which are used by large animals.

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Chapter 2

Management of honey bee colonies for crop pollination

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REASON FOR THE PRACTICE

Worldwide, honey bees (*Apis mellifera*) are major crop pollinators. Several characteristics make them well adapted for this task:

- Honey bee colonies are accessible worldwide as they are continuously managed for honey production.
- Honey bee colonies function year-round and their activity is not limited to specific season.
- Individual honey bees show a high level of constancy which allows them to transfer pollen efficiently among flowers of the same species.
- Honey bee visitation rate is high, enabling them to transfer a large amount of pollen among flowers.
- Similar to many other bees, the honey bee's body is covered with branched hairs which allow for efficient transfer of pollen grains
- The honey bee as a species is a highly generalist pollinator and will visit a wide spectrum of flowering plants, in contrast to specialized pollinators that restrict their visits to a few species.
- Honey bees can forage under a broad range of temperatures—from approximately 15 °C to 40 °C.
- Large honey bee colony populations (5 000–50 000 individuals) and their artificial nest (beehive) allow easy and fast transportation of very large populations to and from the target crop area (Figure 1).

Due to these characteristics, the honey bee is by far the most economically managed pollinator of crops worldwide (Watanabe, 1994). In the United States of America alone, the marginal increase in value attributable to honey bees, i.e. the value of the increased yield and quality achieved through pollination by honey bees, was USD 14.6 billion in 2000; in Canada this value was estimated at USD 780 million in 1998, in the EU at USD 4.24 billion, and in the United Kingdom of Great Britain, at £200 million; in Australia, this figure was USD 2.4 billion in 2002, and in Israel, USD 230 million (for references, please see Dag, 2011). Gallai *et al.* (2009) estimated the economic value of the pollination services, from all pollinators worldwide to be 153 billion euro (considering impacts on agriculture only).

While it forages on a wide range of host plants, the honey bee continuously monitors, samples and collects information on the most rewarding food source available and has a highly developed system for recruiting nest mates to these sites. Thus, under certain conditions, maintaining honey bees on target crops is extremely difficult, due to the fact that other crops or plants in flower may compete for, and win, the attention of a honey bee colony (Jay, 1986). This chapter describes several main management practices that allow for efficient use of honey bees for crop pollination.

Figure 1.

Truck loaded with beehives brought for almond pollination in California

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HOW TO IMPLEMENT

Stocking rate

The aim of efficient crop pollination in an economic context is to maximize pollination with the lowest number of hives (assuming the grower is paying for the pollinating hives). The recommended hive density depends on the attractiveness of the crop, the density of it flowers, and its pollination requirements (number of required visits and demand for cross-pollination), abundance of competing food sources, weather, growers' experience, and the population density of non-managed bees. A grower can generally consider 2.5 hives per hectare as a starting point in the decision-making process (Free, 1993; Delaplane and Mayer, 2000). There are two more scientific approaches to determining optimum stocking density. Indirect extrapolation from densities of foraging bees observed in small plots, along transects away from colonies, or in cages; and, direct tests of colony densities over an entire field (Delaplane *et al.*, 2013). For the grower it would be beneficial to have some criterion (e.g. required number of bees per tree or area) for favorable foraging conditions which would allow adjusting the stocking rate according to the required bee activity on the target crop.

Hive strength

Colony strength (population) has a direct effect on its pollination activity. To ensure that only suitable honey bee colonies are used for pollination, many countries have set minimal standards for them. These standards are usually set for 'populated frames' (Figure 2) and 'brood frames' which give a good perspective on colony strength on the one hand, and are easy to assess on the other. Generally, during spring-autumn time, colonies should have at least ten populated frames, six or more of which should be populated with brood. The colony should have a laying queen and be healthy according to beekeeping standards. Since the growers who rent the hive generally have no beekeeping skills, along with those standards, an auditing service should be made available.

Distributing the beehives within the crop

Beehives need to be uniformly distributed throughout the crop site to achieve best pollination results. Hives can be placed in groups of four to allow easy transportation and easy management of the colonies during the pollination period. It is generally recommended that the largest distance between hive and pollinating plant be no more than 150 m. With greater distances, bee density might decrease, along with pollination level and yield. Under unfavorable climatic conditions, foragers' flight distance is reduced, and the distance between the beehive and

Figure 2.

Populated frame with brood and honey

© Arnon Dag

pollinating plant should be reduced to no more than 50 m. The grower can provide the beekeeper with a map of the desired placement locations or can label them in the field. In addition to distance from the crop and uniform distribution, it is best not to place hives around nearby crops which have been treated with pesticides (any substance, or mixture of substances of chemical or biological ingredients intended for repelling, destroying or controlling any pest, or regulating plant growth to avoid the risk of bee stings).

Timing of beehive introduction

The timing of a colony's introduction to a crop, in relation to the latter's blooming stage, strongly influences the number of bees visiting that crop. Many reports have shown that placing a hive in the pollinated crop before the main flowering has occurred leads to abandonment of the crop in favor of competing flowers in the vicinity with which the bees establish constancy. Therefore, it is recommended that placement of bee colonies be delayed until after blooming has started (Kevan, 1988). Although introduction of colonies at the correct time exposes the bees to massive blooming of the target crop, they still tend to gradually widen their forage area, and may even end up abandoning the target crop altogether. To overcome this problem, growers can introduce additional colonies at a later date: these new bees will first be attracted to the target crop's bloom, before discovering the competing bloom. This sequential introduction has been found to raise the number of bees foraging on the target crop. In addition to reducing the effect of competing flora, sequential introduction also improved bee mobility in the target crop, thereby increasing cross-pollination level (Stern *et al.*, 2001).

Feeding

Feeding honey bee colonies sugar syrup has been shown to increase the amount of pollen collected, which might be very useful in crops that must be pollinated by pollen collectors, such as kiwifruit where flowers do not produce nectar (Goodwin and Ten Houten, 1991). Feeding with pollen supplements or substitutes is recommended when placing colonies for pollination in enclosures (Figure 3). This feeding sustains stable levels of brood production, which are needed to achieve efficient pollination under these conditions (lack of natural forage) (Kalev *et al.*, 2002).

Figure 3.
Beehives placed for nethouse avocado pollination

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SUCCESSFUL EXAMPLES OF APPLICATION

The African shrub coffee, a pillar of tropical agriculture, was considered to gain nothing from insect pollination. However, a study conducted by Roubik (2002) showed that honey bees can enhance pollination and boost crop yield by over 50 percent.

GENERAL DO's AND DON'Ts

- Use healthy, strong honey bee colonies for pollination.
- Introduce the beehives only after the crop has started to bloom.
- Do not use pesticides which are toxic to honey bees, during the pollination period.
- Monitor bee activity in the crop and if needed, adjust the stocking rate.

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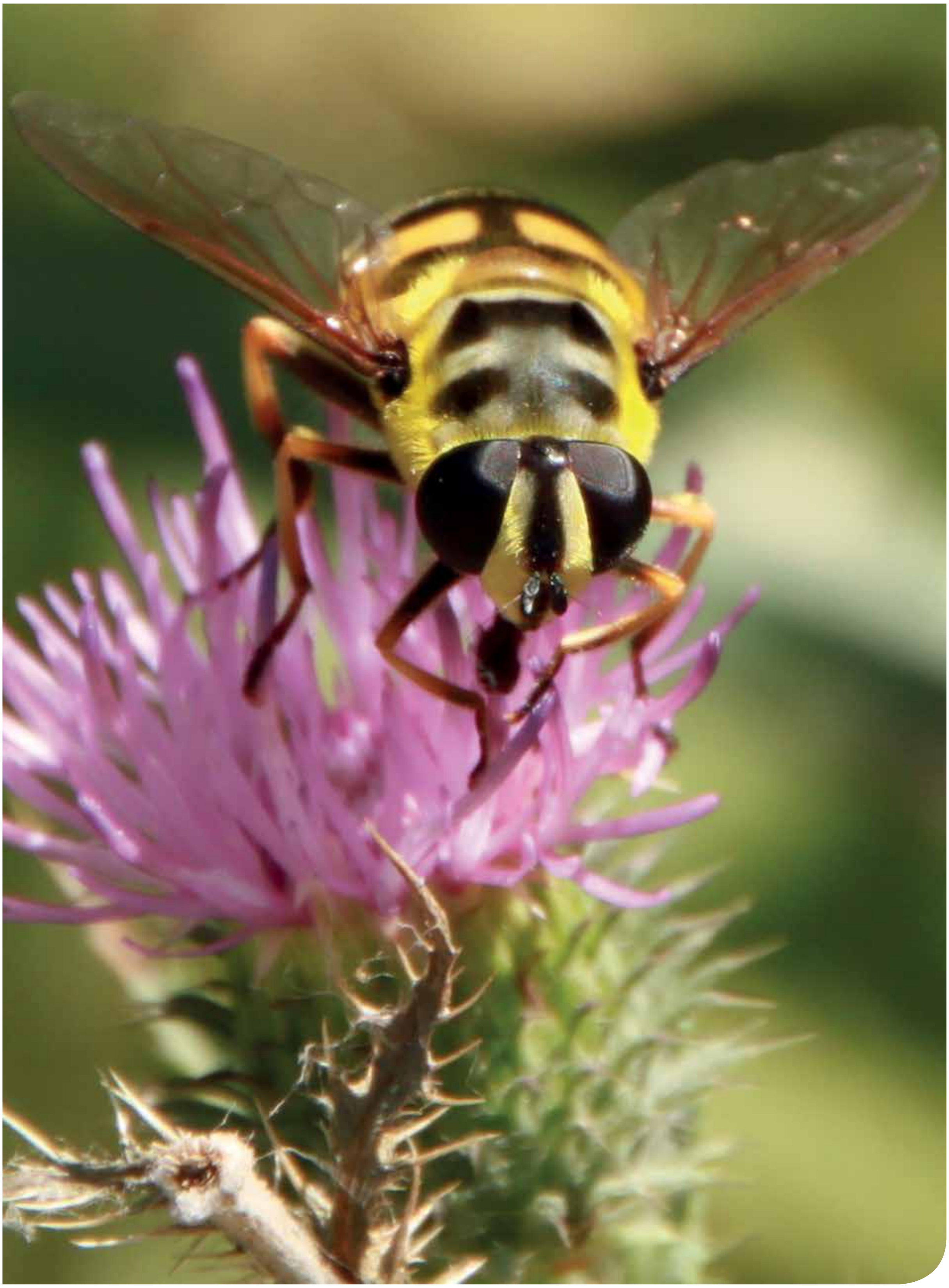

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Chapter 3

Soil management for ground-nesting bees

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REASON FOR THE PRACTICE

Ground-nesting bees: Important crop pollinators

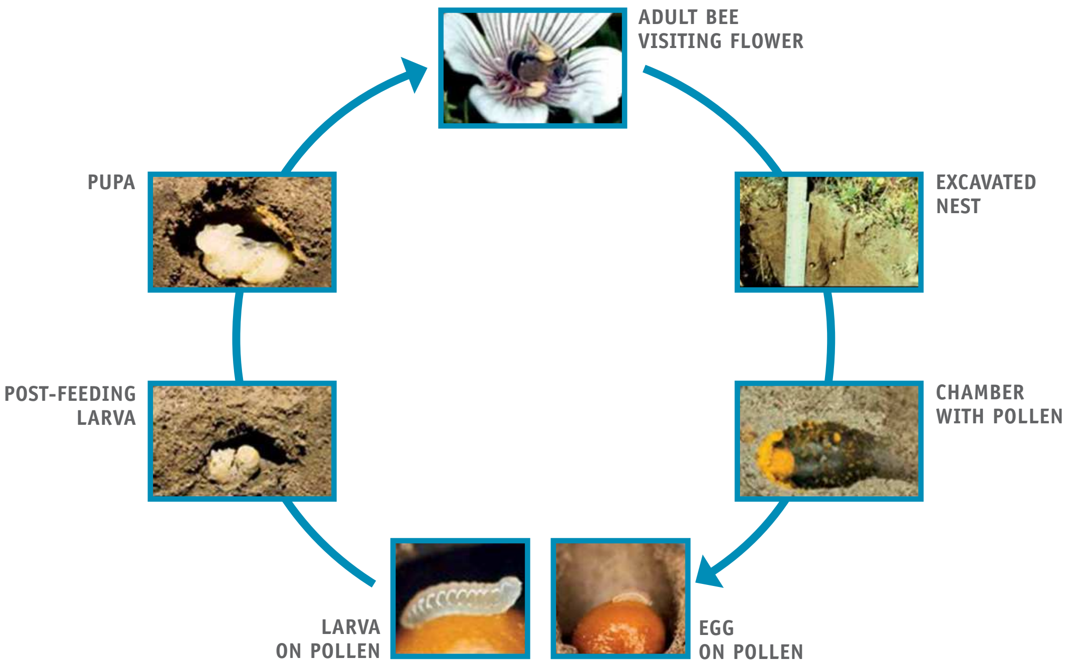
Wild bees are among the most important crop pollinators worldwide. They can increase crop yields even when managed honey bees are present (Garibaldi, 2013a). This benefit to yield is enhanced by including diverse species that contribute to pollination in different ways (Klein *et al.*, 2003). For example, different species might visit flowers during different weather, at different times of the day, or favour flowers in different parts of the plant (Hoehn *et al.*, 2008; Winfree and Kremen, 2009; Brittain *et al.*, 2012). In some cases wild pollinators are more effective than honey bees at pollinating crops (Cane, 1997, 2002, Goodell and Thomson, 1997) and can even make honeybees themselves more efficient (Greenleaf and Kremen, 2005; Brittain *et al.*, 2013). The majority of the important crop pollinating bee species nest in the ground. Managing for ground-nesting bees is, therefore, a critical component of sustainable crop pollination (Cane, 1997).

The extent to which farming practices impact ground-nesting bees will depend on the bee species. However, for many of the world's ground-nesting bees, there are no detailed management guidelines. Therefore, it is important to start by exploring what is known about the diversity of ground-nesting bees and their natural history, with an emphasis on characteristics that inform farm management practices. Then, major agricultural practices and their impact on ground-nesting bees are reviewed. Finally, management recommendations based on what is currently known about ground-nesting bees are made, acknowledging that these management guidelines should be updated as new research is published. In general, best management practices for ground-nesting bees include the following: (1) identify and protect existing nests; (2) minimize intense forms of soil disturbance (e.g. deep tillage, hot and frequent fires, intense grazing); (3) avoid surface disturbance (e.g. weed control) at times when bees are out foraging or nesting; and (4) avoid letting water pool on the soil surface.

Life cycle of ground-nesting bees

The majority of bee species, about 67 percent, create nests in the ground (Michener, 2007; Cane and Neff, 2011). Throughout the growing season and around the world, ground-nesting bees dig tunnels in soil. These tunnels end in a small cell or chamber excavated by the bee. The mother bee first provisions the cell with pollen moistened with nectar, and then lays a single egg on or in the provision. Most bees seal the finished cell with soil and proceed to excavate new side tunnels and cells, which they provision (Michener, 2007). The eggs hatch into soft-bodied larvae that

Figure 1.
Life cycle of a ground-nesting solitary bee



All photos by Dennis L. Briggs, except for the post-feeding larva and pupa which were taken by Robbin Thorp.

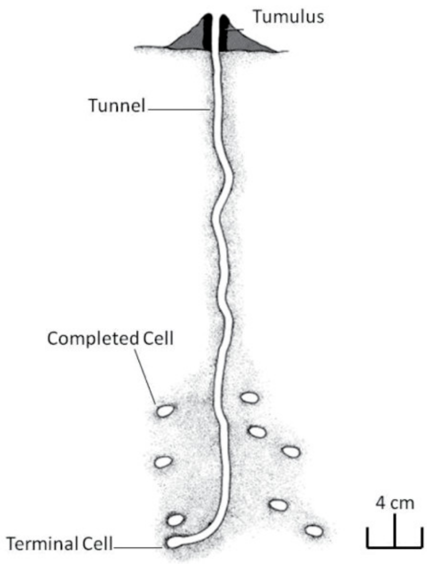
quickly eat the pollen provisioned by their mother (Figure 1). The majority of a ground-nesting bee's life is spent in this soft-bodied, immobile state. For this reason, it is important to be aware of how and when soil on a farm is disturbed by farming practices. The cycle is completed when those offspring emerge from the ground as adults.

Although most ground-nesting bees only live for one year, a particular nesting location might be used by a species of bee for many years. This fidelity to nest sites is another reason why managing land for ground-nesting bees may benefit long-term crop yields. For example, nesting aggregations of the alkali bee (*Nomia melanderi*) can persist for more than 50 years (Cane, 2008). Alternatively, bees might move their nesting location every year. This is thought to be the case for the sunflower bee, *Dieunomia triangulifera* (Minckley *et al.*, 1994) and a number of other bee species (see Rozen and Buchmann, 1990).

What do ground-nesting bee nests look like?

Bee nests do not all look alike because there are so many different species of ground-nesting bees; scientists estimate that there are 13 000 species of ground-nesting bees in the world (Cane and Neff, 2011). However, in general, the nests of all ground-nesting bees have a hole at the soil surface and a main tunnel that leads to cells where eggs and pollen are placed (Figure 2). The

Figure 2.
Nest of the bee *Tapinotaspi tucumana*



Different bee species will dig nests that display different nest architecture

Drawing courtesy of J. Rozen and the American Museum of Natural History (Rozen 1984).

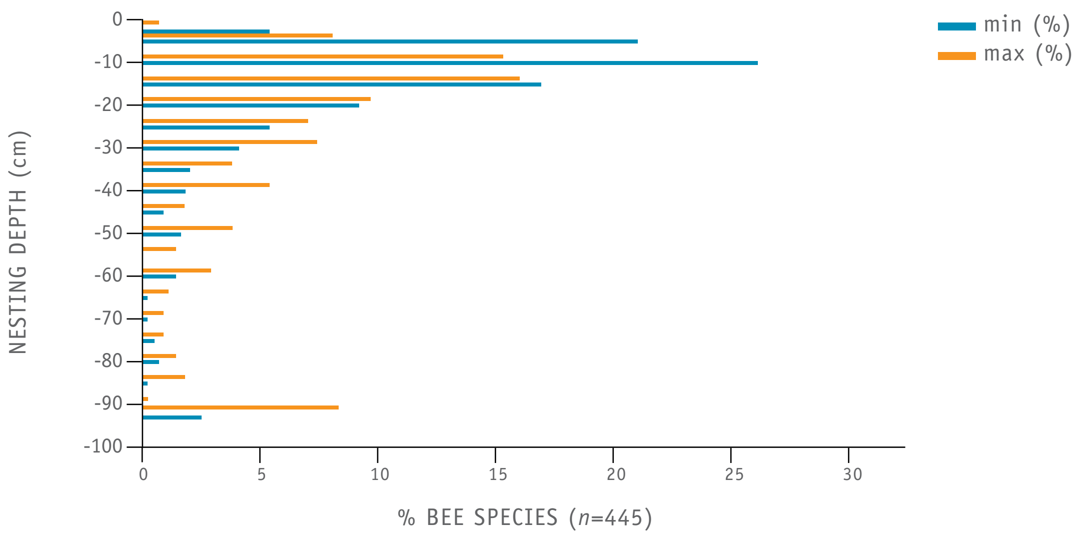
entrance and hole are usually a perfect circle just big enough to fit the bee, so their sizes are determined by that of the bee. The entrance can be located in an existing crack in the ground, against the edge of a rock, in a grass tuft or underneath plant debris. Often, it is surrounded by a small mound of soil, the "tumulus". The number of nest entrances within a given area can also vary; some species like to nest alone, while others, such as the sunflower bee (*Dieunomia triangulifera*) will nest in aggregations of up to 40 nests/m^2 (Minckley *et al.*, 1994). Managed *Nomia melanderi* will nest even more densely, with up to 1 000 nests/m^2 (Cane, 2008 and references therein).

Depending on the bee species, a nest entrance may lead to one offspring or more than ten offspring. For example, *Habropoda pallida* creates a single tunnel leading to one cell (Bohart *et al.*, 1972). In contrast, *Perdita portalis* creates a complex series of shared tunnels with many cells (Danforth, 1991). These offspring will provide pollination services later in the season if the bee species has multiple generations a year (e.g. is multivoltine) or pollinate next year's crop if the bee species has one generation a year (e.g. is univoltine).

There is also variation both within species and between species in how deep a bee will dig her tunnel. Most species nest within 60 cm of the soil surface (Cane and Neff, 2011; Figure 3). A few bee species build shallow nests within 5 cm of the soil surface (Cane and Neff, 2011). At the other extreme, females of some species nesting in sandy more arid soils dig very deep nests, apparently to access moister soil (e.g. *Habropoda pallida* digs tunnels up to 1.8 m deep; Bohart *et al.*, 1972).

Figure 3.

Minimum and maximum nesting depth for 445 species of ground-nesting bees



This data set only represents four percent of known ground-nesting bees worldwide

Source: Cane and Neff, 2011.

Where are bee nests located?

Ground-nesting bees are found around the world, including in tropical, desert, temperate and sub-polar regions. In addition to nesting in their natural habitat, bees will nest in and around farm fields and gardens. Being aware of where bees nest will help identify nests and areas where it might be important to minimize soil disturbance.

Some ground-nesting bees form nests in the ground beneath or near the blossoms they pollinate. For example, in North, Central and South America squash bees of the genus *Peponapis* only collect pollen from squash and pumpkins and prefer to nest under the vines of these plants (Hurd *et al.*, 1974; Julier and Roulston, 2009; Sardiñas *et al.*, 2016). Bees that collect pollen from a variety of crops and wildflowers sometimes also nest in or around crop fields. In Kenya, for example, sweat bees (*Lasioglossum* spp.) were found nesting in watermelon fields (Njoroge *et al.*, 2004). Additional on-farm locations where bees are known to nest include field edges, orchard floors, small garden plots and dirt roads (Table 1 and Figure 4).

In addition to nesting amid these on-farm features, some crop-pollinating, ground-nesting bees are thought to nest in the natural or uncultivated habitat surrounding farms and visit fields to collect pollen and nectar (Kim *et al.*, 2006). All bees are central nest foragers that fly

Table 1.

Examples of some farm features where ground-nesting bee nests are found

FARM FEATURE	CITATION
Crop field	Kim *et al.*, 2006; Julier and Roulston, 2009; Minckley *et al.*, 1994; Njoroge *et al.*, 2004; Cane *et al.*, 1996; Cane, 1994
Fallow crop field	Minckley *et al.*, 1994
Orchard floor	Xie *et al.*, 2009
Field edge	Mathewson, 1968; Kim *et al.*, 2006; Cane, 2008; Polidori *et al.*, 2010
Unpaved farm road	Wuellner, 1999
Hedge	Sardiñas, unpublished data
Flower strip	Williams, unpublished data
Forest fragment	Polidori *et al.*, 2010; Cane, 1994
Grassland	Straka and Rozen, 2012; Sardiñas and Kremen, 2014
Grass lawn	Cane, 1995; Hurd *et al.*, 1974
Garden bed	Cane, 1995; Gemmill-Herren, pers. observation
Sandpit	Rajotte, 1979; Gebhardt and Roehr, 1987; Riemann, 1988; Heneberg *et al.*, 2013
Levee and dykes	Westrich, 1985; Cane, 1996; Ullmann, pers. observation

Figure 4.

Some ground nesting bees nest in aggregations such as this one pictured below

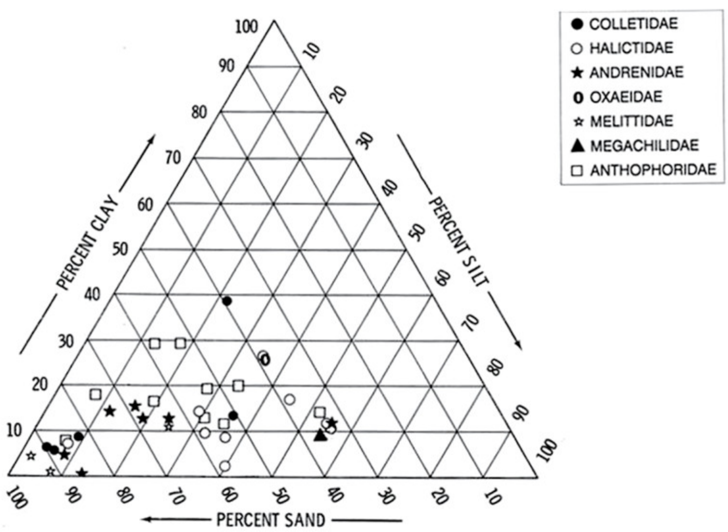
© Katharina Ullmann

out from a nest to collect resources for their offspring. They will only be able to collect pollen from flowers and pollinate crops within flying distance from their nests. Large ground-nesting bees can fly more than one kilometer from their nests (Greenleaf *et al.,* 2007). Small sweat bees (*Lasioglossum* spp.), on the other hand, may only fly 50 meters from their nest. As a result, it is important to consider the soil management practices of the crop field *and* the surrounding area.

In general, ground-nesting bees are commonly found nesting in moderately moist sands and loams that have little plant cover and warm soil surface temperatures (Figure 5; Westrich, 1985; Cane, 1991; Potts and Wilmer, 1997; Wuellner, 1999). Some species are very flexible and nest under a variety of environmental conditions. For example, *Habropoda laboriosa*, a blueberry pollinating bee, was found nesting, both in areas with and without leaf litter (Cane, 1994). Other species appear to be highly selective, always nesting in the same microhabitat. For example, in a recent study of sunflower farms and hedgerows, although vegetated field borders had higher numbers of bees nesting in them than did sunflower fields, nests of sunflower specialized bees were found only in sunflower fields. (Sardiñas *et al.,* 2016). Hard and compacted soils are generally avoided by ground-nesting bees such as *Halictus* (Potts and Willmer 1997, Sardiñas and Kremen, 2014) as they are more difficult to excavate, but other species prefer nesting in dirt roadways or clay soils (Roubik, 1989; Wuellner, 1999). In addition, some bees choose to nest on sloped ground, or sandy or clay vertical banks (Michener *et al.,* 1958; Coville *et al.,* 1983; Batra, 1997a; Potts and Willmer, 1997).

Figure 5.

Soil texture associations for different bee families found in the United States of America



Source: Cane, 1991. Figure courtesy of Jim Cane.

HOW TO IMPLEMENT BEST MANAGEMENT FOR GROUND-NESTERS

1. Protect existing nest aggregations

Management methods that induce bees to nest in soil have been extensively worked out for only a few bee species, the best example being *Nomia melanderi* (Fronk and Painter, 1960; Stephen, 1960; and Cane, 2008). For this reason, **the most important recommendation for management is to protect existing nesting sites.**

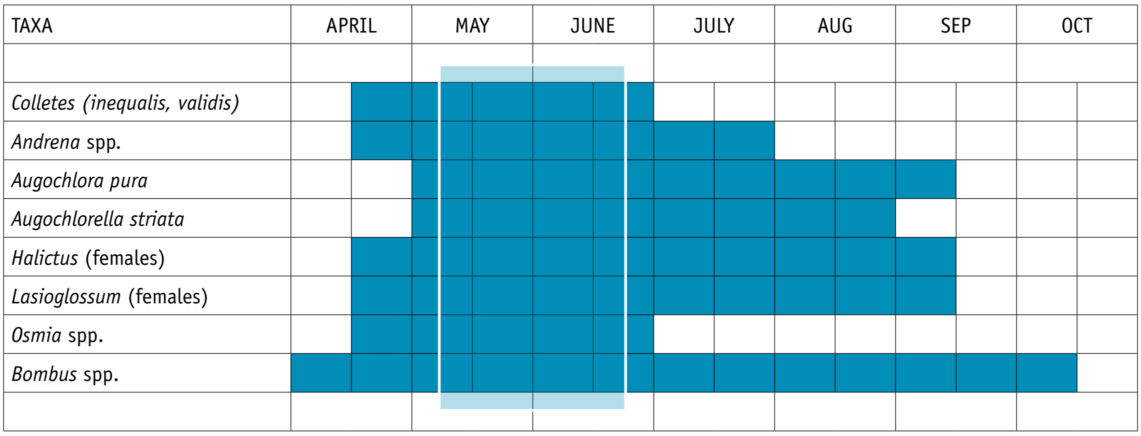
Locate nests on your farm: Walking around a farm, field or garden, you may notice mounds surrounding a hole the diameter of a pencil or smaller. Some of these mounds are the tumuli of bee nests, consisting of the excavated soil a bee pulled up from the tunnel she dug. The tumuli are typically mounded with the circular hole near the center. Or, if the bee is nesting in sand, there might be a pile of sand pushed to one side of the hole). Unlike ants, the soil clumps of bee nests are irregularly sized (as they typically push rather than carry soil loads away). Some genera add a soil turret or tunnel on the surface. To ensure the entrance belongs to a bee and not another soil dwelling organism you can either observe the hole or place a clear cup over the nest entrance. Sit and watch the cup or check it within an hour. If you see a bee with pollen on its legs trying to get into the nest entrance or a bee trapped under the cup, you will know that you have a bee nest (Barthell *et al.*, 1998).

Avoid disturbing bee nests: After a bee nest or nesting aggregation has been identified, avoid disturbing the area for at least one year, so that bees within can successfully complete their life cycle. In cases where the species is known to have persistent nest sites, consider setting aside that piece of land. Additionally, if possible, maintain the management practices that led to the persistence of that aggregation. For, example, if the area has always been mowed, keep mowing it. Major forms of disturbance, such as deep tilling, should be avoided (Mathewson, 1968). Agricultural practices that may affect soil-nesting bees include tillage, irrigation, fire and livestock management. We assume that the intensity of the disturbance and the timing relative to that of the bee life cycle are important to consider.

In temperate zones, many bees will fly as adults for four to six weeks and spend the rest of their lives underground developing or quiescent. Many bees have one generation a year (univoltine) and emerge from the ground sometime in spring to summer. Among species which have two or three generations in a given year (multivoltine), the first generation typically emerges in early spring and the last generation emerges in early fall. Whether univoltine or multivoltine, most ground-nesting bees are in a vulnerable state, underground, between late fall and early spring (Table 2).

Table 2.

Flight periods of pollinators of blueberry in Canada



The dark blue boxes show the flight periods of pollinators. The light blue box shows the timing of blueberry bloom. *Colletes* spp., *Andrena* sp., *Augocholora* sp., *Augochlorella* sp., *Halictus* spp., and *Lasioglossum* spp. are all ground-nesting bees. *Bombus* spp. will also nest in old rodent burrows or under thatches of grass. White boxes show the time when bees are developing in their nests and subsurface disturbance should be avoided

© Data from Steve Javorek, Agriculture Canada

Consider setting aside land for bees: For many land managers or farmers, it will be difficult to see or find bee nests unless they come across a large aggregation. An alternative or complementary strategy is to encourage and protect on-farm features that experience minimal disturbance (e.g. hedges or weedy field borders) and the surrounding natural habitat. In addition, given that detailed nesting requirements for most species are unknown, simply creating diverse microhabitats or potential nesting areas, on the farm might prove beneficial. However, research needs to be conducted to determine how effective this management strategy is.

2. Minimize frequent, deep tilling

Tillage practices are used to incorporate soil amendments, prepare seedbeds, and manage crop residues, weeds, and some pests and diseases. Deep tillage practice includes the use of moldboard, chisel, and rotary ploughs. Of these three implements, the chisel plough is thought to be the least intense. Shallower tillage practices include the use of field cultivators, disks and harrows (Shearin *et al.*, 2007). Both deep and shallow tillage practices disturb or turn soil. **The impact of a particular tillage practice on ground-nesting bees will likely depend on the depth, type, frequency and timing of the practice, the biology of the bee species, and soil and climate conditions.**

Not surprisingly, below-ground nesters are more negatively affected by tilling than above-ground nesters, such as those leafcutter bees that nest above ground (Williams *et al.,* 2010). Many ground-nesting bees nest within 30 cm of the soil surface (Roulston and Goodell, 2008). However, the extent and impact of tillage on ground-nesting bees are unknown (Ullmann *et al.,* 2014). The potential negative effects of tilling include deadly injuries from compaction, cracking the impervious cell lining (Cane, 1981), or encountering the implement as it passes through the soil. Tilling may also expose bee larvae or pupae to pests, diseases and desiccation, and alter soil moisture and temperature (Roulston and Goodell, 2008). These soil characteristics may act as emergence cues for ground-nesting bees. Alternatively, tilling may potentially benefit bees by creating open bare ground, loosening compacted soils, or changing the predator community.

Anecdotal evidence suggests that tillage can directly impact bee survival and emergence. For example, a squash bee (*Peponapis pruinosa*) nesting aggregation that had persisted for two years on a field margin was greatly reduced after the farmer tilled the margin (Mathewson, 1968). Similarly, a sunflower bee (*Dieunomia triangulifera*) nesting aggregation in a dirt road that was tilled emerged four days later than bees nesting in a dirt road that was not tilled (Wuellner, 1999). However, studies on squash and pumpkin (*Cucurbita* spp.) farms in the United States gave conflicting results; in one case there was no difference in the abundance of bees between tilled and untilled farms (Julier and Roulston, 2009), while in the second study, tillage had a substantial impact (Shuler *et al.*, 2005). These two studies did not directly measure the impact of tillage, but instead looked to see if the number of bees in a field was related to whether or not the previous season's crop had been tilled. A third study on squash bees *(Peponapis pruniosa)* found that a tillage treatment that included disking (15.24 cm deep) and chiseling (40.64 cm deep) killed roughly 50 percent of the overwintering larvae (Ullmann, unpublished data). However, tilling did not always have a negative effect on offspring survival.

Additional studies from other soil macrofauna, including earthworms, beetles and flies (Kladviko, 2001) indicate broadly consistent effects of tillage. In general, tilling has a negative effect on some species, with larger organisms being disproportionately more sensitive to tillage than smaller organisms (Kladviko, 2001). One study in the United Kingdom found that 50 percent more sawflies emerged in fields left untilled than in fields that had been ploughed to a depth of 25 cm (Barker *et al.,* 1999). Similarly, in Maine in the United States, beetle activity was more than 50 percent higher in untilled fields and fields that had been chiseled 20 cm deep than in fields that had been mouldboard ploughed 25 cm deep or rotary tilled 15 cm deep (Shearin *et al.,* 2007).

Recommendations in relation to tillage practices:

- When possible, use reduced-tillage practices the year after bees are seen nesting in the field. This will be particularly important for fields planted in crops known to attract ground-nesting bees.
- When possible, consider minimizing the frequency and depth of tilling. For example, strip tillage has been used to provide nesting opportunities for alfalfa seed pollinators in Europe.
- *Note*: Many species have some larvae nesting below most tillage zones (Figure 2). Therefore, while tillage is thought to have a negative impact on offspring survival, the extent of that negative impact will depend on the nesting depth of the species and the type of implement used.

3. Minimize flooding, but keep soil moist

In arid climates or during droughts, farmers will irrigate their fields. Irrigation methods include flood, furrow, drip, sprinkle and hand-watering. These methods differ in their efficiency and the extent to which they allow water to pool on the soil surface (Prichard *et al.*, 2013). Many ground-nesting bees coat their larval chambers with a waterproof lining (Cane, 1981); however, for most, it is not known how long a chamber can withstand saturated soils. In addition, if the nest is under construction and a larval chamber not yet sealed, water can flood the cell. For some species, prolonged flooding of established nests can cause entire populations to die (Fellendorf *et al.,* 2004) although other species seem impervious to flooding (Cane *et al.,* 1996). A species' ability to withstand being submerged under water will likely depend on what it usually experiences under natural conditions and the nature of its cell lining. For example, a number of bee species that nest in dry ponds, marshes and flood plains in temperate, Mediterranean and tropical zones can withstand flooding (Roubik, 1989; Norden *et al.,* 2003; O'Toole and Raw, 1999; Visscher *et al.*, 1994; Cane, 1996). Nonetheless, when exposed to water, some developing bee species will die (Greenberg, 1982). Therefore, **over-watering may negatively impact ground-nesting bee survival.**

The majority of bees forage for pollen and nectar during the day, typically during warm, dry and sunny conditions. Females use landmarks around their nest to orient themselves (Zeil *et al.*, 1996). If these landmarks are altered by watering while females are out foraging, then they may have difficulty finding their nest upon their return. When not collecting pollen provisions female bees excavate their nest. As they work some females will plug up the nest at or near the nest entrance using soil from excavated tunnels (Hurd *et al.*, 1974.) The next morning they will dig their way out. Watering at night may, therefore, be better for ground-nesting bees than watering during the day if using overhead, furrow or flood irrigation. Observations of squash bees (*P. pruinosa*) found "no adverse conditions" from watering at night (Hurd *et al.*, 1974.)

Despite the risks of flooded nests, soils with at least some moisture are easier for the bee to excavate, and at cell depth, seems important for larval water balance and uptake (May, 1972). Many ground-nesting bee species will nest in moist soil and some species, such as the sunflower bee (*Dieunomia triangulifera)*, actually prefer to nest in moist soils (Cane, 1991; Wuellner, 1999; Potts *et al.,* 2005). In addition, soil moisture stimulates some species, such as lab-reared sweat bees (*Lasioglossum zephyrum*), to excavate nests (Greenberg, 1982). In fact, a large scale study found that farms that used overhead or drip irrigation had more squash bees (*Peponapis pruinosa*) than fields that were not irrigated (Julier and Roulston, 2009). In addition, irrigation can have the indirect effect of increasing pollen and nectar resources by stimulating flowering (Boreux *et al.,* 2013).

Recommendations in relation to irrigation management:

- Avoid irrigation methods that cause cells to be inundated with water, especially during the cell-provisioning phase. These methods include flood irrigation, furrow irrigation and heavy hand-watering.
- If soils are hard or compacted, consider irrigating using methods that minimize pooling of water, but still moisten the soil such as drip irrigation, light hand-watering and overhead micro-sprinklers.
- If flood, furrow or overhead irrigating, avoid watering during the day when bees are actively foraging. Instead, water at night or when weather is unfavorable to bee flight (e.g. when it is cold, windy and/or overcast).

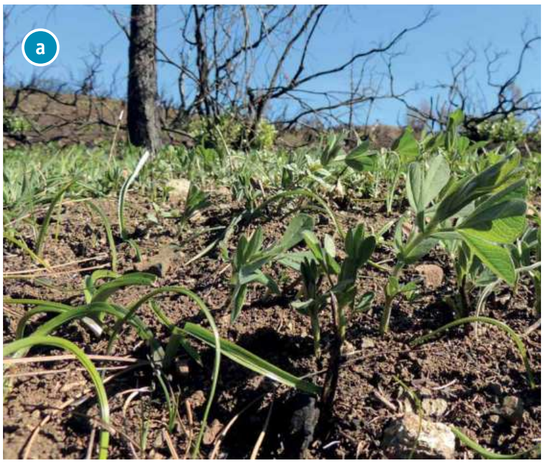
4. Avoid hot, frequent fires

Fire or burning is a management technique used to control weeds, remove field residue or create new fields. Burning may benefit ground-nesting bees by creating open space for flowering plants and bare ground for nesting (Figure 6). However, fire may also kill bees and potentially change bee development or emergence time.

Slash-and burn-practices are thought to reduce ground-nesting bee populations (Eardley, 2009). However, other studies in temperate zones found that most bees (e.g. bee species that nest deeper than 10 cm) will survive fires, and only the shallowest nesting species (e.g. those that nest less than 5 cm below the soil surface) will be lethally heated (Cane and Neff, 2011). The likelihood that a bee will die from fire will depend on how hot the fire burns, fire residence time, ashing of any duff layer, and bee nesting depth (Cane and Neff, 2011). Fires will burn hot when soils and dry surface fuels are plentiful.

Figure 6.

Fires can burn and snag above-ground bee nesting habitat and can remove floral resources in the short term (6a). However, fires can also open up space for wildflower seed in the seed bank to germinate and provide abundant and diverse blooms (6b)



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Both photos were taken in northern California, United States of America after a fire burned through a natural reserve

A number of studies of bees in natural areas found that there were more species of bees in the years immediately following a fire than in old burn sites (Potts *et al.*, 2005). In these cases, fire benefits bees by creating patches of bare, open ground where bees can nest and flowers can grow. Since only small fires were studied, foraging bees could have readily flown from beyond the fire perimeters. Over time, though, the burned area will become overgrown, potentially covering up nesting sites and crowding out some flowering species, unless another burn occurs.

Recommendations in relation to fire management:

- When possible, avoid very intense fires at high frequencies (lop-and-scatter residue rather than piling slash to burn).
- When possible, avoid burning an entire area or field, instead consider burning patches of an area.
- Periodic burning of natural vegetation – at low intensities and when flowers are not in bloom – may benefit bees by creating open space and room for flowers to grow.

5. Minimize intense grazing and mowing

Livestock, including cattle, sheep, goats, pigs and poultry, have traditionally been used to remove crop or weed residue from fields while adding fertilizer (e.g. manure). Mowing or mechanical weeding can also be used in fields to remove weeds or cut back crop residue. Grasslands are used as forage for livestock, either by allowing livestock to graze the grasslands or by mowing the grasslands to produce hay. The impact of livestock and mowing on ground-nesting bees will likely depend on the type of livestock kept, stocking rates, the timing, duration and intensity of grazing or mowing, and the soil type. Potential negative impacts of grazing include loss of bloom, trampling of adult bees, soil compaction and destroying established nests and nest landmarks (Sugden, 1985; Gess and Gess, 1983). Mowing is thought to have similar negative impacts on ground-nesting bees (Cane, pers. communication). Alternatively, intermediate grazing by livestock may also increase floral resources by minimizing thatch build up and creating open bare ground and microhabitats, such as patches with compacted ground which might enhance ground-nesting bee populations (Kimoto *et al.,* 2010).

Some bees are thought to prefer to nest where cattle graze, when cattle grazing creates bare ground or space for flowers to grow (Vulliamy *et al.*, 2006; Kimoto *et al.*, 2010). Additionally, at least one species of ground-nesting bee (*Osmia (Acanthosmioides) integra*) found in the United States will nest in dried cow dung (Cane, 2012). However, more research is needed to understand the impact of grazing on ground-nesting bees.

Different types of livestock can impact ground-nesting bees in different ways. For example, a study from Mongolia found that there were fewer pollinators in areas grazed by sheep than in areas grazed by cattle (Yoshihara *et al.,* 2006). Intensive grazing regimes are thought to more negatively impact bees, but studies testing the effect of cattle grazing intensity on bees have produced conflicting results (Vulliamy *et al.*, 2006; Sjodin *et al.*, 2008).

Mowing has potentially similar positive and negative impacts on pollinators; however, mowing cuts back all flowering plants and does not concentrate organic nutrients or replenish soil (Bullock *et al.*, 2011 *in* Woodcock *et al.,* 2014). In a study conducted in temperate United Kingdom, grazed plots had more leguminous flowering plants than mowed plots (Woodcock *et al.,* 2014).

For both grazing and mowing, researchers think the timing and frequency of the practice impacts bee abundance and diversity. In general, there are more flowering plants for bees in grasslands where mowing and grazing are infrequent (Knop *et al.,* 2006; Kearns and Oliveras, 2009). Timing of grazing or mowing seem important, but optimal management strategies are still being developed. However, recently, researchers found that mowing early in the season, but leaving 10-20 percent of an area untouched, benefited bee diversity and abundance the following summer and into the next year (Buri *et al.*, 2014). These areas had more bees and a greater diversity of bees than areas that were mown in their entirety early in the season or late in the season. Untouched areas may act as refuges where nests and floral resources remain undisturbed.

Figure 7.

Abundant wildflowers can bloom and be used by ground nesting bees when grazing is managed properly

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Recommendations in relation to livestock management:

- Avoid grazing, mechanical weeding and mowing when there is ground-nesting bee activity or when flowers are in bloom. If it is necessary to graze, weed or mow, consider grazing sections of a field or allotment rather than the entire area.
- Avoid too frequent or intensive grazing of an entire area if few other floral resources or nesting sites are available in the area. Instead, consider leaving small fenced off areas where grazing or mowing does not occur, or graze pastures in rotation on different annual progressions.
- Periodic grazing at moderate intensities, or brief intensive periods when flowers are not in bloom, may benefit bees by creating open space and room for flowers to grow while lessening grass competition.

SUCCESSFUL EXAMPLE OF APPLICATION

The Alkali Bee (*Nomia melanderi*): The alkali bee provides an illustration of how applying knowledge of bee biology and understanding the agricultural landscape and pollination context can lead to successful management of a ground-nesting bee, and improved pollination services. This bee, which is native to western North America and used to pollinate alfalfa seed, forms large nesting aggregations in bare, moist or silty soils with salty surfaces (Figure 5; Cane, 2008). Even amid intensive conventional agriculture, managed alkali bee populations will grow to vast numbers and their nesting aggregations will persist for decades.

One such protected “nesting bed” of 1.5 ha in Washington State in the United States has persisted for over 50 years, and produces an estimated 5.3 million bees annually to pollinate nearby alfalfa seed production fields. Where shallow (2 m) water tables are lacking, farmers sub-irrigate nesting beds to create the moist soils and salty surface the bee likes; they avoid tilling and surface-irrigating beds. In addition, because nests are relatively shallow, farmers can cut, dig up and relocate 0.03 m^3 blocks of soil with nest cells to seed newly created alkali bee nesting beds. For this unique species, detailed management guidelines on how to establish and manage an alkali bee nesting aggregation are available.

Australian Blue Banded Bee (*Amegilla* spp.): In Australia, blue banded bees (*Amegilla* spp.) can be used to pollinate greenhouse tomatoes (Hogendoorn *et al.*, 2006). In India, this same group of bees pollinates wild cardamom (Kuriakose *et al.,* 2009). Dollin (2006) developed a method to manage blue banded bees in portable adobe blocks. These blocks are formed by filling sections of 10 cm x 6 cm PVC pipe with fine, powdery clay moistened with water and creating two “starter” holes by pushing a pen into the wet soil. When the clay is dry the nest blocks can be placed in clusters near flowers to attract the bees.

Other ground-nesting bees: Methods for managing other ground-nesting bee species are still being developed. In the United States, researchers were able to maintain a Japanese bee (*Anthophora pilipes villosula*) used for blueberry pollination in portable adobe blocks (Batra, 1997b). In New Zealand, methods to transfer a bee for onion pollination, *Leioproctus huakiwi*, using soil cores and porcelain beads were also developed (Donovan *et al.,* 2010).

GENERAL DO's AND DON'Ts

The majority of bee species nest in the ground. However, little is known about their nesting needs. As a result, researchers are still developing best management strategies for many ground-nesting species. The following guidelines are, therefore, a starting point and should be updated as new research becomes available.

- Look for existing ground-nesting bee tumuli and nests and protect these.
- Where crops are grown that are known to need ground-nesting bees, minimize soil disturbance (e.g. deep tillage, hot and frequent fires, intense grazing).
- Avoid letting water pool on the soil surface, especially where bees are likely to nest.
- Create different microhabitats on your farm by using a diverse set of management strategies by:
  - protecting areas that experience minimal disturbance such as hedges;
  - actively creating patches of open, bare ground for bees to nest in and for flowers to grow by applying low and infrequent disturbance in the form of grazing or fire;
  - setting aside and protecting small patches of ground representing different soil types;
  - actively creating or protecting stable, vertical soil banks or berms.

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Chapter 4

Substrate management for cocoa pollinating midges

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REASONS FOR THE PRACTICE

Generally, one thinks of improving pollinator habitat by increasing floral diversity on farms, with hedgerows or flowering buffer strips, for example. However, in the case of cocoa (*Theobroma cacao*), the measures needed to ensure good pollination are quite different.

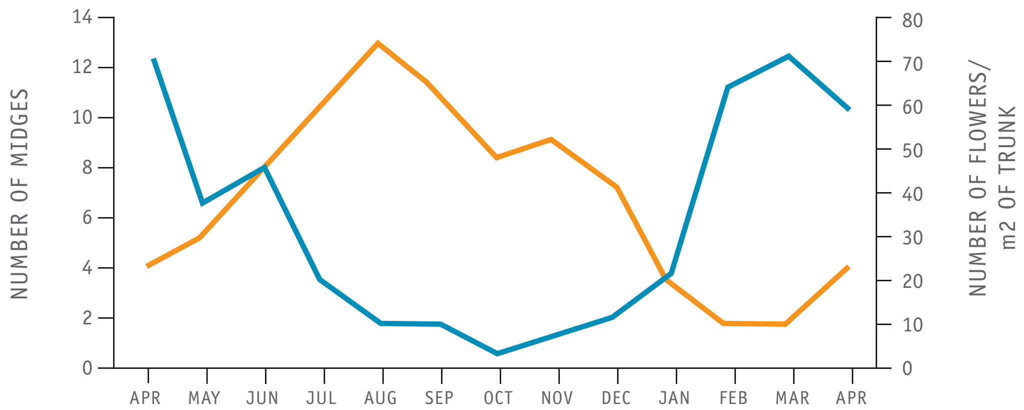
With the exception of the West African Amelonado cultivar (which is being phased out of commercial cultivation due to its low yield and susceptibility to pests and diseases), cocoa is a self-incompatible crop. The plant therefore depends on biological agents to pollinate its flowers. A suite of insects visit the cocoa flower but the majority of them cannot effectively pollinate it, because of the intricate arrangement of the cocoa plant floral parts.

Ceratopogonid midges are currently known to effectively pollinate cocoa flowers. These pollinating midges breed in moist, decaying organic materials including leaf litter, cocoa pod husks, logs and stems of banana and plantain (Kaufmann, 1975; Brew, 1988; Frimpong *et al.*, 2011). The suitability of these substrates depends on the moisture content, which, in turn, is dictated by rainfall. Thus, breeding substrates are plentiful during continuous rainfall and become scarce during spells of dryness.

Most geographical areas suitable for cocoa have distinct prolonged rainfall and short dry seasons leading to major and minor cocoa seasons. Current global climatic changes have resulted in erratic rainfall patterns that will consequently affect availability of suitable breeding substrates for midges. Even under the established climatic conditions, peak flower bloom of cocoa is out of phase with midge population dynamics and supplementary breeding substrate management has been recommended (Young, 1982; Frimpong *et al.,* 2009) (Figure 1).

Figure 1.

Asynchrony in peak population of midges and cocoa flowers



MEAN NUMBER OF MIDGES AND FLOWER PRODUCTION IN COCOA FARMS, KUMASI, GHANA, FROM APRIL 2007 TO APRIL 2008

HOW TO IMPLEMENT IT

Provision of breeding substrates

The objective of this guidance using examples from Ghana, is to help farmers, land managers and other practitioners understand the importance of providing suitable breeding conditions for midges by manipulating breeding substrates within the cocoa agroecosystem.

Leaf litter management: Insecticide spraying against sucking bugs (major cocoa pest) is undertaken during latter parts of the rainy season (August-December). Though depleted adult midge populations appreciably recover after spraying during rainy periods, immature forms are affected (Frimpong-Anin *et al.,* 2013). To reduce the impact of insecticides and enhance midge population recovery, the ground leaf carpet must be overturned to displace contaminated leaves found on the surface, a few days after spraying.

Cocoa pod husk management: In Ghana, cocoa pod husks are identified as the most important breeding substrate and are usually heaped at designated places in cocoa farms during pod breaking (Figure 2). The depth of pod heaps is not critical during the rainy period since high humidity enables the pod husks to stay moistened for long time. However, more pod husks are needed and the heap must be at least one meter high prior to the onset of dry season in December, in order to maintain a satisfactory breeding environment for the midges (Kaufmann, 1975).

Figure 2.
Heap of cocoa pod husks

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Figure 3.
Mud trough filled with cocoa pod husks

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Figure 4.
Chunks of plantain/banana stems

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There is, therefore, the need to take advantage of the abundant pod husks produced in the major harvesting season between July and December.

Banana/plantain stem management: In smaller farms where the quantity of pod husks is inadequate, artificial mud troughs can be constructed to generate moist internal conditions similar to those of voluminous heaps of pod husks (Frimpong, 2009; Figure 3). The mud trough is filled with chunks of banana/plantain stems (Figure 4) or a mixture of banana/pod husks or plantain/pod husks.

Alternatively, mud troughs can be replaced with uncut banana/plantain stems. These can be used throughout the year and can be a useful way of sustaining midge population during erratic rainfall. It is important to note that banana/plantain stems rot faster than the pod husks and thus, have to be replaced regularly.

Agricultural practices

Newly established cocoa farms are usually interspersed with banana or plantain to provide shade for the growing seedlings but these die off when the cocoa canopy closes. Frimpong *et al.,* (2011) found, however, a positive correlation between clusters of standing plantain/banana and midge abundance, and hence fruit-set. Some cocoa trees normally die off as they grow, leaving open spaces (popularly called 'parks' in Ghana) within the closed canopy. These 'parks' can be filled with plantain/banana to build up more midge breeding microhabitats (Figure 5). The plantain/banana can also be planted as hedgerows at the boundaries of cocoa farms (Figure 6). Note that dense clusters are more appropriate.

Figure 5.
Open space filled with banana

Figure 6.
Plantain as a boundary crop

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SUCCESSFUL EXAMPLE OF APPLICATION

Cocoa farmers in Ghana have acknowledged that cocoa trees planted near cocoa pod husk heaps tend to produce more pods than most trees farther away (Kwapong and Frimpong-Anin, 2013). Proper management of pod husks and other substrates, as described in this chapter has proven beneficial in cocoa farms in Kubease, Ghana.

GENERAL DO's AND DON'Ts

- Cocoa pod husks are always available in cocoa farms and therefore, conscientious management must be incorporated into general farm practices.
- Denser plantain/banana clusters are preferable and cut stems must be left at the base of the standing cluster.
- Cocoa pods infested with black pod disease must be separated during pod breaking and subsequently buried. This is because infested pods still harbour the pathogen that causes the disease and can easily spread to infest healthy pods if included in the heaped pod husks.

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Chapter 5

Innovative mud hive for rearing the indigenous honey bee, *Apis cerana*

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REASON FOR THE PRACTICE

In the Hindu Kush-Himalayan (HKH) region, farmers have traditionally managed the indigenous honey bee *Apis cerana* in log and wall hives close to their homesteads (Figures 1 and 2). Space was reserved in the walls of stone houses for the hive, with a small entrance hole to the outside (Figure 2) and a covered space on the inside of the house (Figures 3 and 4), only deep enough to occasionally uncover and harvest honey. This native bee is known to better survive winter in wall hives compared to freestanding hives or wild colonies. But, as there are less and less of these traditional, thick-walled houses, this form of beekeeping is disappearing. It is unfortunate to see the consequent loss in population of this indigenous bee.

Here, we present a new technology for low-cost mud hives for rearing the indigenous honey bee, *Apis cerana*. This technology was developed through an international project funded by the International Centre For Integrated Mountain Development (ICIMOD) in Kathmandu, Nepal during 2007 to 2008; and further tested in farmers' fields from 2009 to 2012 under a National Bank For Agriculture And Rural Development (NABARD) funded project at the Regional Horticultural Research Station, Bajaura (Kullu), Dr. Yashwant Singh Parmar University of Horticultural and Forestry, Nauni, Solan, Himachal Pradesh (HP), India.

This mud hive is a "fixed bee hive", so named because it is fixed in one place and cannot be shifted from one place to other as can be done with Bureau of Indian Standard (BIS) wooden beehives. However, the frame size of the mud hive is exactly the same as that of BIS-type

Figure 1.

Log hives

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Figure 2.

Outside view of two walls

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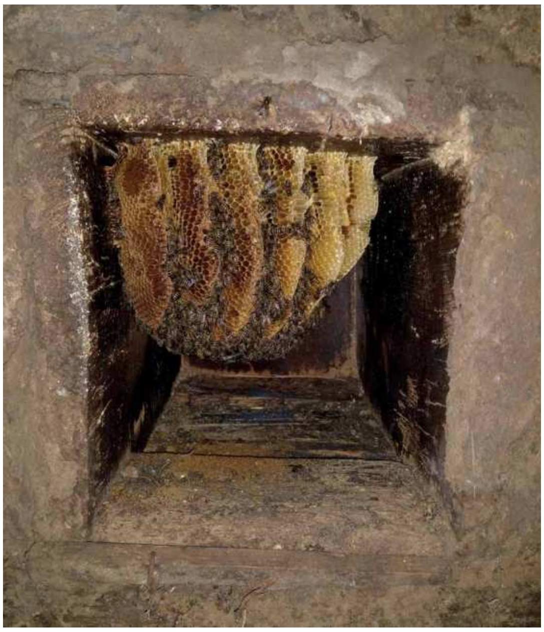
Figure 3.

Inside view of the wall hive before opening

© J.P Sharma

Figure 4.

Inside view of the wall hive



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hives. Therefore, frames of this fixed hive are movable and can be shifted from one fixed hive to another hive, as well as from fixed hives to BIS wooden hives. The mud hive has the qualities of both modern and traditional hives. It is made up of materials easily available to the farmer: clay, cow dung, stones, grass, straw and wooden sticks. However, for rearing bees, the farmers/ growers will have to purchase BIS bee frames, a piece of hessian cloth and a small beekeeping kit comprised of a hive tool, bee veil, knife, small hammer, nails, etc.

After a five-day training programme, a farmer can easily start beekeeping with *A. cerana* using this hive. Even if a farmer must purchase the top cover, inner cover, dummy board and BIS frames (which the farmer could make free of cost by using available materials), estimated costs for this fixed hive are no higher than USD 8, whereas the cost of a BIS wooden hive is around USD 22. Moreover, this hive has performed better than BIS hives under conditions in the Kullu Valley and its adjoining areas of northern India, as bees rear their brood about three times faster in this hive as compared to BIS wooden hives. Absconding has also been reduced in this type of hive due to adequate insulation which, when lacking, is a major problem with indigenous honey bees.

The fixed beehives with movable frames, made in different parts of the Kullu Valley and its surrounding areas, have helped increase the population of this species by providing more suitable sites for its rearing. The results of this project will lead to improved farmer incomes and better livelihood opportunities for the growers/beekeepers through:

- Effective pollination of apple and other fruit crops, thereby increasing fruit set and returns to the growers.
- Sale of honey and other bee products.
- Reduction in spending on hiring bees for pollination.
- Earned incomes from renting out bees to other growers. This is done by shifting bees from a mud hive to BIS wooden hives which are then taken to the desired sites. After pollination, the bees are returned and shifted into the mud hives.

Table 1.

Showing comparison between mud and BIS hives

FEATURE	MUD HIVE	BIS HIVE
Hive temperature in summer	6-8 °C lower than BIS hive temperature	6-8 °C higher than mud hive temperature
Hive temperature in winter	4-5 °C higher than BIS hive temperature	4-5 °C lower than mud hive temperature
Average honey yield (kg) * range values	4.01 (3.5-9.5)*	2.6 (2.1-5.5)*
Bee wax moth incidence	low	medium to heavy
Rodent attack	medium	negligible
Swarming and absconding	rare	frequent
Brood rearing	excellent	good

Source: Sharma, 2012

HOW TO IMPLEMENT IT

This mud hive is constructed on a platform of stones (63.5 cm x 63.5 cm x 30.5 cm) (Figure 5). The side walls of this platform are plastered with mud and cow dung paste or with cement. A cemented channel (5 cm wide and 7.5 cm high) is constructed on the base to check the entry of ants into this hive (Figure 14). Some beekeepers have built mud hives on an iron stand, using a wooden plank (Figure 16). For making one mud hive, about 40 kg of clay soil, 5 kg of fresh cow dung, 2 kg of wheat/paddy straw and 8 kg to 10 kg of small stones are needed. Clay soil, cow dung and wheat/paddy husk are mixed together, in proportion. As needed, water is poured over this mixture for wetting it overnight.

The following day, this mixture is blended completely for preparing the raw material (Figure 6). This raw material should neither be hard nor loose. Then, a block made of an iron sheet or wood is placed over the platform (Figure 7). The block has two parts: inner rectangular four walls (33 cm breadth x 38 cm length x 33 cm height) and outer rectangular four walls (56 cm breadth x 61 cm length x 33 cm height). When both the parts of the block are placed over the platform, a gap of 11.5 cm is left between the inner and outer four walls of the block as shown in Figure 7. This gap is filled with raw mud material (prepared as above) and small stones in such a way that a layer of raw mud material (7.5-10 cm) is first added to the base, followed by a layer of stones (5-7.5 cm). Thereafter, alternate layers of raw mud material and stones are put inside this gap until it is filled up (Figures 8 and 9). Care must be taken that bottom and the top layers are of the raw mud material. While filling the gap with the raw material and stones, a small, rectangular wooden block measuring 11.5 cm x 5 cm x 2.5 cm that fits well in the gap is placed on the base of the front side of the hive, and serves as an entry gate for incoming and outgoing honey bees.

In the same way, another wooden block of 11.5 cm x 10 cm x 10 cm is placed on the backside of the hive for proper ventilation. This wooden block should be kept 10 cm above the bottom and in the middle of the back wall. This block should be kept in a slanting position, so as to avoid direct light to the bee frames from the ventilator. Once the gap is filled with the mud raw material (as described above), it is kept undisturbed for three to four days or more depending upon the weather conditions so that it dries up properly, before the removal of the iron block (Figure 9). The space left inside the inner four walls of the block is the same as that of a BIS brood chamber (Figure 9).

Thereafter, the main block along with the two small wooden blocks are removed. In this way, a brood chamber of desired dimensions with 11.5 cm thick walls of raw material, is erected over the platform (Figures 10 and 11). A space for placing wooden frames of BIS dimensions is then made by plastering a 1.25 cm inch thick layer of the raw material up to 23 cm in height from the platform on the front (entrance gate) and back wall of this mud hive (Figure 12). Take care to fix a wire gauge of 10 cm x 10 cm on the hollow space kept for ventilation on the backside before plastering the hive, to create space for placing wooden frames.

After a few days, when the walls of the hive dry completely, a fine plastering with a thin mixture of clay soil, cow dung and husk is made to repair minor cracks and give a better finish to the outer and inner surfaces of the newly prepared mud hive. When the structure is completely dry, the final coat of cow dung paste is applied on the inner and outer surfaces of the mud hive. After this, the structure is ready for use as a bee hive.

When the mud hive is ready, *A. cerana* bees can be reared in it. This hive can accommodate up to 12 BIS frames (Figure 15). *A. cerana* honey bees can be transferred from movable frame hives by transferring the frames with bees into this hive by using the standard procedure (Figure 13). Bees can also be transferred from traditional hives, or a bee swarm can be settled into such a mud hive during swarming season. After transferring bees into the brood chamber, it should be covered by hessian cloth followed by the inner and top covers. The top cover of this hive is a roof-like structure which can be made of different materials like wood, straw, etc., and can take a shape that mimics roofs of the region, if desired (Figure 14). The growers in the valley have made various types of the top covers for their mud hives as shown in Figures 16 and 17.

Figure 5.
Platform of stones

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Figure 6.
Blending of raw material

© H.k Sharma

Figure 7.
Placement of iron block

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Figure 8.
Filling iron block with raw material

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Figure 9.
Filled iron block

© J.P Sharma

Figure 10.
Mud hive after removal of iron block

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Figure 11.
Brood chamber of mud hive (within four walls)

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Figure 12.
Making space by placing frames at 23 cm. from the bottom

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Figure 13.
Shifting bees in the hive after placing frames

© H.k Sharma

Figure 14.

Complete mud hive

© N. Azzu

Figure 15.

Mud hive with frames and bees

© J.P Sharma

Figure 17.

Mud hive with flat top cover

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Figure 16.

Images showing mud hives with different shapes of top covers made by growers in the valley

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How it was implemented?

- By demonstrating the fixed bee hive with movable frames for rearing *A. cerana* bees in different areas of the Kullu Valley, to over 200 growers at various sites.
- By organizing institutional beekeeping training camps for the beneficiaries so as to train them for beekeeping.
- By organizing awareness camps at demonstration sites so as to popularize the use of this new technology of rearing bees; people becoming aware of the important role of bees in crop pollination and enhancing income generation through the sale of bee products.
- By attending to the queries of the beneficiaries and visiting their places as and when required.

SUCCESSFUL EXAMPLES OF APPLICATION

In total, over 200 fixed mud beehives were constructed for demonstrating this new technology at the stations and at farmers' fields. Of these, more than 150 were constructed in farmers' fields and

51 at the Regional Horticultural Research Station, Bajaura, and its satellite sub-stations during the three year period of the project. Six frames of bees with brood and a queen were provided to each beneficiary out of the project funds. The bees in fixed beehives at the university research stations were provided from the station apiary, maintained at the Beekeeping and Horticultural Research Station, Katrain and Horticultural Research Station, Seobagh in the Kullu Valley of Himachal Pradesh. Most of the beneficiaries are from the Kullu Valley and its surrounding areas, whereas some beneficiaries were from Shimla district. All the beneficiaries underwent five to seven days of beekeeping training at the Horticultural Research Station, Seobagh, Kullu during the project period.

This technology has also been demonstrated in Nagaland and other parts of the North Eastern States by L.R. Verma, a renowned beekeeping scientist and administrator. According to the information provided by Verma, farmers are very enthusiastic in taking up this technology, as bees perform better in this hive. Keeping in view the success of this beehive, one farmer-based NGO, the Society For Technology and Development (STD), Mandi, H.P., has a project from Council of Scientific and Industrial Research (CSIR), Government of India for constructing 100 beehives and providing bees to the beneficiaries in Mandi district of Himachal Pradesh. Similarly, one beneficiary beekeeper, Deen Dyal from the Kullu village of Kradsu, trained in our project and is being hired by the growers associations as well as by the farmers to make these hives in various villages of Kullu Valley and other parts of the state. Deen Dyal has made about 40 such beehives on iron stands (Figure 16) and kept them on the roof of his house. He is selling bee frames with bees at USD 6 per frame to growers as well as to government agencies.

One local beekeeper, Hem Raj from Targali village of Banjar in the Kullu Valley, has successfully reared *A. cerana* colonies in mud hives. He constructed 26 mud hives and started *A. cerana* beekeeping in these hives. The colonies built up well in these hives and Hem Raj sold 300 extra bee frames for USD 6 per frame from the existing stock. He rented out 15 colonies for pollination to the apple orchardists of the nearby area at about USD 10 per colony. He extracted about 100 kg honey in 2013.

Another successful example of this technology is Bir Chand, a beekeeper from Bhatkral, Kullu Valley, who reared 19 *A. cerana* colonies in mud hives. He harvested 30 kg of honey in mid-November 2013 from these colonies by shifting them into movable frame wooden hives and successfully undertook a long migration to the plains of Northern India in Rajasthan. He had six honey harvests and collected 215 kg of honey from 19 *A. cerana* colonies by February 2014. These colonies gained strength and expanded, from filling an average of between five and 10 bee frames.

Figure 18.
Hives along with beneficiaries

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GENERAL DO's AND DON'Ts

- To counter the rodent menace (which has been observed only in neglected/poorly managed mud hives in less than 2 percent of cases), the height of the platform should be over 30.5 cm.
- The brood chamber should be completely enclosed by an inner cover of proper size leaving behind no space for the entry of bee enemies, particularly rodents.
- These hives should never be made in shady areas. The hives should get sunlight for the maximum period during the day; otherwise, bees will perform poorly and may abscond during winter.
- Plastering the inner and outer walls of this hive with cow dung paste at least twice a year or as required, is recommended for the best performance of this hive, as it keeps the ants, wax moth and other enemies at bay.
- The top covers of these hives should be properly made so that no rainwater gets into the brood chamber; otherwise, the moisture problem will adversely affect the success of these hives.

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Chapter 6

Encouraging cavity-nesting bees

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REASON FOR THE PRACTICE

The nesting biology of bees generally dictates how easy it will be to encourage or manage them to nest within a habitat and provide pollination services for horticultural crops, urban gardens, or for "at risk" plant species in marginal habitats. For instance, cavity-nesting bees, primarily those in the family *Megachilidae*, nest in a variety of pre-existing small cavities. In natural settings, such cavities include emergence holes of wood-boring beetles and other similar insects (Figure 1a), pithy plant stems (Figure 1b), abandoned snail shells, or crevices under stones, etc. Habitats lacking such potential nesting sites will have lower diversity and abundance of these bees (Sheffield *et al.*, 2008a, 2013) as nesting site availability is one of the main factors limiting populations of some bee species. However, many cavity-nesting bees will accept artificial nesting substrates (Stephen, 1961; Krombein, 1967), especially masons of the genus *Osmia* (Figure 2), and leafcutter bees of the genus *Megachile* (Figure 3), which are among the most promising wild bees for management as crop pollinators. By providing nesting sites made out of materials such as drilled wooden blocks or laminates (Figure 4), bundles of paper tubes (Figures 2 and 5) or natural substrates such as reeds and other hollow stems, cavity nesting bees can be encouraged to nest in a range of habitats (Sheffield *et al.*, 2008a). Additionally, these artificial nests facilitate the collection of important biological data on the occupants that are required to understand factors affecting their diversity, their specific requirements or preferences (e.g. Sheffield *et al.*, 2008a), their floral preferences (e.g. Cripps and Rust, 1989a and b; MacIvor *et al.*, 2014), and nesting associates (e.g. Krombein, 1967; Sheffield *et al.*, 2008a; Barthélémy, 2012).

Figure 1.

a) An old tree stump with many holes created by wood-boring beetles, an ideal natural nesting site for cavity-nesting bees (Boulder, Colorado); b) a female *Ceratina calcarata* (Apidae, Xylocopinae) nesting in an old raspberry stem (Avonport, N.S., Canada)

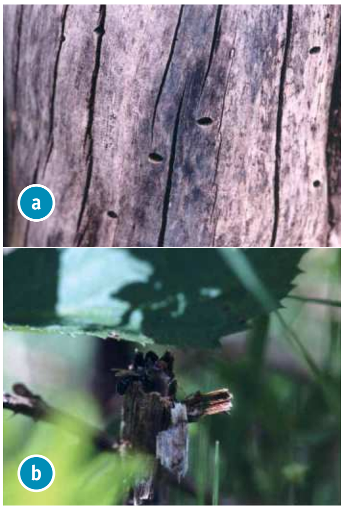

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Figure 2.

A male Blue Orchard Bee, *Osmia lignaria*, at nest entrance on an artificial nesting block within a Haskap orchard (Birch Hills, Sask, Canada)

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Figure 3.

a) Artificial paper nesting site used by a female *Megachile* inermis, showing the linear series of natal cells made from leaf pieces; b) leaves cut by a leafcutter bee (*Megachile* sp.)

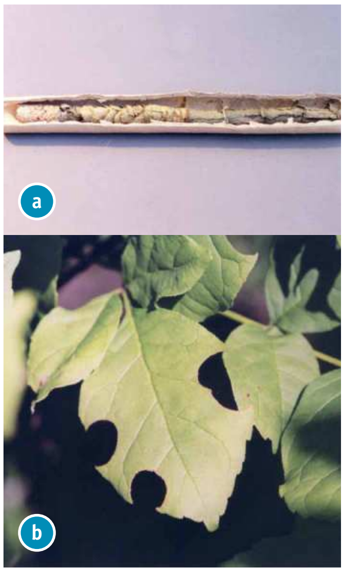

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Figure 4.

Wooden laminate nesting blocks used for the Blue Orchard Bee, *Osmia lignaria*, an important orchard crop pollinator in North America (Wolfville, N.S., Canada)

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Figure 5.

a) Inside of a paper nesting tube, showing pollen mass and egg of Blue Orchard Bee (*Osmia lignaria*), and last year's cocoons; b) artificial bee nesting blocks (or trap-nests) made from paper tubes supported within a milk carton (Wolfville, N.S., Canada)

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HOW TO IMPLEMENT IT

Conservation

Protect existing nesting sites

In natural habitats, cavity-nesting bees use a range of natural pre-existing cavities for nesting (Figure 1a). As such, agricultural landscapes containing woodland or other non-managed habitat adjacent to crop systems often have more diverse and abundant bee communities (e.g. Watson *et al.*, 2011) as they provide ample nesting sites (Figure 6) (see Sheffield *et al.*, 2008a, 2013), and exhibit better crop pollination (Morandin and Kremen, 2013). Many natural cavities may be chosen in preference to artificial nesting substrates by some species (Sheffield *et al.*, 2008a) so these nesting options should be encouraged. Some species have very specific nesting preferences – many *Osmia* nest in snail shells or under stones (Cane *et al.*, 2007; Rightmyer *et al.*, 2013; Sheffield *et al.*, 2014).

Figure 6.

A wooded border adjacent to a Haskap orchard (Birch Hills, Sask., Canada) provides rich nesting habitat for cavity nesting bees

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Providing artificial nests

Many bees will nest in any sites that are readily available, and thus accept any cavity which is suitable (i.e. usually only open at one end). Therefore, increasing the number of available nesting sites may be as simple as using a drill to create smooth-sided, closed-ended cavities in trees, fence posts, or wooden blocks (see Figures 2, 3a, 4 and 5). For habitats lacking natural woodland borders, one can also provide a range of nests through the use of artificial nesting blocks (e.g. Krombein, 1967; Sheffield *et al.*, 2008a; Barthélémy, 2012; Cardoso and Silveira, 2012; von Orlow, 2019) which can increase the diversity and abundance of pollinators in many habitats.

Agricultural practices

Agricultural chemicals

Like all bees within agricultural landscapes (e.g. Gradish *et al.*, 2012a; Henry *et al.*, 2012; Krupke *et al.*, 2012; Ramanaidu and Cutler, 2012; Whitehorn *et al.*, 2012), cavity-nesting species are negatively affected by the use of chemicals used to control pests (e.g. Tasei *et al.*, 1987; Abbott *et al.*, 2008; Gradish *et al.*, 2012b). For bees, negative chemical interactions can occur at many locations, including via contact with the crop plant(s) flowers and the respective floral resources collected, flowers within the field and adjacent habitats, and directly at the nest site (see Moroń *et al.*, 2013). Additionally, as most cavity-nesting megachilid bees collect rather than secrete nesting materials (e.g. leaf pieces, masticated leaf fibers, mud, pebbles, etc.), an additional risk exists in coming into contact with contaminants in these settings (e.g., Krupke *et al.*, 2012; Moroń *et al.*, 2013; Gemmill-Herren and Strohm, 2014). As such, artificial nesting blocks should be placed in areas where contact with chemical is minimized.

Land management

Often in agricultural landscapes, the habitats surrounding the crop of interest are also highly modified, usually crops themselves, and do not provide suitable nesting sites or food resources for bees (Sheffield *et al.*, 2013). In some cases, trees which provide possible nesting sites and/or food plants are removed from these landscapes as they also serve as potential sources for pest species, or make access to the crop by machinery more difficult. In addition, non-crop food plants are often removed from areas adjacent to crops as they are suspected of competing with the crop for water and/or soil nutrients. However, these flowers also serve as food plants for many beneficial insects which supply pollination (Blaauw and Isaacs, 2014) and biological control of pest species (Thies and Tscharntke, 1999; Landis *et al.*, 2000; Fiedler *et al.*, 2008). 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; Ekroos *et al.*, 2014).

Food for bees in agricultural landscapes

Wild bees often have an active flight period which is considerably longer than the flowering period of the crop. As such, agricultural systems may offer a rich source of floral resources for bees for a short period of time, and then very little (Peters *et al.*, 2013). This "boom-then-bust" scenario ultimately affects the fecundity of female bees nesting in these habitats; agricultural crops with lots of alternative forage typically support bee communities with more fecund females (Sheffield *et al.*, 2008a and 2008b). In order to build populations of bees for pollination in subsequent years, and 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; Korpela *et al.*, 2013; Peters *et al.*, 2013; Saunders *et al.*, 2013; Blaauw and Isaacs, 2014).

SUCCESSFUL EXAMPLE OF APPLICATION

Leafcutter bees (*Megachile*)

The alfalfa leafcutter bee, *Megachile rotundata*, is the world's most intensively managed non-Apis bee and is used for pollination of many crops around the world (Pitts-Singer and Cane, 2011). A species from the Old World, the alfalfa leafcutter bee was developed as a manageable crop pollinator in North America where it had long been observed as a pollinator of alfalfa, and years of research went into developing ways of increasing the numbers of the species in crop settings by providing nesting sites (e.g., Stephen, 1961). This species is now used for pollination of several crops (Stubbs *et al.*, 1994; Sheffield, 2008), though some of these crops are grown in areas where this species may not be temporally or climatically well-suited (see Sheffield, 2008). Extensive research has also focused on winter management techniques and pest control options for this species (see Pitts-Singer and Cane, 2011).

Mason bees (*Osmia*)

Other success stories include several species of Mason bees of the genus *Osmia* (Sedivy and Dorn, 2014). In North America, this mainly includes the blue orchard bee, *Osmia lignaria* (Figure 2) as a pollinator of rosaceous tree fruit crops (see Bosch and Kemp, 2001), though several other species in the subgenus Osmia have been partially evaluated (reviewed by Sedivy and Dorn, 2014). Many other species certainly also show promise (e.g. Batra, 2001; Gruber *et al.*, 2011).

Other bee taxa for consideration

Many other non-ground nesting bees do not readily accept the previously discussed artificial nesting sites, but may show promise as managed pollinators, and indeed many may be developed for crop pollination in the future. One group of considerable promise is the carpenter bees of the apid subfamily Xylocopinae. Carpenter bees make their own cavities, so differ from those species nesting in pre-existing cavities as discussed above. The large carpenter bees of the genus *Xylocopa* construct nests in hard wooden structures of size suitable to accommodate their bumble bee sized bodies, while the little carpenter bees (i.e. *Ceratina*) excavate into pithy stems (Figure 1b). Such species show much promise as managed pollinators when occupied nests are moved into areas adjacent to crop systems (e.g. Junqueira *et al.*, 2013).

Other bees use cavities of different configurations, though may still be encouraged to nest in artificial nesting sites. A recent example from North America (Newfoundland, Canada) includes mason bees which normally nest under stones (see Hicks, 2009). *Osmia inermis*, a species often associated with lowbush blueberry (*Vaccinium angustifolium*) in northeastern North America, can be encouraged to nest under clay plant pot saucers (Sheffield *et al.*, 2014), and can be quite prolific. Considering the large sizes of some lowbush blueberry fields in North America, if might be possible to encourage these bees to nest throughout the crop system.

GENERAL DO's AND DON'Ts

- Have fun and put out artificial nesting sites for bees. Watch them, and learn what they require.
- Become familiar with the local cavity-nesting bee fauna and their specific nesting requirements.
- Support surveys of biodiversity.
- Conserve and encourage natural nesting sites for cavity-nesting bees.
- Provide a range of artificial substrates for cavity nesting bees which encourage them in habitats lacking natural nesting sites.
- In crop settings, keep buffer zones which project nesting sites and food plants.
- Provide food plants for bees for periods outside the flowering period of the crop.

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Chapter 7

Management of stingless bee colonies for crop pollination

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REASON FOR THE PRACTICE

At present, numbers of both wild and managed bee colonies are declining rapidly, causing global concern for pollination services. Stingless bees have been shown to be excellent alternative candidates, comparable to honey bees (*Apis mellifera*) in the provision of pollination services for tropical crops (Slaa *et al.*, 2006). Stingless bees (family *Apidae*, tribe *Meliponini*) are members of native bee populations in tropical and subtropical ecosystems of the world. Many of the over 400 species of stingless bees have been identified as effective pollinators of both wild and cultivated plants that are important in rural livelihoods (Roubik, 1995). Several stingless bee species have been found to forage effectively under enclosed conditions, indicating their potential as pollinators of greenhouse crops. Species range in size from quite large, to slightly larger than *Apis* honey bees, to very tiny, just a few millimeters long. The size diversity in stingless bees enables them to have access to many kinds of flowers whose openings are too narrow to permit penetration by other bees (Heard, 1999). Their inability to sting is also an advantage to farmers who are able to manage them with ease for the pollination of their crops.

In Australia, nine species of crops have been confirmed as being effectively pollinated by stingless bee species. They have also been found to contribute to the pollination of nearly 60 other crops. In Malaysia, 32 species have been identified as pollinators of crops such as star fruit, guava, citrus, mango, avocado, watermelon, durian, and coconut (Norowi *et al.*, 2009). In Ghana, most of the ten species of stingless bees identified so far as occurring in the country have been found to be effective pollinators of important cash crops such as cashew, coconut and cocoa. The tiny stingless bee, *Liotrigona parvula* was found to pollinate top canopy cocoa flowers in major growing areas (Kwapong *et al.*, 2013). *Liotrigona parvula* Darchen and *Dactylurina staudingeri* Gribodo were among honey bees and seven other solitary bees that were found to be the main pollinators of cashew flowers in Ghana (Aidoo, 2009). Karikari (2012) also identified four stingless bee species (*Liotrigona parvula, Dactylurina staudingeri, Meliponula ferruginea* and *M. bocandei*) as pollinators of coconut and citrus crops in southern Ghana.

HOW TO IMPLEMENT

The culturing of stingless bees within farming communities will improve the presence of foraging bees to provide the essential pollination services to important fruit and vegetable crops. Farmers can carry stingless bee hives to their farms for the pollination of their crops. Additionally, stingless bee hives are a good source of products that are useful to humans. Honey, propolis, pollen and wax can be harvested and used in various ways. These bee products play important roles in the health delivery systems of the indigenous people of areas where stingless bees are found.

Culturing stingless bees

Some basic facts of stingless bees

The culture of stingless bees should begin with some background knowledge of their social organization and behavior. Stingless bee colonies are perennial and highly social, usually consisting of hundreds or thousands of bees. They have a queen, sterile female workers and drones (males) in the nests (Michener, 2000). Unlike the honey bees of the genus *Apis*, they construct numerous elliptical cells (pots) with wax, resins and propolis for storing pollen and honey. The brood section of the nest is usually found in the center and is surrounded by pots containing honey and pollen. Swarming in stingless bees takes place when workers find a new nest site and begin to stock it with nest materials from the mother colony. Then a young virgin queen from the mother nest mi- grates to the new nest with some workers. The new nest remains dependent on the mother nest for some time until well established.

Stingless bees, just like other bees, depend on flowering plants for forage resources and for some materials for nest building. Water is essential for their survival and some species collect sweat of humans probably to obtain essential salts. Though stingless bees lack the sting apparatus they are able to protect themselves against intruders through various means such as the massive use of propolis in securing the nest including the entrance. They may mass attack with biting, pulling of hair and in some species the spitting of offensive substances onto the skin of the intruder.

Obtaining stingless bee colonies

1. Collection of wild nests

If nests cannot be obtained from stingless bee keepers, one can try to collect a nest from the wild. However, it is important not to over-collect from the wild, and to learn to multiply colonies that have been collected, so as not to impact wild populations.

The process of culturing stingless bees could begin by obtaining a colony from the wild. Search for stingless bee foragers on flowers in agricultural fields, orchards, forests, woodlands and vegetation around human settlements. Often nests are found near human populations, but usually remain undetected. Search on trunks and branches of trees, fallen logs, mud walls of buildings and abandoned ant hills. Look out for the entrance tubes of colonies in such places (Figure 1). Some species may be found nesting in cavities of unused wooden structures; they have been found in old doors, for example. However one species, *Dactylurina staudingeri* found in Ghana and other parts of West Africa, builds an exposed nest with gums, resins and wax in the form of a ball attached to a stem or branch of a tree (Figure 7b). Once a nest is located, removal can be carried out with appropriate tools depending upon the material used in constructing and where it is found. The following precautions must be taken when removing a wild nest of stingless bees:

- Where necessary a bee veil or some form of protection must be worn since some colonies could be angry and attack as a result of excessive disturbance.

Figure 1.

Nest entrances of the stingless bee species in Ghana. a) *Meliponula* sp.; b) *Liotrigona* sp.; c) *Dactylurina staudingeri*

- The orientation of the nest must be noted and maintained to avoid a situation where a colony could be placed upside down.
- Nest collection should be carried out in the cool of the evening when flying bees have returned.
- The nest entrance should be covered with a net during transport to stop the loss of bees.
- All other gaps and openings in the structure – for example, an old log in which the bees may be nesting – must be sealed to protect the nest against attack by ants and other pests.

2. The use of trap nests

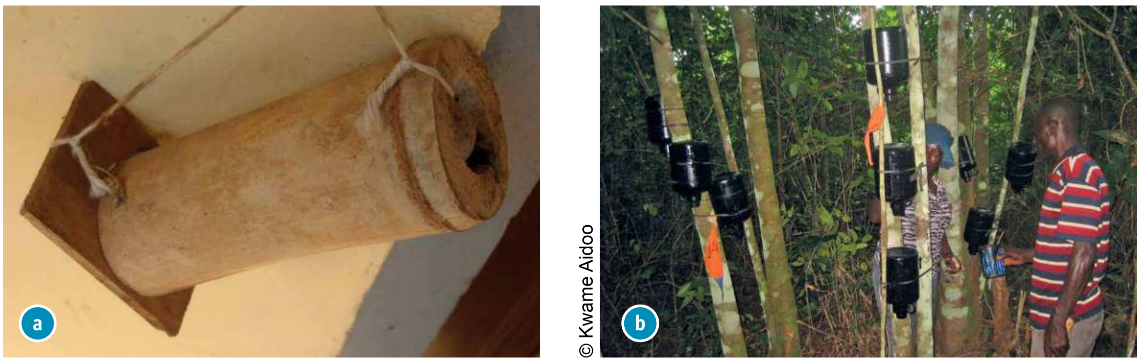
Various structures can be adopted as hives for keeping stingless bees. These include wooden boxes, hollow logs, bamboo internodes, calabashes, coconut shells, clay pots and plastic bottles (Figure 2) These receptacles should be baited with stingless beeswax or propolis tincture (as collected from an existing nest) and then placed at several locations where wild colonies occur. It may take a while for colonies to occupy the hives so a monthly inspection of the traps will become necessary to check their state and re-bait if required. In addition, baiting success may be largely dependent on the species – and nest preferences of most species are not well known. Once nests are colonized, they can be relocated into farms or transferred into more permanent hives for pollination.

3. Buying a nucleus colony from a stingless beekeeper

Stingless bees develop queen cells in their nest most of the time, so bee keepers may take advantage of this behavior to split colonies (one led by the old queen, the other having queen cells) to sell or as a means to multiply stocks. Stingless beekeepers are few, but in some areas old and new practitioners are keeping the knowledge and tradition alive.

Figure 2.

The use of trap nests for catching swarms of stingless bees using a) bamboo internode; b) painted plastic containers



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Transferring nests to hives and multiplying colonies

Colony multiplication should be carried out at the beginning of the honey flow season when forage resources are abundant to allow the mother and daughter colonies to grow and establish. One note of caution before any transferring operation is planned: it is critically important to secure nests after opening by sealing all holes and openings against intruders. Small hive beetles (*Aethina tumida*) have been found to be the greatest enemy of stingless bee colonies in Ghana, whereas phorid flies may devastate colonies by laying eggs in open pollen pots and brood cells in many parts of the world. The only effective solution to these problems is to secure the nest against entry of the beetles and flies. Well-constructed hives, use of clay and cellotape are good means to seal all holes and openings in the nest. The bees then augment this with propolis to make the nest intruder-proof.

Transferring colonies into bee hives

It is very important to re-establish stingless bee colonies from natural nests into well-constructed beehives. This will enable the colony to develop properly and store substantial volumes of honey and pollen for harvest by the beekeeper without difficulty. Colonies can also be moved and man- aged more easily for pollination services when established in a hive. The hive should be designed taking into consideration the cavity volume of the natural nest. This should have sufficient space to enable the colony store food and also raise their brood. Locally available materials and receptacles that are appropriate may be used for the construction of stingless bee hives. These may require modifications in one way or the other to provide an acceptable cavity for the bee colony. Materials for hive construction may include sawn timber and planks, bamboo, clay, etc. The important issue here is that the hive should offer maximum protection of the colony (Figure 3).

Steps:

1. Clean the beehive and set it up near the natural nest.
2. By means of appropriate tools such as a hand saw, cutlass, chisel and hammer, open the nest with care. Avoid crushing or killing the bees.
3. Remove the whole brood section of the nest and place this inside the new beehive close to the entrance.
4. Shake all bees into the new hive (young bees and the queen do not fly very well).
5. Close the new hive and secure it by sealing all openings.
6. Place the new hive at the position of the old nest to allow in returning foragers.

Figure 3.
The transfer of *A. meliponula* nest from a log into a hive

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7. The food content (pollen and honey pots) of the natural nest must not be added to the new hive but processed and used by the beekeeper. This will prevent contamination and possible pest infections.

8. The new colony could be fed with sugar syrup, if necessary (50 percent granulated sugar and 50 percent water by volume and dispensed inside the hive by means of simple feeders).

9. The old empty nest must be removed from the site to avoid attracting hive pests.

10. Monitor the new hive regularly.

Precautions:

- Colonies should be transferred during the early parts of the beekeeping season when food and other resources are abundant in the environment. This will help colonies to establish and grow quickly.
- The beekeeper should carry out the transfer operation as quickly as practicable to prevent pests invading the nest.

Colony multiplication

Well-established stingless bee nests (at least one year old) can be used in the production of daughter colonies. The beekeeper can use these to multiply his or her stock (Figures 4 and 5).

Steps:

1. Place the new hive close to the established nest.
2. Open up the old nest and find the brood section.
3. Remove the involucrum and pillars around the brood cells.
4. Divide the brood section of the nest into two either horizontally or vertically depending on species. In species with vertical brood arrangement, the brood section should be cut vertically. With a brood section that is arranged in a cluster as in *Hypotrigona ruspolii*, part of it could be taken.
5. Place half of the brood section into the new hive and sweep about half as many bees into the new hive.
6. Try to find the old queen; if she is in the old nest then it is critical to remove some queen cells (larger than other brood cells) from the old nest into the new one. This will enable the new colony to raise a queen.
7. Close the hives firmly and move the old nest further away from its position. Place the new nest at the position of the old nest to allow in foragers from the old nest.
8. Monitor the progress of both old and new colonies regularly.
9. Where the hive is made of supers, separate the brood supers and replace each with fresh brood super.

Figure 4.

The brood section of a nest of *Meliponula bocandei*

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Figure 5.

Steps in the colony division of a *Liotrigona* hive

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Precautions:

- Remember not to remove any food from the old nest into the new one; this avoids any possible infection of the new nest.
- Produce daughter colonies from strong and well established hives.
- This activity must be carried out during the early parts of the beekeeping season when food and other resources are abundant.
- Secure both mother and daughter hives against pests.

General management of colonies:

- Stingless bee colonies must be given protection against extreme weather conditions. It is ideal to build a shed to shield the bees from high temperatures and rain (Figure 6).
- There should be structures on the shed to stop ants and other crawling animals such as lizards and spiders from attacking the colonies; for example, by sealing them as described earlier.
- All holes and openings in hives other than the entrance should be sealed against small hive beetles and other internal pests. Hive beetle larvae will consume nectar and pollen in a stingless bee nest and this will result to absconding or death of the colony.
- Where nests are placed under the shade of trees, the site should be kept clean of weeds. This will avoid the situation where the flight paths of colonies would be blocked by weeds.
- Nests could be closed or covered with netting materials to prevent foragers from flying out for a day if pesticide spraying is going to take place within the forage range of the bees. Alternatively, spraying could be carried out in the evening or late afternoon when foraging by the bees has ended.
- Water is essential and must be provided near the nest especially during the dry season.
- When it becomes necessary for supplemental feeding of colonies, sugar syrup (50 percent granulated sugar and 50 percent water by volume) could be used.
- The colonies should be monitored regularly to correct anything that goes wrong in and around hives.

Management of colonies for pollination

The ease of handling stingless bees is a great advantage for their use in the pollination of crops. Farmers can adopt several methods in the use of the bees for pollination on farms:

- Raise several colonies in hives near the home and move them to the farm during the crops' flowering period (Figure 7a). It is best to move them at night or close the entrance to make sure no bees are lost and all bees re-orientate at the new site.

- Set up several trap nests on the farm to attract stingless bee colonies. Manage these permanent nests to pollinate crops on the farm (Figure 7b).
- Build sheds for raising colonies on the farm and use them for pollinating the crops.
- Where natural nests of stingless bees occur on the farm, provide protection and conserve these to provide the needed pollination of the crops.

SUCCESSFUL EXAMPLES OF APPLICATION

The ancient Mayas of the Yucatan peninsula domesticated stingless bees, particularly *Melipona beecheii* and used them for the production of honey, beeswax, pollen and propolis. The stingless bees kept were also used for the pollination of their crops. Other indigenous communities in Mexico, Brazil and other South and Central American countries have cultivated stingless bees for centuries (Crane, 1992).

In Malaysia, preliminary works by researchers suggest that at least 11 species of stingless bees have been domesticated and of these, four species – *Trigona itma, T. thoracica, T. atripes* and *T. peninsularis* – are being utilized to pollinate several agricultural crops including star fruit, guava, citrus, mango, watermelon, durian and coconut (Norowi, 2009).

Australia has about ten species of native stingless bees (genera *Tetragonula* and *Austroplebeia*). Commercial pollination services with these bees are already available and have produced impressive results, particularly with macadamia and watermelon crops (www.croppollination.com.au; www.stevesnativebees.com.au).

Figure 6.

A bee shed with *Meliponula* hives

© Kwame Aidoo

Note the use of cellotape in securing the colonies

Figure 7.

a) A *Dactylurina* nest attached permanently to an orange stem in an orchard; b) Stingless bee hives placed near a farm for the purpose of pollination

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Since 1997, the Japanese researcher, Kazuhiro Amano (2011) has been screening several stingless bee species from Australia and South America for pollination of crops cultivated under greenhouse conditions in Japan. Results are promising but according to the researcher, experiments to assess crop pollination efficiency by stingless bees and to improve colony management techniques are needed before they can be confidently used for the pollination of crops in greenhouses.

Meaeta *et al.*, (1992) used the stingless bee *Nannotrigona testaceicornis* successfully to pollinate strawberries in a greenhouse in Japan.

In Ghana, the International Stingless Bee Centre (ISBC) based in the University of Cape Coast is championing the promotion of the culture of stingless bees for hive product development and also for use in the pollination of agricultural crops (Aidoo *et al.*, 2011). Capacities are being built for farmers, beekeepers, extension agents and interested members of the public to conserve stingless bees. Many members of farming communities in all 110 districts of the country have been trained and now keep different species of stingless bees on their farms for crop pollination.

GENERAL DO's AND DON'Ts

Management of stingless bees in orchards:

- Hive placement and distribution within orchards should be carried out, bearing in mind that stingless bees have short flight range, just about 500 m from their nest. Stocking rates can be determined with careful observations and trials of the species involved; stingless bee researchers would be interested to hear of anyone's observations in this respect, and will continue to share information as they gather it.
- Provide shelter against extreme weather conditions for the colonies.
- Secure colonies against both internal and external pests.
- Take precautions and protect the bees when agrochemicals are to be used in the orchard.
- Provide protection to the bees from any other farm activity that will affect colony survival, e.g. use of fire, smoke, etc.
- Provide additional resources to the bees if necessary (water, supplementary feed, etc.).

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Section 2

MEASURES AT FARM SCALE

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Chapter 8

Promoting non-crop flowering plants for specific insect pollinators

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REASON FOR THE PRACTICE

Pollinator life cycles are often longer than the flowering periods of individual plant species, particularly mass-flowering crops. Pollinating insects therefore often require numerous additional flower sources to complete their life cycle and contribute to subsequent generations. Mass flowering, monocultural crops that produce floral resources simultaneously may only flower for a fraction of the active season of many pollinators. For the remainder of their lives, they therefore rely on alternative foraging resources, often including, but not limited to non-crop flowering plants occurring throughout the agro-ecosystem or in other semi-natural habitats in the vicinity. The availability of these 'weeds' is therefore potentially important to the persistence of pollinators in agroecosystems throughout the year, and for the continued conservation of these species from one year to the next.

For example, although many bumblebee species can take advantage of mass flowering crops such as oilseed rape (*Brassica napus ssp. oleifera*) (Westphal *et al.*, 2003), these resources are only temporarily available and may support only a small proportion of the species assemblage. In particular, flowering crops are usually unavailable in the early spring when bumblebee queens are attempting to establish colonies, or in late autumn when foraging is required to build up winter food stores. Increasing the local availability of floral rewards is expected to result in greater fitness benefits such as longevity and fecundity of pollinators (e.g. Goodell, 2003).

Figure 1.

A strip of sweet alyssum flowers planted between rows of a lettuce crop to attract hoverflies

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The larvae of the hoverflies provide a pest-control service, while the adults are local pollinators

More specifically, it may be possible to target specific pollinator groups to benefit particular crops. Growers of a certain crop may be able to help conserve the most beneficial pollinator species by encouraging the most rewarding and attractive non-crop flowers to those pollinators. For example, in the United Kingdom of Great Britain a fallow field or field border with a high density of flowering legume species will attract mostly long-tongued bumblebee species, and a farmer growing crops such as field beans in the United Kingdom of Great Britain is likely to benefit from this specific pollinator enhancement (Fussell and Corbet, 1992).

HOW TO IMPLEMENT

Studies have shown that peripheral areas around crops containing varied wildflower species have positive effects on the abundance and diversity of many insect pollinators such as honeybees, bumblebees, butterflies, hoverflies and other insects (e.g. Lagerhöf *et al.*, 1992; Carreck and Williams, 2002; Carvell, 2002; Carvalheiro *et al.*, 2011). These areas can take the form of hedgerows, field margins, ditches, set-aside land, field corners or "nodes", fallow fields, strips of wildflowers sown between crop rows (Figure 1) or temporary flowering cover crops (Figure 2). In all of these cases, the flowering areas can be created by either conserving the non-crop flowers already present, or planting specific flowering species. Often, the addition of such flowering species can have secondary benefits such as supporting natural enemies of pests or suppressing noxious weeds (Wratten *et al*., 2012).

Conserving non-crop flowers

To conserve non-crop flowers already present in field margins or fallow fields, some selective weeding may be required as not all species are beneficial to pollinators, and some weeds may outcompete useful plant species. Many arable "weed" species are annual and self-compatible and are likely to be unsuitable to insect pollinators (Gabriel and Tscharntke, 2007). Similarly, some alien wildflowers may not be present within the range of their co-evolved pollinators, limiting their usefulness to native pollinator species (Corbet *et al*., 2001). Furthermore, certain flowers maybe toxic or unrewarding to some important insect species (e.g. some Asteraceae to *Bombus* (Praz *et al*., 2008), *Cucumis* spp. and coriander to *Osmia cornifrons* (Abel and Wilson, 1998).

The non-crop flowering species to conserve depends on the target pollinators, the focal crop and the seed bank of the peripheral areas. Studies abound with reports on the most beneficial flower species to different insects, but currently there is no comprehensive list. A list of some suitable flower species for different groups of pollinators are shown in Table 1, but this is by no means exhaustive. To find the most useful local species, see the advice in the section below.

Planting specific flowers

In a number of countries, there are a range of commercially available seed mixes which claim to benefit "wildlife" including pollinators. For example, in New Zealand Kings Seeds and the University of Lincoln's Bio-Protection Research Centre collaborated to produce a locally relevant seed mix (Figure 3). However, a number of studies have argued that some mixes are not always universally appropriate. For example, while the *Tübingen* mix developed in Germany is effective in supporting honeybee and wild bee populations in temporary bee pastures (Engels *et al*., 1994), it is inappropriate for the United Kingdom of Great Britain as species' flowering times occur at the same time as those of major crop-forage sources and therefore attract few insects (Carreck and Williams, 1997).

The ideal contents of seed mixes are still under development. In European, temperate settings for example, Carvell *et al.* (2006) have argued for the inclusion of annuals such as *Borago officinalis* in wildflower mixes and that most species in both annual and perennial mixtures contribute little and can be replaced with more suitable forage plants such as *Centaurea cyanus* or *Vicia sativa*. Lye *et al.* (2009) also recommended that early flowering plants such as *Lamium album, L. purpureum, Symphytum officinale, Silene dioica* and *Ulex europaeus* be encouraged close to potential nesting sites to benefit spring queens.

Ideally, local knowledge of the pollinator species important to the focal crop should be gathered so that individual planting regimes can be designed. At the regional scale, an excellent protocol for identifying and testing regionally important forage plants was developed in the United States of America and successfully introduced to Central Asian countries (Isaacs *et al.*, 2009). This protocol involves the screening of plant species native to the focal region in replicated trials of their attractiveness to pollinators. High ranked species are then selected for planting schemes based on overlapping blooming periods to ensure constant forage availability through the active season of beneficial insects (Isaacs *et al.*, 2009). At a more local, or individual farm scale, information about the most rewarding and attractive flowering species can be gathered through personal and local observation of pollinators visiting flowers, from discussion with local botanists, beekeepers and entomologists, and by following a scaled down version of the protocol suggested by Isaacs *et al.* (2009). However, practitioners should be sure to also check the Do's and Don'ts section below.

Further information about attracting insect pollinators can be found at the following websites, including publications on selecting locally appropriate flower species and contact details of experts:

- USA: The Xerces Society for Insect Conservation – www.xerces.org/pollinator-resource-center
- USA: Pollinator Partnership – www.pollinator.org/guides.htm

Figure 2.

A species of *Acaena* planted beneath grape vines

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The low growing plant suppresses annual weeds and the flowers provide a nectar source for pollinators and natural enemies of pests

Figure 3.

The pollinator seed mix developed by Kings Seeds and Lincoln University

© Gerard Martin, Kings Seeds

- UK: Royal Horticultural Society – www.rhs.org.uk/Gardening/Sustainable-gardening/Plants-for-pollinators
- Canada: Pollinator Partnership – http://pollinatorpartnership.ca/index.html
- FAO: Global Action on Pollination Services for Sustainable Agriculture www.internationalpollinatorsinitiative.org/pims.do
- International Pollinators Initiative – www.internationalpollinatorsinitiative.org

SUCCESSFUL EXAMPLE OF APPLICATION

Conserving non-crop flowers

Carvalheiro *et al.* (2011) conducted a study within sunflower plantations in South Africa combining pollinator exclusion experiments with honey bee behaviour analysis. Within nine farming areas, each with 2-4 sunflower fields, they set up a number of study plots ranging in their distance to natural habitat and in the relative abundance of weeds growing within the crop. They reported that the presence of weeds, particularly *Senecio apiifolius* and *Tagetes minuta* (Figure 4), helped pollinator populations to persist, with weed diversity and abundance locally increasing pollinators. The presence of weeds within the crop even cancelled out the negative effects of isolation from natural habitat, although not surprisingly both a high number of weeds and the close proximity of natural habitat were the best conditions for pollinators. Interestingly, the enhanced diversity of pollinators in areas of sunflower fields with more weeds actually improved the movement of honeybees between sunflower heads. Finally, they reported that both the proximity of natural habitat and the abundance of weeds were positively associated with seed mass.

Planting specific flowers

Within tree-fruit crops in Nova Scotia, Canada, the solitary bee genus *Osmia* is one group of pollinating insects that show great promise for replacing the honeybee as the main crop pollinator. In particular, *Osmia lignaria* has recently been introduced to evaluate its ability to pollinate apple trees. Subsequently, Sheffield *et al.* (2008) investigated how to support this species when apple trees are not in bloom in order to develop management strategies. They found that the secondary food plant bigleaf lupine, *Lupinus polyphyllus*, was an excellent alternative forage plant, as the flowering period slightly overlapped with that of apple, providing floral resources throughout the lifespan of the bee without competing with apple flowers for pollinators. Furthermore, population recovery of *O. lignaria* nests was high and was shown to be greater closer to lupine plots.

Figure 4.

A bee of the halictidae family feeding from a flower of *Tagetes minuta*, one of the "weed" species allowed to grow among a sunflower crop

GENERAL DO's AND DON'Ts

- When planting strips of non-crop flowers, their success is dependent on subsequent management and maintenance.
- Get to know a) your target pollinators (the best species for your crop), b) their flying range and period, c) other flower species they are attracted to and d) their other resource needs.
- Pollination as a service is more stable and efficient when the pollinator community is diverse. Therefore, aim to conserve a diverse community of insect pollinators by planting/promoting a diverse range of flowers.
  - Plant/promote flowers in a few large clumps, instead of lots of isolated individuals.
  - Promote natural habitats nearby to also encourage biodiversity.
- Plant or promote a range of flower species so that flowers are provided throughout the flying season of most insect pollinators.
  - Use native plants where possible.
- Avoid the use of fertilizers and chemical applications in planted/promoted areas to prevent the proliferation of annual weeds.

Table 1.

Some examples of preferred non-crop flower species for some of the most important insect pollinators

POLLINATOR SPECIES	CROP	PREFERRED NON-CROP FLOWER SPECIES	REFERENCE	COUNTRY
Apis mellifera (Honeybee)	Many fruit, vegetable, nut, stimulant, spice and oil crops (see Klein *et al.* 2007 for full list)	*Borago officianalis*	Carreck and Williams (2002)	UK
		Phacelia tanacetifolia	Pontin *et al.* (2006)	New Zealand
		Rubus fruticosus agg., *Cirsium vulgare, Epilobium hirsutum, Heracleum sphondylium, Brassica napus*	Fussel and Corbet (1991)	UK
		Matricaria species, Lamium purpureum, Persicaria maculosa, Dipsacus fullonum, Chamerion augustifolium	Kells *et al.* (2001)	UK
		Diplotaxis muralis, Borago officianalis, Phacelia tanacetifolia, Sinapis arvensis	Hogg *et al.* (2011)	CA, USA
		Alchornea spp., *Baccharis* spp, *Cassia* spp., *Cecropia* spp.,*Croton* spp., *Euphorbia* spp., *Miconia* spp., *Mimosa* spp., *Piptadenia* spp., *Solanum* spp., *Tibouchina* spp., *Trema* spp., *Vernonia* spp.	See Ramalho *et al.* (1990) for a review	Neo-tropical regions
		Bidens pilosa, Croton macrostachys, Justicia flava, Tithonia diversifolia, Solanum mauretianum, Cordia abyssinica, Desmodium repandum	Hagen and Kraemer (2010)	Kenya
A. cerana, A. dorsata and *A. florea*	Watermelon, pumpkin, canola, coriander, apple, pear, plum and longan	Local forest species	Boonithee *et al.* (1991)	Thailand
BUMBLEBEES				
B. terrestris	Oilseed rape, tomato, peppers, kiwifruit tree strawberry	Boriginaceae, Geraniaceae, Small flowered annuals	Pywell *et al.* (2005); see also Carvell *et al.* (2007)	UK
		Melampyrum pratense, Trifolium pratense, Papaver rhoeas, Onobrychis viciifolia, Rubus sp., *Impatiens glandulifera, Trifolium repens*	Kleijn and Raemakers (2008)	England, Netherlands and Belgium
		Trifolium pratense, Echium vulgare	Goulson and Hanley (2004)	New Zealand
B. pascuorum	Field beans, red clover, tomato	Red/purple Asteraceae, Onagraceae, Fabaceae	Pywell *et al.* (2005)	UK
		Lamium album, Trifolium pretense, Stachys spp., *Dipsacus* spp.	Fussell and Corbet (1992) See also Kleijn and Raemakers (2008)	UK
B. hortorum	Field beans, red clover	*Trifolium pratense, Digitalis purpureum, Lamium* spp., *Melampyrum pratense, Rhinanthus* spp., *Symphytum officinale*	Kleijn and Raemakers (2008)	England, Netherlands and Belgium
		Lamium album, Trifolium pratense	Fussell and Corbet (1992)	UK
		Trifolium pratense, Echium vulgare	Goulson and Hanley (2004)	New Zealand
B. californicus	Watermelon	*Nepeta mussinii, Borago officinalis, Phacelia tanacetifolia, A. foeniculum*	Patten *et al.* (1993)	WA, USA

POLLINATOR SPECIES	CROP	PREFERRED NON-CROP FLOWER SPECIES	REFERENCE	COUNTRY
B. impatiens	Blueberry, watermelon, cucumber	*Silphium perforatum, Liatris aspera, Solidago speciosa, Lobelia siphilitica, Agastache nepitoides*	Tuell *et al.* (2009)	Michigan, USA
STINGLESS BEES				
Melipona favosa	Peppers	*Spondias mombin, Paidum guajava*	Sommeijer *et al.* (1983)	Trinidad
Trigona nigra	Avocado, longan, mango	*Hura crepitans, Cecropia peltata, Chlorophora tintoria, Paidum guajava L.*	Sommeijer *et al.* (1983)	Trinidad
Melipona and *Trigona* spp.	Peppers, tomato, hog plum	*Myrtaceae, Melastomataceae, Solanaceae* and *Leguminosae; Alchornea* spp., *Baccharis* spp., *Cassia* spp., *Cecropia* spp., *Croton* spp., *Euphorbia* spp., *Miconia* spp., *Mimosa* spp., *Piptadenia* spp., *Solanum* spp., *Tibouchina* spp., *Trema* spp., *Vernonia* spp.	See Ramalho *et al.* (1990) for a review	Neotropical regions
SOLITARY BEES				
Osmia lignaria	Blueberry, cherry, peach, apple, apricot, plum, oilseed rape	*Lupinus polyphyllus*	Sheffield *et al.* (2008)	*Canada*
		Cercis canadensis, Quercus sp., *Acer negundo, Brassicaceae, Salix* sp., *Fraxinus* sp., *Rubus* sp.	Kraemer and Favi (2005)	Virginia, USA
		Cercis occidental, Salix spp., *Quercus lobata, Lupinus* spp., *Prunus domesticus, Fragaria ananassa, Malus* spp., *Ceanothus oliganthus*	Williams and Kremen (2007)	CA, USA
Megachile rotundata	Cranberry, soybean, field beans	*Medicago sativa, Sinapis arvensis, Melilotus officinalis*	O'Neill and O'Neill (2011)	Montana, USA
Habropoda laboriosa	Blueberry	*Vaccinium* sp., *Gelsemium sempervirens, Quercus alba, Cercis canadensis*	Cane and Payne (1988)	FL, GA and AL, USA
HOVERFLIES				
Eristalis tenax	Apple, peppers	*Tripleurospermum inodorum, Daucus carota, Anthemis tintoria*	Frank (1999)	Switzerland
		Leontodon autumnalis	Frund *et al.* (2010)	Germany
		Coriander	Ambrosino *et al.* (2006)	Oregon, USA
		Members of Asteraceae plus: *Justicia americana, Rhus glabra, Cicuta maculata, Eryngium yuccifolium, Perideridia americana, Sium suave* and many others	Tooker *et al.* (2006)	Illinois, USA

(This list of species is not exhaustive)

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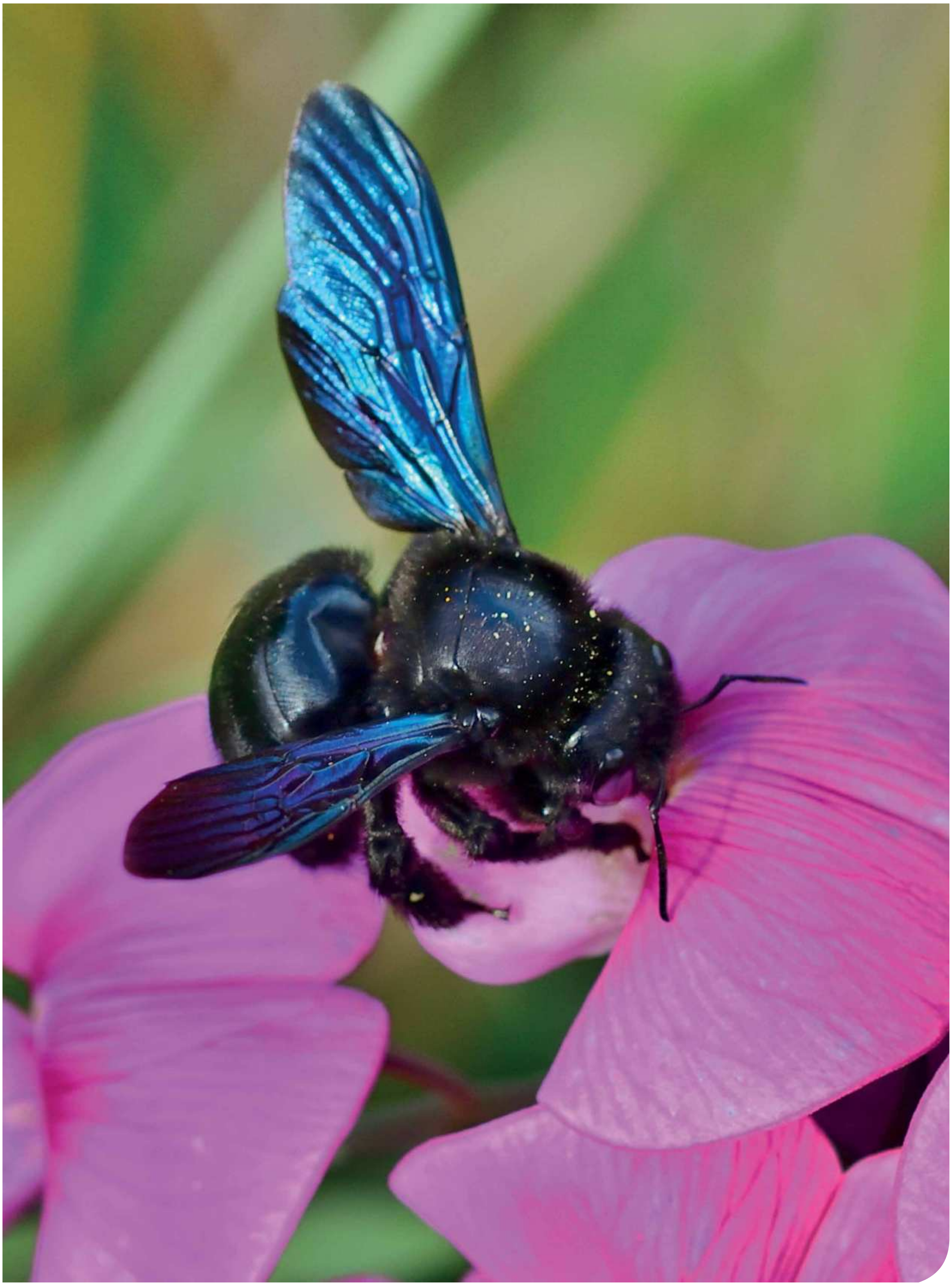

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Chapter 9

Benefits of planning shade-tree cultivation to favour pollinators

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REASONS FOR THE PRACTICE

In the emerging field of pollination biology, the focus of research has been on plant-pollinator systems involving a single plant species associated with one or a few pollinator species. Yet increasingly, many have argued that pollination systems are more often generalized and that a study of entire communities would help in better understanding plant-pollinator interactions (Waser and Ollerton, 2006). In a community, there can be several species of plants that might compete for pollinators or help in sustaining pollinator populations by flowering in different times of the year. Furthermore, many different flowering plant species in a community may attract several pollinator species because of differential attraction or due to differences in quantity and quality of resources offered (Manning, 2001; Klinkhamer *et al.*, 2001; Müller *et al.*, 2006). The diversity of pollinators may also depend on available floral resources, such as weeds in and around crop fields (Reader *et al.*, 2005). Hence, spatial occurrence and composition of multi-species plant patches could be of key importance in determining the strength of facilitative and/or competitive interactions (Bell *et al.*, 2005; Makino *et al.*, 2007; Ghazoul, 2006; Hennig, 2011).

Equally, the occurrence over time of floral resources could be critical to facilitating the persistence of key pollinators in ecosystems. Since agricultural crops are, in general, seasonal, the pollinator(s) on which they depend may be supported for only a short period in any given year. Hence, it is important to consider the flora available in the same location or region to understand how the pollinator populations survive in the “off seasons”, making it necessary to look at the entire community of flowering plants and the diversity of pollinators. In this chapter, an attempt is made to explain the importance of shade tree species in conserving pollinator populations in coffee and cardamom plantations of southern India.

Specific reasons for the practice in India

Traditionally, coffee (*Coffea arabica* and *C. canephora*) and cardamom (*Elettaria cardamomum*) are cultivated under the shade of natural forest trees (Figures 1 and 2) in southern India. Cardamom is native to the Western Ghats of India. Coffee was introduced to India about 400 years ago, and may have been planted first under the shade of forest trees on the Chandragiri Hills in Chikmagalur district, in southern India. Since the plants grew well under the shade of forest trees, it probably became the tradition. Until about 200 years ago, cardamom was collected from the wild and used in medicines locally, or traded. With the more intensive cultivation of coffee commencing in the 1800s, cardamom was introduced into coffee plantations initially as a mixed crop.

It is a general practice that coffee and cardamom are cultivated under the shade of natural forest tree species in the Western Ghats (Raman, 2004). Before planting coffee, forest plant species are selectively removed; coffee is planted on the slopes, and cardamom closer to the

Figure 1.

Coffee plantation under the shade of natural forest trees

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valley. However, there are pure coffee and pure cardamom plantations as well. The shade level is regulated through tree management, which includes selective lopping of overgrown branches to maintain about 40 to 60 percent shade. This operation is done in alternate years, usually in the month of February. Generally, no conscious efforts are made to retain any particular tree species. The removal of trees for planting coffee or cardamom is more or less random. More recently, farmers have resorted to removing all the forest tree species for timber, and planting a single species such as silver oak (*Grevillea robusta*), which is a fast-growing evergreen tree, as shade for new plantations.

Shade trees in coffee and cardamom plantations confer several advantages such as buffering temperature extremes and improving soil fertility through incorporation of organic matter from leaf litter (Beer *et al.*, 1998). Regulating shade and maintaining light intensity at around 30 percent has shown to improve yields and reduce pest and disease incidence. Studies conducted in India, Costa Rica, Colombia and other places discuss the advantages to the coffee crop in terms of nutrient availability, suppression of weeds lower incidence of borer pests (Beer 1987, 1998; Staver *et al.*, 2001; Muschler, 1997) and enhancement of faunal diversity (Faminow, 2001). Albertin and Nair (2004) studied farmers' perspectives on shade trees in coffee plantations. Interestingly, these authors recognize the knowledge of farmers about importance of shade for coffee in summer but not from the perspective of conserving pollinators, when coffee is not flowering.

Figure 2.

Cardamom plantation under the shade of natural forest trees

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Importance of shade trees for coffee pollination

Coffee and cardamom both greatly depend on bees for pollination. Arabica coffee – although self-fertile – doubles fruit set with bee visitation. Robusta coffee and cardamom heavily depend on bees for pollination (Belavadi and Parvathi, 2000; Belavadi *et al.*, 2005; Sinu and Shivanna, 2007). Coffee produces flowers in southern India in March and April and the flower duration in any given location is only three days. Cardamom flowers between May and October with peak flowering in July and August. Given this, in a pure coffee plantation, bees have access to forage only for three days in a year in March or April. In plantations with cardamom, forage resources may be abundantly available in July and August for bees such as *Apis cerana* and *Apis dorsata* that readily visit both coffee and cardamom flowers. A dearth period of flowering resources thus occurs between April and July, and again from September until March. Hence, an attempt was made to look at the flowering phenology of shade trees to record additional benefits. The study was conducted in the Central Western Ghats of India. Twenty plantations were selected in Mudigere and Chikmagalur taluks of Karnataka State.

Fifteen plantations produced pure coffee and five were mixed plantations. The sizes of plantations varied greatly (from 2 ha to 100 ha). The shade tree species and their frequency in different plantations were recorded. Further, the flowering phenology of the most frequent species was recorded at Mudigere.

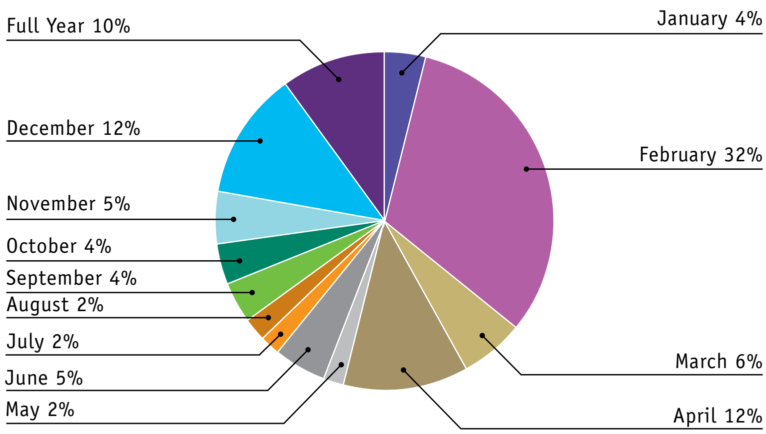
Shade tree species and their flowering phenology

We recorded a total of 132 species of shade trees and a few climbers in coffee and cardamom plantations and could record the flowering phenology of 107 species. Shade trees that have distinct flowering phenology compared to the target crops play a very important role in conserving pollinator populations (Table 1; Figure 3). When coffee flowers in March to April, 28 to 33 species (12 to 14 percent) of shade trees also flower, implying that these plants compete for pollinators. In contrast, during peak flowering of cardamom, only 4 to 6 percent of shade trees flower, indicating that cardamom, being a native plant, does not face much competition for pollinators.

Thus, in the Central Western Ghats of India an investigation was carried out to identify the benefits for coffee and cardamom pollination from the flowering patterns of shade trees. In 20 plantations in Mudigere and Chikmagalur taluks of Karnataka State, 132 species of shade trees and a few climbers in coffee and cardamom plantations were recorded. When the flowering phenology of 83 species in Mudigere were noted, it was evident that shade trees, with their flowering periods being quite distinct from target crops, play a very important role in conserving pollinator populations.

Figure 3.

Flowering phenology of shade trees in coffee and cardamom plantations



(Percentage of total flowering species that are in flower in a given month.)

Table 1.

Shade tree species in plantation ecosystems of Western Ghats of Karnataka that are important in conserving pollinators

SL. NO.	BOTANICAL NAMES	FAMILY	LOCAL NAMES	FLOWERING TIME	SOURCE		OTHER USES
					Nectar	Pollen	
1	*Acacia auriculiformis*	FABACEAE		OCT – NOV		*	Fuel wood, gum
2	*Acacia concinna*	FABACEAE	Seege kaie – 2	FEB	*	*	Medicinal, hair shampoo
3	*Acacia mangium*	FABACEAE		JUN – JULY		*	Timber
4	*Acnistus arborescens*	SOLANACEAE	Brazil Plant	DEC - MAY	*		Support birds & bees
5	*Acrocarpus fraxinifolius*	FABACEAE	Havalige (Red cedar)	FEB – MAR	*		Afforestation, Forage
6	*Albizia lebbeck*	FABACEAE	Bhage	JAN – FEB		*	Forage, timber
7	*Albizia odoratissima*	FABACEAE	Bilvara	JAN – FEB	*		Timber, agricultural implements
8	*Albizia chinensis*	FABACEAE	Hottusege mara	JUL – AUG	*	*	Timber, N fixing
9	*Alstonia scholaris*	APOCYNACEAE	Paale mara	FEB	*	*	Pencils, coffins, implements
10	*Anacardium occidentale*	ANACARDIACEAE	Geru hannu (Cashew)	JAN - APR	*		Fruits, nuts
11	*Apodytes beddomei*	ICACINACEAE	Kari Mara	MAR - APR	*	*	Medicinal
12	*Aporosa lindleyana*	EUPHORBIACEAE	Pattugarige	APR	*		Medicinal
13	*Bischofia javanica*	EUPHORBIACEAE	Neelimara (Neerulli)	MAR – APR	*	*	Timber, fruits & seeds edible
14	*Bombax ceiba*	BOMBACACEAE	Bhoorga	FEB – MAR	*	*	Timber, silk for pillows, medicinal
15	*Bridelia retusa*	EUPHORBIACEAE	Gooje mara	JAN – FEB	*	*	Medicinal

SL. NO.	BOTANICAL NAMES	FAMILY	LOCAL NAMES	FLOWERING TIME	SOURCE		OTHER USES
					Nectar	Pollen	
16	*Bridelia tomentosa*	EUPHORBIACEAE	Kunkumada mara	NOV	*	*	Medicinal
17	*Caesalpinia pulcherrima*	FABACEAE	Kenjige mullu	DEC – MAY	*		Medicinal
18	*Capparis sp.*	CAPPARACEAE		JAN		*	Fruits
19	*Careya arborea*	LECYTHIDACEAE	Gaula – 2	JUN - AUG	*	*	Fruits for birds, monkeys
20	*Cassia fistula*	CASIALPINIACEAE	Kakke	FEB	*	*	Pods eaten by wild animals
21	*Celtis timorensis*	ULMACEAE	Bende mara	NOV - DEC	*	*	Medicinal
22	*Chukrasia tabularis*	MELIACEAE	Kallu Garige	JAN			Timber
23	*Cinnamomum iners*	LAURACEAE	Ealaga – 2	JAN - FEB	*	*	Medicinal
24	*Citrus aurantifolia*	RUTACEAE	Nimbe	JAN - APRIL		*	Fruits
25	*Cryptocarya bourdillonii*	LAURACEAE	Kulumaavu	DEC – FEB		*	Timber
26	*Dalbergia lanceolaria*	FABACEAE	Hasirugane	MAR – APR	*		Timber
27	*Dalbergia latifolia*	FABACEAE	Beete (Rose wood)	MAR - APR	*		Timber
28	*Dendrophthoe falcata*	LORANTHACEAE	Bandalike	JAN - MAY	*	*	Parasitic species
29	*Dillenia pentagyna*	DILLENACEAE	Kadu Kanagalu	DEC – FEB	*		
30	*Emblica afficinalis*	ENPHORBIACEAE	Bettada nalli	MAR – APR	*		Fruits
31	*Erythrina sp.*	FABACEAE	Haluvana	FEB –APR	*	*	Shade
32	*Euonymous sp.*	CELASTRACEAE	Kallu Sodle	FEB	*		Medicinal
33	*Eucalyptus globulus*	MYRTACEAE	Neelagiri	NOV – DEC	*	*	Medicinal, timber
34	*Flacourtia montana*	FLACOURTIACEAE	Jefool	FEB	*	*	
35	*Garcinia indica*	CLUSIACEAE	Maanthpuli	FEB	*		Fruits
36	*Garuga pinnata*	BURSERACEAE	Godda – 1	FEB		*	
37	*Gmelina arborea*	VERBENACEAE	Shivane	OCT	*		Medicinal
38	*Grewia disperma*	TILIACEAE	Tadasalu	AUG - JAN	*	*	Fruits, medicinal
39	*Helicteres isora*	STERCULIACEAE	Kaurikane	JUN – JAN	*		Medicinal
40	*Hevea braziliensis*	EUPHORBIACEAE	Rubber	JUL – AUG	*	*	
41	*Hopea glabra*	DIPTEROCARPACEAE	Bogi	JAN - FEB	*	*	Timber
42	*Ixora nigricans*	RUBIACEAE	Kadu coffee	JULY - AUG	*	*	Medicinal
43	*Lagerstroemia lanceolata*	LYTHRACEAE	Nandi	MAR - APR	*		Timber
44	*Leucaena leucocephala*	FABACEAE	Subabul	JAN-DEC		*	Fodder
45	*Litsea sp.*	LAURACEAE	Karike	JAN	*	*	Medicinal
46	*Litsea wightiana*	LAURACEAE	Hemmade, Halmadde	NOV	*		Medicinal
47	*Memecylon malabaricum*	MELASTOMATACEAE	Papanasini	APR – MAY	*		Medicinal, fuel wood
48	*Mimusops elengi*	SAPOTACEAE	Bakula	FEB – APR	*		Timber, fruits edible
49	*Naravelia zeylanica*	RANUNCULACEAE	Bellulli beelu	DEC – FEB	*		Climber, medicinal
50	*Ormocorpum sennoides*	FABOIDEAE	Kadu nugge – 2	MAR – MAY	*		Medicinal

SL. NO.	BOTANICAL NAMES	FAMILY	LOCAL NAMES	FLOWERING TIME	SOURCE		OTHER USES
					Nectar	Pollen	
51	*Poeciloneuron indicum*	CLUSIACEAE	Hulube (Karbalige)	MAY	*	*	Timber
52	*Pongamia glabra*	FABACEAE	Honge (Pongamia)	APR	*		Timber, medicinal
53	*Pterocarpus marsupium*	FABACEAE	Honne (Indian Kino)	FEB	*	*	Timber, medicinal
54	*Sapindus emarginatus*	SAPINDACEAE	Antuvala (Soap nut)	OCT - DEC	*		Medicinal
55	*Sarcostigma kleinii*	ICACINACEAE		MAR	*		Medicinal
56	*Schefflera sp.*	ARALIACEAE	Maragala beelu	MAY			None
57	*Schefflera sp.*	ARALIACEAE	Hannu Hittina Beelu	MAY	*	*	None
58	*Schefflera walachiana*	ARALIACEAE	Anagalu	APR – JUN	*		None
59	*Schefflera venulosa*	ARALIACEAE	Anagalu, Betthu	APR - MAY	*		None
60	*Muntingia calabura*	MUNTNGIACEAE	Singapoor Cherry	JAN-DEC	*	*	Fruits, bats and birds
61	*Spondias mangifera Willd*	ANACARDIACEAE	Amate	FEB -APR	*	*	Fruits
62	*Spondias pinnata*	ANACARDIACEAE	Godda – 2	FEB	*	*	Fruits
63	*Sterculia foetida*	STERCULIACEAE	Pathaga	FEB	*		Oil
64	*Sterculia urens*	STERCULIACEAE	Karadi. To	APR	*		Oil
65	*Syzigium cuminis*	MYRTACEAE	Nerale	JAN – FEB	*	*	Fruits
66	*Syzygium heyneanum*	MYRTACEAE	Kunnerale	MAR	*	*	Fruits
67	*Syzygium jambos*	MYRTACEAE	Pannerale	FEB & AUG	*	*	Fruits
68	*Tamarindus indica*	FABACEAE	Hunase Mara	APR	*		Fruits
69	*Tectona Grandis*	VERBENACEAE	Tega	APR	*	*	Timber
70	*Terminalia bellirica*	COMBRETACEAE	Tare	FEB		*	Timber
71	*Terminalia coriacea*	COMBRETACEAE	Matthi	APR – MAY	*	*	Timber
72	*Terminalia paniculata*	COMBRETACEAE	Hanaal tare	MAR – APR	*		Timber
73	*Thespesia populnea*	MALVACEAE	Bugurikai	JUN	*		Musical instrument
74	*Toona ciliata*	MELIACEAE	Garige	JAN	*		Timber
75	*Trema orientalis*	ULMACEAE	Gorakalu mara	MAR & SEP		*	Fuel wood, Medicinal
76	*Trichilia connaroides*	MELIACEAE	Majjigemara	JAN - AUG	*		Medicinal
77	*Trichilia sp.*	MELIACEAE		DEC	*	*	Medicinal
78	*Vateria indica*	DIPTEROCARPACEAE	Dhoopada mara	APR – JUN	*	*	Medicinal
79	*Vernonia arborea*	ASTERACEAE		FEB - MAR	*		Medicinal
80	*Vitex negundo*	VERBENACEAE	Lakki soppu	MAR	*	*	Medicinal
81	*Vitex pinnata*	VERBENACEAE	Naviladi (Banjige)	MAR – APR	*	*	Medicinal, fuel wood
82	*Wendlandia notoniana*	RUBIACEAE	Talige Guthi (Mara)	JAN - APR	*	*	Medicinal
83	*Ziziphus rugosa*	RHAMNACEAE	Chotte hannu	APR - JUN	*		Fruits

Figure 4.

Schefflera venulosa* in bloom, visited by *Apis cerana

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Figure 5.

***Hefflera wallachiana* in bloom**

© V.V. Belavadi

HOW TO IMPLEMENT

It is important to maintain natural forest tree species for shade in coffee and cardamom plantations. While planning new plantations, care should be taken to recognise and retain those species that flower before coffee, or after cardamom - preferably those that flower between October and February or in April and May, just after coffee flowering in the southern Indian context. An interesting example is that of *Schefflera* spp. Species of *Schefflera* are perennial climbers, which climb on shade trees and establish as huge independent plants, often killing the supporting tree. Hence, they are also called 'stranglers'. Two species of *Schefflera*, namely *S. venulosa* and *S. wallachiana* (Figures 4 and 5), flower almost immediately after coffee, and help retain pollinators for cardamom.

SUCCESSFUL EXAMPLES OF APPLICATION

Since both coffee and cardamom are commercial crops, almost all farmers maintain shade trees in their plantations. There are pressures and competing advice, in some instances, to maintain "sun coffee" without shade trees, or to use fast-growing trees such as silver oak for shade trees (see below). The experiences of coffee production in locations where coffee is grown without shade (such as Costa Rica) is that this system may require higher inputs in terms of water, pesticides and other agricultural chemicals. The benefits of shade trees for providing floral resources for pollinators over a longer season are shown here. Additional benefits of maintaining a diverse flora are that the trees provide nesting sites for many bee species, while providing the required resources in the off seasons. These trees not only make create the environment to grow cardamom but provide an additional benefit as they are also used to support a third - climbing - crop in mixed cropped plantations, most commonly black pepper (Kuruvilla *et al.*, 1995).

GENERAL DO's AND DON'Ts

- It is essential to identify those shade trees that have significance for the conservation of pollinators. During shade regulation operations (which are cultural operations taken up in April/May to regulate shade before onset of monsoon) care should be taken to prune branches of those trees which are likely to flower when coffee or cardamom is flowering. Similarly, care also should be taken not to prune the trees/plants that are likely to flower immediately after coffee and before cardamom. For example, *Schefflera* sp. vines flower in the last week of April or in the beginning of May in the Indian context. These vines should not be cut or pruned during shade regulation, as it may lead to the loss of local pollinators for cardamom.
- Recent trends of removing the original forest tree species and replacing them with quick growing silver oak should be avoided. Silver oak is not retained long enough to flower, and does not help pollinators in any way.

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Chapter 10

Agroforestry and cover cropping for pollinators

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REASON FOR THE PRACTICE

Introduction

In recent years, conservation measures in Europe and the United States of America targeting bees and other pollinators have emphasized the importance of protecting and restoring natural habitat on and adjacent to farms. While research findings support the value of such an approach, opportunities for the protection and restoration of natural areas may be limited, especially on smallholder and tenant farms. Yet despite that challenge, even within crop production areas themselves, cover cropping and diverse agroforestry systems may offer an opportunity to supplement the habitat requirements of bees.

Agriculturally important bees typically have three basic habitat needs. These include: (1) food in the form of pollen and nectar for adults; (2) nest sites; and (3) protection from harmful land management activities, such as insecticide use (Vaughan *et al.*, 2007). While natural areas can supply these habitat requirements, in some areas – especially in intensively farmed landscapes – explicit measures are usually required to restore the conditions that are optimal for pollinators.

In the absence of existing natural habitat and on farms that do not have space to restore natural habitat, diverse agroforestry systems and cover cropping with bee-attractive plants are two approaches for integrating pollinator habitat directly into the farm (Figure 1).

Figure 1.

Native wildflowers allowed to grow between vineyard rows in Washington, United States of America

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In this chapter, we examine these approaches and related systems, such as hedgerow planting and the use of temporary insectary strips. While specific plant species used in these systems vary widely from region to region, the work of the Xerces Society's pollinator conservation programme and other sustainable agriculture organizations have found that both of these approaches are broadly adaptable to small farms across the world. As an example, model systems for the tropical Pacific Island region developed in collaboration with the U.S. Department of Agriculture's Natural Resources Conservation Service (NRCS) are provided in this chapter, as are cover cropping examples from row crop and tree fruit systems in the United States of America.

Agroforestry for pollinators

Agroforestry represents a diverse set of approaches for integrating trees into farm systems, typically as a harvestable resource (e.g. fruit, nut or wood production). However, in some cases the trees may simply support a primary production system, such as by providing shade or fodder for livestock or a canopy for shade-dependent crops (Wojtkowski, 1998, Elevitch and Wilkinson, 2000).

These specific end goals directly guide the physical placement of trees in agroforestry systems. For example, where livestock grazing is the primary goal (silvopasture), the trees may be widely spaced, creating a savanna-like landscape. In contrast, alley cropping is an agroforestry system that arranges trees in linear rows alternated with rows of herbaceous annual crops. Many other tree placement systems exist based upon the primary agroforestry goals, including boundary systems (to define property edges or exclude animals), diverse forest farms with multiple canopy levels providing harvestable resources, and more.

Regardless of the specific model, agroforestry systems typically foster greater plant species diversity than most row crop farms or livestock paddocks. In the context of pollinator conservation, this enhanced plant diversity can often provide expanded pollen and nectar resources, as well as additional vegetative structure to support the nesting habits of wild pollinators (Carvalheiro *et al.*, 2012). With pollinator conservation as an explicit goal, farmers may choose to intentionally expand the range of trees and shrubs planted into their agroforestry system to maximize pollinator value.

HOW TO IMPLEMENT

Agroforestry design guidelines

Based on habitat restoration experiences, it is recommended that farmers designing agroforestry systems for pollinators first consider the future mature size of trees and shrubs being selected for planting. When trees will be planted directly adjacent to a row crop field (e.g. alley cropping or strip cropping), farmers may want to focus on using smaller tree species that will not significantly shade the nearby crops, unless those crops are known to be shade-tolerant or shade dependent. Where farmers have a wider area to work with, a multi-row, multi-tiered planting design that includes taller trees incorporated with smaller shrubs and herbaceous plants may be possible (Vaughan and Black, 2006a, Vaughan and Black, 2006b).

In addition to plant selection and placement, transplanted trees in many regions need irrigation during the establishment phase immediately after planting. With this in mind, some farmers prefer to first install irrigation systems prior to planting or to position trees where irrigation during establishment will present the fewest challenges.

Tree maintenance for pollinators in agroforesty

Depending on plant selection, location and goals, it may be necessary to actively manage the growth of trees in agroforestry systems (e.g. to prevent their growth into adjacent fields or to limit their shading of other species). Depending on farm goals, and on the tree species, some larger plants can be periodically cut back to a stump and allowed to re-sprout (coppicing) to produce multiple bushy stems (Mäder *et al.*, 2014). After establishment, however, ideally no more than 30 percent of an agroforestry system should be disturbed in any one year to ensure against large-scale loss of habitat for beneficial insects.

Hedgerows and windbreaks

Hedgerows and windbreaks are linear rows of trees and shrubs, sometimes with wildflowers and grasses in the understorey (Figure 2). Hedgerows and windbreaks are typically located along property boundaries, fence lines, roads, and as barriers to physically separate crop fields. Hedgerows and windbreaks have long been recognized for their many farm benefits, including protecting farms from wind and dust, catching drifting snow, providing habitat for wildlife and pollinators, capturing runoff from adjacent agricultural lands, and providing renewable sources of firewood and harvestable wild fruits and herbs (Adamson *et al.*, 2011, Mäder *et al.*, 2011).

In some regions of Europe, very old hedgerows have persisted on raised berms (approximately a meter or more in height). Berms likely have resulted from biomass deposition over hundreds of years, as well as the placement of field stones and other farm debris into the hedgerow. These bermed hedgerows can provide greater windbreak and screening benefits, and building on a berm may be a consideration when designing new hedgerow systems. While creating a bermed hedgerow or windbreak requires more initial work, the major long-term benefit is that the resulting hedgerows tend to be more difficult to dismantle, and thus may be more likely to survive for multiple generations, providing long-term habitat for pollinators and other beneficial wildlife (Mäder *et al.*, 2014).

Figure 2.
Newly planted California pollinator hedgerow

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Finally, while hedgerows and windbreaks can be used to provide habitat for pollinators (it is important to note that these hedgerows and windbreaks should be kept a safe distance from areas with pesticide use), they can also be used to protect beneficial insects from pesticide spray. For example, windbreaks consisting of dense, small-needled evergreen trees – *that are not attractive to bees* – can reduce pesticide drift from adjacent cropland when located on the upwind of pollinator habitat (Adamson *et al.*, 2011, Lee-Mäder *et al.*, 2014). Such pesticide screening may be an especially important consideration for organic producers adjacent to farms that use pesticides.

Cover cropping for pollinators

Cover crops are temporary or permanent plantings of ground cover on fallow crop fields, between rows of perennial crops, or in the understorey of orchards and vineyards. Cover cropping can have multiple conservation objectives such as reducing erosion, improving soil fertility, preventing weed growth, breaking pest and disease cycles, and providing pollen, nectar and shelter for beneficial insects including pollinators.

To establish a cover crop, growers must first identify species that fit between rotations of cash crops, or identify areas of the farm that can be used for cover crop establishment rather than cash crop production (note that in some cases cash crops and cover crops may be inter-planted). Seeding rates and sowing time for cover crops vary by species, equipment availability, and region. Local subject-matter experts should be consulted when integrating cover crops into a farm for the first time.

Common cover crops include various legumes, brassicas, and grasses. Of these groups, legumes are widely recognized for their contribution to soil fertility as green manure crops and for their value as nectar plants—including, in some cases, serving as important honey plants. Brassicas, another common cover crop group, are commonly used to absorb excess nutrients, alleviate soil compaction and to suppress soil pests like nematodes. Like legumes, some brassicas are valuable nectar plants supporting bees and other beneficial insects. Grasses, also noted for their ability to capture excess soil nutrients, prevent weed growth and reduce erosion, are (in contrast) typically regarded as low quality pollen sources for bees. Their other values, however, may make them important for including in cover crop mixes.

Additional cover crops outside of these broad taxonomic groups, include lacy phacelia (*Phacelia tanacetifolia*) and buckwheat (*Fagopyrum esculentum*), both of which are used for various applications, including the support of beneficial insects. Depending on the objectives, several different cover crop species can also be seeded together to provide complimentary benefits (Figure 3).

Figure 3.
Sunn hemp cover crop strips maintained beneath coconut trees in Tamil Nadu, India

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Legumes

Legume cover crops that provide pollen and nectar for beneficial insects include perennial, biennial and annual species, as well as species of diverse growth habits ranging from vines to erect herbaceous plants to woody shrubs (Lee-Mäder *et al*. 2014). Globally, some of the commonly used legume cover crops which also are recognized as bee-attractant plants include the genera *Trifolium, Vicia, Melilotus* and *Medicago* species in temperate climates, and various species in the genera *Desmodium, Medicago, Vinga* and *Crotolaria* in tropical climates. Many other legume genera beyond just these are planted as cover crops to varying degrees depending on location. However, not all of these are particularly bee-attractive. It is important, therefore, not to assume that all leguminous cover crops provide foraging benefits for bees.

Brassicas

Common brassica cover crops include several species of rapeseed (*Brassica napus*), mustards (*Brassica* spp. and *Sinapis* spp.) and forage radish—sometimes called oilseed or daikon radish (*Raphanus sativus*). Besides attracting pollinators when allowed to flower, a growing body of research demonstrates that brassica roots produce chemical compounds (glucosinolates) that suppress weed growth, soil borne plant diseases and nematodes (Lee-Mäder *et al*., 2014).

Many brassicas are annual or biennial species, with flowering in some species triggered by seasonal day length. In temperate climates this timing can be complicated when brassicas are fall-planted as a cool weather cover crop resulting in frost injury or winterkill before the plants flower (and hence, they may fail to provide pollinator resources in such cases). Finally, a few brassicas are recognized to have weedy tendencies in some regions, and can be alternate host plants for pests and diseases of brassica food crops, requiring thoughtful planning when used in conjunction with rotational vegetable or oilseed crops (Lee-Mäder *et al.*, 2014).

Buckwheat

Buckwheat (*Fagopyrum esculentum*) is a broadleaf annual traditionally produced for seed (as an alternative grain crop), that matures in only 30 to 45 days. This rapid growth allows it to be used as a smother crop on fallow fields to quickly out-compete annual weeds, so long as enough water is available. When allowed to mature, buckwheat flowers prolifically and provides an abundance of nectar for bees, as well as attracting other beneficial insects such as syrphid flies and parasitoid wasps. Because of its rapid development, two or more sowings of buckwheat can be performed in climates with extended growing seasons (in contrast, it does not grow vigorously in cool weather).

Anecdotal reports from Canada and the United States of America suggest honey production rates from buckwheat flowers can be as high as three to four stored kilograms per hectare per day by strong honey bee colonies. Based upon local market prices for buckwheat honey and the suitability of local growing conditions, buckwheat may be one of the few cover crops for which planting costs are more than offset by the value of honey produced from the crop (Ramsay, 1987).

Lacy phacelia

Lacy phacelia (*Phacelia tanacetifolia*) is a native wildflower of the United States of America that has been used extensively as an annual cover crop in Europe. Its use as a cover crop in the United States of America has steadily been increasing and low-cost seed is now widely available from seed suppliers; however, its use outside of Europe and North America remains limited.

Each lacy phacelia plant produces a large number of flowers that continue to open in succession over a period of several weeks. Successive seeding of phacelia can further extend the flowering period. Large numbers of bees – honey bees and bumble bees, in particular – are attracted to phacelia, but syrphid flies and various beneficial wasps are also common flower visitors. Phacelia is not cold hardy and thus requires spring planting in cool climates. In warmer climates it can be fall-sown for spring bloom (Lee-Mäder *et al.*, 2014).

Cover crop mixes

Many other cover crop species beyond those described here are available for specific uses and may be useful for providing pollen and nectar resources for pollinators. Additionally, in the U.S. there is a growing interest in the use of diverse, multi-species cover crop mixes (sometimes containing ten or more plant species) (Lee-Mäder *et al.*, 2014). An advantage for pollinator management with such an approach is that bloom period can be prolonged with the integration of successively flowering species, and plant species diversity may foster greater pollinator diversity (through the inclusion of diverse flower shapes and sizes).

Managing cover crop plantings for pollinators

Beyond species selection, several management issues should be considered when using cover crops to support pollinators. First, where possible, allowing the cover crop to complete flowering before termination (e.g. incorporating it into the soil as a green manure) is preferable. In the absence of other pollen and nectar resources, termination of the cover crop at or prior to peak flowering may negatively impact pollinator populations dependent upon that resource. Where the cover crop must be terminated before it is finished flowering, leaving remnant strips of it to continue blooming may be a preferable compromise to eliminating all of it (Figure 4).

Second, where cover crops are planted with the goal of attracting and sustaining pollinators, it is critical that they be protected from direct insecticide applications, insecticide drift and planting where they may absorb and sequester insecticide residue. For example, planting cover crops following a rotation with crops that were treated with systemic neonicotinoid insecticides may allow those cover crops to absorb insecticide residue for the soil or previous crop’s debris, resulting in a risk to pollinators foraging on that cover crop.

Figure 4.

Diverse cover crop with flowering vetch, radish, phacelia and other species in North Dakota, United States of America

Temporary insectary strips

A smaller and more targeted approach to cover cropping for pollinators consists of planting single rows of fast blooming annual flowering plants between rows of the primary crop. For example, low cost annual herbs such as dill (*Anethum graveolens*) and coriander (*Coriander sativum*), as well as flowers like lacy phacelia (*Phacelia tanacetifolia*) and sunflower (*Helianthus annuus*) can be inter-sown as a separate row within a larger primary crop to help sustain pollinator populations and encourage their visitation within the larger crop field (Lee-Mäder *et al*,. 2014).

Insectary strips are usually established at the same time as the primary crop and plowed under at the end of the season (Figure 5). While they can help support pollen and nectar feeding insects, their temporary nature does not provide long-term shelter for egg-laying and overwintering. Therefore, their use is probably optimal when complementing more permanent nearby habitat features, rather than substituting for permanent habitat.

Since insectary strips are usually integrated into crop fields, it is imperative that they not be exposed to insecticides. For this reason they are probably best used by farmers who do not apply insecticides.

Figure 5.

Temporary insectary planting established on a California farm

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Permanent cover crops

Although most cover crops consist of annual plant species, in some farm systems – such as tree fruit orchards – perennial cover-crop species may be more suitable. In many cases, perennial herbaceous plants may be more challenging to establish from seed, and may take longer to mature before flowering. The tradeoff, however, is that well-established perennial cover crops may persist for many years and provide competition against invasion by noxious weeds. Perennial cover crops also provide an opportunity to include grasses for pollinator overwintering and nesting (such as by bumble bee species that nest under grass tussocks) (Vaughan and Black, 2006c). Finally, unlike annual cover crop species, native perennial plants within their region tend to be resilient to local conditions, and do not typically require irrigation after they are established.

Long-term management of agroforestry and cover crop systems for pollinators

Several long-term pollinator management issues should be considered in both agroforestry and cover cropping systems. These issues broadly cover both the protection of pollinators from other farm activities, and the protection of larger local ecosystems. A sampling of these key issues is provided below.

Optimize pesticide use

Pesticides, especially insecticides, can not only kill pollinators, but sub-lethal doses can affect their foraging and nesting behaviors. Even herbicides, which may not directly impact pollinators, can reduce wild plant populations that pollinators depend on when crops are not in bloom.

To reduce unintended impacts on bees, broad-spectrum chemicals should be avoided if at all possible. If pesticide use cannot be avoided, they should be applied directly to target plants to prevent drift. Similarly, crops should not be sprayed while in bloom and sprayed at night where possible, when most bees are not foraging. Periods of low temperatures may also be beneficial for spraying because many pollinators are less active in cooler conditions. However, the residual toxicity of many pesticides tends to last longer in cool temperatures. Dewy nights may cause an insecticide to remain wet on the foliage and be more toxic to pollinators the following morning (Vaughan and Black, 2006d).

In general, while pesticide labels may list hazards to honey bees, the potential dangers to other bees and other pollinators are often not listed. Many wild bees are much smaller in size than the European honey bee and may be affected by lower doses of chemicals. Also, honey bee colonies may be covered or moved from a field, whereas wild bees will continue to forage and nest in areas that have been sprayed.

The use of selective pesticides that target a narrow range of insects, such as *Bacillus thuringiensis* (Bt) for moth caterpillars, is one way to reduce or prevent harm to beneficial insects like bees. (Note: Bt is toxic to non-pest butterflies and moths and should be used carefully where this is a concern.) Generally, dusts and fine powders are more dangerous than liquid formulations. This is partly because the dust and fine particles of the pesticide become trapped in the pollen-collecting hairs of bees, and the chemicals are consequently fed to developing larvae. Alternatives to insecticides are also available for some pests, such as kaolin clay barriers for fruit crops. Finally, farmers who enhance habitat for pollinators will inevitably be providing habitat for other beneficial insects that help control insects naturally. This may result in less dependency on pesticides (Vaughan *et al.*, 2007).

Reduce pesticide drift

Windbreaks, hedgerows and conservation buffers can be effective barriers to reduce pesticide drift from adjacent fields, but it is important that these pesticide barriers are not attractive to pollinators. Spray drift can occur as either spray droplets or vapors. Factors affecting drift include weather, method of application, equipment settings and spray formulations. Weather related drift increases with temperature, wind velocity, convection air currents and during temperature inversions. Pesticide labels will occasionally provide specific guidelines on acceptable wind velocities for spraying a particular product. Ideal spraying conditions are at wind speeds of 6–19 km/hr, which equates to a Beaufort strength number of 2 or 3. Always check and follow those recommendations when present.

Spray equipment methods and equipment settings also strongly influence the potential for drift. Small droplets are more likely to drift the longest distances, so mist blowers should be avoided where feasible. Standard sprayers should be operated at the lowest effective pressure and with the nozzles used as low as possible to deliver insecticide within the crop canopy where it is less likely to be carried by wind currents. Regardless of the chemical or type of application equipment used, sprayers should be properly calibrated to ensure that excess amounts of pesticide are not applied.

Minimise the impacts of mowing, grazing and cultivation

Disturbance in a farm setting is often frequent and abrupt and can occur as tilling, mowing or grazing. With pollinators in mind, it is important to consider the timing, amount and intensity of such disturbance. A general rule is that only 25 to 33 percent of pollinator habitat should be disturbed by mowing or grazing at any one time in order to minimise impacts on pollinators, as well as on other wildlife. The area disturbed should not totally eliminate a resource critical to pollinator habitat, such as the only area providing pollen nectar resources during a given period.

This will allow for re-colonization by pollinators of the disturbed area. In order to minimise negative impacts on foraging and egg-laying opportunities, disturbance activities should be avoided while plants are in flower (Lee-Mäder *et al.*, 2001) (Figure 6).

Protecting wood-nesting bees

In agroforestry systems, wood-nesting bees will often nest in the abandoned tunnels of wood-boring beetles and the hollow centers of plant stems (such as bamboo). Allowing snags and dead trees to stand (so long as they do not pose a risk to property or people) and protecting plants with pithy or hollow stems will provide nesting opportunities for those bees (Vaughan and Black, 2006c).

Floral diversity

Diversity is an important factor in the design of new pollinator habitat (Figure 7). Flowers should be available throughout the entire growing season, or at least whenever adjacent crops needing pollination are not in bloom. It is desirable to include a diversity of plants with different flower colors, sizes and shapes, varying plant heights and growth habits to encourage and benefit the greatest numbers and diversity of pollinators. Most bee species are generalists, which mean that they feed on a range of plants throughout their life cycle. Other pollinators only forage on a single family or even a single genus of plants. Choose plants with a variety of flower shapes in order to attract a diversity of pollinators. Some flowers appear almost closed, which require bees to crawl inside the petals to obtain nectar rewards. Other species are long and tubular-shaped requiring insects like butterflies that have long tongues to obtain the resources. Color is another important consideration. Bees typically visit flowers that are purple, violet, yellow, white and blue. Butterflies visit a similarly wide range of colors including red, whereas flies are primarily attracted to white and yellow flowers. Thus, by having several plant species flowering at once, and a sequence of plants flowering throughout the growing season, habitat enhancements are able to support a wide range of pollinating insects (Mäder *et al.*, 2011).

Plant bloom time

Plant diversity should also be measured by the number of plants flowering at any given time. Research conducted in the U.S. and Europe has found that when eight or more species of plants with different bloom times are grouped together at a single site, they tend to attract a significantly greater abundance and diversity of bee species. In some of those same studies, bee diversity continues to rise with increasing plant diversity and only starts to level out when twenty or more different flower species occur at a single site.

Figure 6.

Apple orchard in Wisconsin, United States of America with flowering understorey weeds allowed to grow for bees

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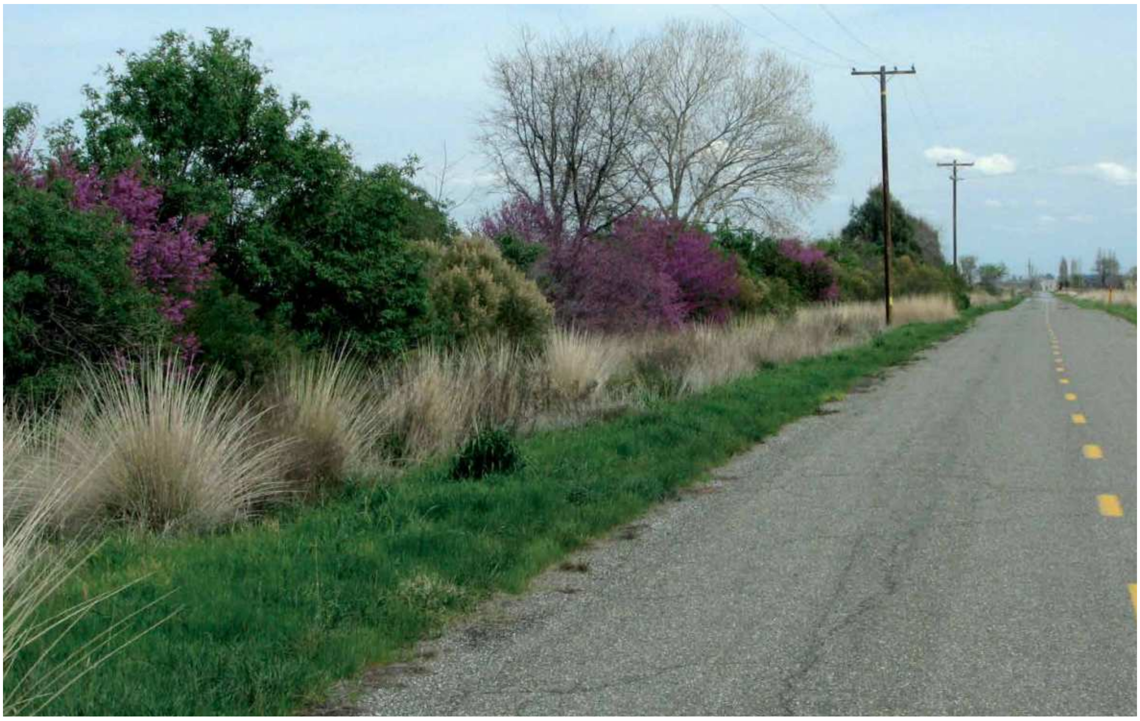
Figure 7.

Mature California hedgerow consisting of diverse flowering species



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Native plants

Native plants are adapted to the local climate and soil conditions where they naturally occur. Native pollinators are generally adapted to the native plants found in their habitats. Some common horticultural plants do not provide sufficient pollen or nectar rewards to support larger pollinator populations. In addition, some non-native plants have the ability to invade and colonize new regions at the expense of existing native plant communities. Often native plants have co-evolved with the pollinators that frequent them and are uniquely adapted to be most efficiently pollinated by those native insects. Native perennial plants are advantageous because they generally:

- require less fertilizer and do not usually require pesticides for maintenance;
- may require less water than other non-native plantings;
- are less likely to become invasive than non-native plants; and
- support local biological diversity.

Using native plants will help provide connectivity to existing native plant populations particularly in regions with fragmented habitats. Providing connectivity on a landscape level increases the ability for species to move in response to environmental shifts and increases the genetic variability potential.

While in most cases native plants are preferred, non-native ones may be more appropriate for some cover crops or agroforestry understorey plantings. Often it is necessary to include non-native or introduced species to fill in gaps of bloom times, or when native plants are not available or are prohibitively expensive (Mäder *et al,*. 2011).

Avoiding nuisance plants

When selecting plants, avoid ones that act as alternate or intermediate hosts for crop pests and diseases. Similarly, economically important agricultural plants (or closely related species) may be a poor choice for cover crops or agroforestry because they may serve as a host reservoir for insect pests and crop diseases. For example, brassica vegetable farmers may prefer not to use mustard species as cover crops since they may harbor insect pests and diseases. It is prudent to be familiar with the crops and their commonly associated pests and diseases within the local area.

SUCCESSFUL EXAMPLES OF APPLICATION

Multi-storey agroforestry for Pacific Island farms

Multi-storey farming is a common practice among farmers in the tropical Pacific Island region. Using this farming approach, existing or planted stands of trees and shrubs are managed as an overstorey with an understorey of woody and/or non-woody plants that are grown for a variety of products. Typically, overstorey tree-to-tree distance is wide enough to let sufficient light through to understorey or groundcover plants (Figure 8).

A model multi-storey agroforestry system designed by the U.S. Department of Agriculture's Natural Resources Conservation Service (NRCS) for the Pacific Islands recommends an overstorey of pollinator-attractive trees such as macadamia (*Macadamia* spp.), avocado (*Persea americana*), neem (*Azadirachta indica*), ohia lehua (*Metrosideros polymorpha*), or mango (*Mangifera* spp.), and an understorey of shade-tolerant pollinator-dependent plants such as coffee (*Coffea* spp.), cacao (*Theobroma cacao*), vanilla (*Vanilla planifolia*), or cardamom (*Elettaria* spp. and *Amomum* spp.). In such combination plantings, the diversity of species provides extended bloom periods for pollinators, as well as more complex vegetative structure for nesting by leafcutter bees, carpenter bees, and other insects.

Because multiple levels of the plant canopy are farmed at the same time, such systems may enhance farm profit potential and product diversification. An example of this system type is highlighted in the report *Shade-Grown Coffee for Hawai'i: Results of a twelve farm study in Kona* (http://www.agroforestry.net/caf/Hawaii_shade_coffee.pdf).

Figure 8.

Terraced forest farm with diverse multi-storey food plants and fruit trees in American Samoa

Insectary windbreaks for the tropical Pacific Island region

Windbreaks consist of one or more rows of closely spaced trees and/or shrubs planted in linear configurations. The wind shadows created to the leeward side of these barriers protect crops, livestock, soil, as well as homes and farm structures, and can reduce soil moisture loss. When planted with pollen- and nectar-rich flowering trees and shrubs, windbreaks can also be valuable habitat features for pollinators and other wildlife, so long as they are not capturing drifting insecticides from adjacent farms.

In the tropical Pacific Island region, windbreaks have been demonstrated to have particular value in protecting farms from strong trade winds and typhoons. To incorporate pollinator benefits into a windbreak design, Xerces Society pollinator biologists worked with the USDA- Natural Resources Conservation Service (NRCS) to identify high-value pollinator plants that provide functional value as windbreak species. These include gliricidia (*Gliricidia* spp.), avocado (*Persea americana*), dwarf banana (*Musa* spp.), kou (*Cordia subcordata*), milo (*Thespesia populnea*), mango (*Mangifera* spp.), tree-like varieties of hibiscus (*Hibiscus* spp.), and coconut (*Cocos nucifera*). In providing design recommendations to farmers, Xerces and United States Department of Agriculture (USDA) biologists note the value of including multiple tree and shrub species to provide more continuous floral resources, as well as to enhance nesting resources for pollinators. Multi-species windbreak designs may also increase their effectiveness by improving windbreak density at multiple heights.

Several valuable resources for windbreak design are available, including the Molokai NRCS Plant Materials Center presentation *Windbreaks for Agroforestry* (http://www.plant-materials.nrcs.usda.gov/pubs/hipmssy6712.pdf) and the University of Hawaii Extension publication *Trees and Shrubs for Windbreaks in Hawaii* (http://www.ctahr.hawaii.edu/oc/freepubs/pdf/C1-447. pdf).

Cover crops for honey bees and other pollinators in the northern Great Plains, United States of America

Federal conservation agencies, such as the United States of America's Department of Agriculture's Natural Resources Conservation Service (USDA-NRCS) in the U.S. and agri-environment schemes in Europe may provide financial incentives and technical support for farmers interested in implementing cover cropping systems to support pollinators.

In the United States of America, Xerces Society pollinator biologists worked with the USDA-NRCS to develop a list of cover crop species that may be planted in the northern Great Plains to support wild bees and over-summering colonies managed by migratory beekeepers. To have maximum benefit for the migratory beekeeping community, these cover crops primarily need to be spring-planted annuals that bloom mid- to late-summer. The list is indicative of what can be planted in similar cold- winter temperate climates.

In providing design recommendations to farmers, Xerces and USDA-NRCS biologists note the value of including multiple cover crop species in a single planting to provide more continuous and diverse flowering plants, as well as to better manage weeds. For example, the NRCS in North Dakota is conducting field tests of diverse cover crop mixes ("cocktails") that can include ten or more species, including melliferous cover crop species such as rapeseed, radish, Phacelia, sunflower and more. These diverse cover cropping systems likely also support a wider diversity of bees and other pollinators.

One major concern not currently addressed in the research literature is the extent to which cover crop species planted after rotations of row crops that were treated with systemic insecticides will uptake and express insecticide residues in flower pollen and nectar. Even trace concentrations of residues of 5 to 20 parts per billion could have a dramatic effect on the reproduction and foraging of bees foraging on these cover crops.

Pollinator cover crop systems for the tropical Pacific Island region

Working with the USDA-NRCS, pollinator biologists at the Xerces Society were asked to develop a model cover crop system for the tropical Pacific Island region.

Cover crops are already actively promoted by the USDA-NRCS for reducing soil erosion, adding fertility and organic matter to the soil, improving soil tilth, and increasing infiltration and aeration of the soil. Depending on the plant species used, cover crops may also suppress pests, such as nematodes, through root exudates and they can prevent the encroachment of weeds on fallow cropland.

In the Pacific Island region, Xerces Society scientists and USDA-NRCS agronomists identified two model approaches to supporting pollinators with cover crops. They can be incorporated into rotation with short-term row crops (e.g. seed corn and tomatoes), or they can be used as an understorey planting in agroforestry systems (e.g. below coffee or koa tree crops). Based upon the results of field trials conducted by local partners, four optimal cover crop species were identified that could be used in these two model systems: sunn hemp (*Crotalaria juncea*), buckwheat (*Fagopyrum esculentum*), white sweet clover (*Melilotus alba*) and cowpea (*Vigna unguiculata*). While each of these species individually provides pollen and nectar for bees and other beneficial insects (including those that prey upon crop pests), Xerces and USDA-NRCS recommend combining them into multi-species seed mixes to provide a longer bloom period, and to support greater insect diversity. Similarly, Xerces and USDA-NRCS identified benefits from the inclusion of a grass, such as oats (*Avena sativa*), in multi-species cover crops to enhance insect diversity by providing greater vegetative structure for some beneficial insect groups.

Cover crop systems for the Pacific Island region continue to be researched and improved on an ongoing basis, and fact sheets are available from many regional colleges, universities, and agencies. For some current findings, see the *Adoption of Cover Crop Technology* website (http://www.oahurcd.org/covercrops) maintained by Oahu Resource Conservation and Development Council, and *Cover Crops and Green Manures for Hawai'i* (http://www.ctahr.hawaii.edu/ sustainag/Database.asp), a website maintained by the University of Hawaii's Sustainable and Organic Agriculture Programme.

Pollinator cover cropping for almonds in California, USA

Researchers, government conservationists, and a non-governmental organization worked with almond growers to develop annual understorey cover crop plantings designed to support wild bees, managed solitary bees, and migratory honey bees that pollinate California's almond orchards. The goal of this effort was to find primarily native annual plant species that bloom before and after the almond bloom – thus minimizing competition with the almond flowers – pose little or no weed risk, and support a diversity of important bee species. The understorey cover also could not interfere with almond harvest or management, which meant that plants chosen for this mix needed to be less than two feet tall (0.6 m) and break down rapidly after bloom so that the orchard understorey was mostly clear of debris to allow for the gathering of nuts shaken from the trees during harvest in late summer. In addition, low growing plants minimize the risk of early spring frost damage to the adjacent trees. Finally, the mix needed to be inexpensive enough so that it was affordable for growers. To keep costs down, and to help improve soil health and productivity by fixing nitrogen, non-native crimson clover was added. In addition, to keep costs down, certain inexpensive species, such as globe gilia, were included at relatively higher rates (Figure 9).

Although designed specifically for almond orchards, this mix would be suitable for most orchard crops, including cherries, apples and stone fruit. Because many of the species in the mix are also attractive to a diversity of different beneficial insects (e.g. predators or parasites of crop pests) this mix also would be suitable to non-pollinator dependent perennial crops, such as walnuts.

The final mix used in California (which should be adapted and modified to specific local contexts) contains 32 percent (by seed count) crimson clover (*Trifolium incarnatum*); one percent five spot (*Nemophila maculata*); six percent baby blue eyes (*Nemophila menziesii*); five percent great valley phacelia (*Phacelia ciliata*); nine percent Chinese houses (*Collinsia heterophyllus*); 15 percent California Poppy (*Eschscholzia californica*); 30 percent globe gilia (*Gilia capitata*); and two percent tidy tips (*Layia platyglossa*). Partners at University of California, Davis have documented significant bee visitation and little competition with almond bloom, research is currently underway to measure increases in bee abundance supported by such plantings, and the subsequent economic benefit when cost of seed and planting is taken into account.

GENERAL DO's AND DON'Ts

- In the absence of existing natural habitat, agroforestry systems and cover cropping can provide two approaches for integrating pollinator habitat directly into the farm.
- Where possible, the protection and restoration of locally native plant communities and wild pollinator habitats should be prioritized.
- The integration of pollinator resources into active farmland through artificial measures like hedgerows and cover crops (Table 1) is extremely valuable and should be considered a supplement rather than a replacement for the protection of true natural habitat.
- The combined approaches of cover crops and agroforestry practices should ideally function together within agroecological farm systems, and thus serve as pollinator-friendly corridors between intact natural areas.

Figure 9.

Lacy phacelia and other flowers established as a strip planting near California, United States of America almond orchard

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Table 1.

Example annual cover crop species that provide significant benefit for honey bee forage in the north-central United States of America

SPECIES	LIFE HISTORY	PLANTING WINDOW
Brown Mustard (*Brassica juncea*)	annual	spring into early summer (soil temp >4.5 °C)
Rapeseed (*Brassica napus*)	annual	early spring into early summer (soil temp >4.5 °C)
Field Mustard/Turnips (*Brassica rapa*)	annual	early spring into early summer (soil temp >4.5 °C)
Partridge Pea (*Chamaecrista fasciculata*)	annual	early spring into early summer (soil temp >15.5 °C)
Buckwheat (*Fagopyrum esculentum*)	annual	spring into mid-summer (soil temp >10 °C)
Annual Sunflower (*Helianthus annuus*)	annual	spring (soil temp >7.2 °C)
Lacy Phacelia (*Phacelia tanacetifolia*)	annual	late spring into mid-summer
White Mustard (*Sinapis alba*)	annual	spring (soil temp >5.5 °C)
Berseem Clover (*Trifolium alexandrium*)	annual	early spring into early summer (soil temp >5.5 °C)
Crimson Clover (*Trifolium incarnatum*)	annual	spring into early summer
Common Vetch (*Vicia sativa*)	annual	spring
Hairy Vetch (*Vicia villosa*)	annual	spring (soil temp >15.5 °C) or mid to late summer
Cowpea (*Vigna unguiculata*)	annual	early summer (soil temp >14.5 °C)

These cover crop species include options that are typically planted in spring as a summer-fallow cover that blooms mid- to late-summer

Source: Clark, 2007; USDA-NRCS, 2014; USDA-PLANTS, 2014; Sattell *et al.*, 1998

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Chapter 11

Conducting cost-benefit analysis for wild pollinator conservation on farmland

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REASON FOR THE PRACTICE

While there is a vast literature detailing the benefits of farmland habitat management to insect pollinators, in many countries the level of uptake of these recommendations still falls below that required to make a significant impact on pollinator and other wildlife populations. This may be because the required changes to farming practices and farm architecture often call for an uncertain amount of capital outlay, together with recurring and/or hidden costs (Table 1). Furthermore, negative effects can occur from conserving weeds for pollinators, for example; particularly, if the weeds are strong competitors with the crop (e.g. Landis *et al.*, 2000). Many landowners and farmers may therefore be reluctant to undertake such changes without some control over the costs and benefits.

Evaluating the economic efficiency of practices such as habitat management, selective weeding and non-crop flower provision will help farmers and managers make decisions about which measures they can afford to adopt and to what extent they will be profitable. However, while many attempts have been made to value pollinator conservation on a range of scales, these valuations often use data that are unavailable to individual farmers, such as "insect dependence factors" (Tait and Cullen, 2006). To engage farmers and land managers in assessing the benefits of adopting specific pollinator-friendly practices, methods that are currently available to take account of the value of secondary benefits, the hidden costs and benefits, and other non-monetary aspects of pollinator conservation can be adapted for these purposes. This chapter aims to outline some of these methods and how they might be used for farm-level decisions.

Table 1.

The costs and benefits of conserving pollinators on farmland by habitat management, selective weeding and non-crop flower provision

COSTS	BENEFITS
OBVIOUS FACTORS	
• Loss of cultivated land and corresponding crop yields • Potential loss of yield due to variability of wild pollinators • Costs of restoring non-crop vegetation (flower seeds, specialised machinery) • Labour	• Increased yield and revenue from higher quality produce due to increased pollination service to crops • Small savings in production costs • Savings in honeybee hive rental fees • Potential subsidies from agri-environment schemes or price premiums for organic or 'environmentally friendly' products by reducing the amount of cultivated land
LESS OBVIOUS, DELAYED OR NON-MONETARY FACTORS	
• Training of habitat enhancement techniques • Monitoring enhancement areas for successful establishment of flowers and beneficial insect populations • Maintenance costs of new habitats • Increase in pests attracted to wildflowers • Increase in weeds • Increase in diseases • Possible lack of spill-over (pollinators are attracted to wildflower margins and do not enter crop)	• Increase in biological control – optimization in pesticide use • Optimized pesticide use decreases likelihood of resistance developing • Landscape manipulation helps other ecosystem services, such as erosion control • Increased soil fertility • Suppression of weeds • Alternative crop potential – sale of wildflower seeds or timber • Aesthetic value of improved landscape • Improved water quality • Improved plant and insect conservation • Other wildlife benefits • Community benefits beyond farm boundary

Obvious factors, which are usually easy to value in monetary terms, and the less obvious, delayed or "priceless" costs and benefits, which require more creative methods of valuation, are presented

Adapted from Wratten *et al.*, 2012

HOW TO IMPLEMENT

The most common and simplest form of cost benefit analysis (CBA) is to compare scenarios of "with" versus "without" (Cullen *et al.*, 2008). In theory, if the total benefits exceed the total costs of a project, the project should be implemented. In the case of the introduction of management practices to encourage pollinators, the obvious costs (the top half of Table 1) include implementation expenditure and the removal of land from production, but these will be potentially offset by the obvious benefits of an increase in yield and/or income.

Of these factors, the most problematic for a farmer to value is the change in yield or revenue following pollinator conservation because it requires knowledge of the efficacy of local pollinators, data that are often missing (Cunningham and Le Feuvre, 2013). The best way to value the change in yield, quality or revenue is to conduct field-scale experiments like those of Bommarco *et al.* (2012) described below in the section titled: *Successful examples of application*. An alternative experiment would be to compare the yield and quality of crops grown close to semi-natural areas of high floral diversity, with those grown in isolation of floral resources, as pollinator diversity and abundance is likely to be greater at the crop edge (e.g. Free and Williams, 1976). These are simple experiments that require little equipment and time, although repetition and replication are important to ensure that results are not chance events. Although this valuation method carries a number of problems, it can be a source of information easily attainable by individuals.

The above is an over simplified CBA method. We would encourage farmers to go further in their CBA and take account of some or all of the factors listed in the bottom half of Table 1, often overlooked in CBA (Jackson *et al.,* 2007). For example, often measures that improve conditions for wild pollinators on a farm can also enhance populations of natural enemies of crops pests (Wratten *et al.*, 2012). Therefore, depending on the cropping system, pollinator habitat enhancement could also lead to reduced pest numbers, reduced crop losses and a reduction in the number of chemical applications required. The difficulty is that a precise value cannot be placed on some of these costs and benefits. These problems often relate to the lack of a market, and therefore a price for such factors – for example, you cannot buy or sell pollination (Gomez-Baggethun *et al.*, 2010) and no one "owns" it (Zhang *et al.*, 2007). The farmer through a period of careful trial and measurement can value many of these factors in the absence of relevant scientific study. Alternatively, proxies can also be obtained using some of the commonly used ecosystem service valuation methods listed in Table 2.

Individuals, or groups of farmers, or even by groups pressuring local governments or universities to collect such locally relevant data can gather many of the values from Table 2. A final suggestion for those farmers not privy to such information or to scientific expertise is the use of a method developed by Farber *et al.* (2006). They suggest a simple decision making process for use when economic values are not available. A "service matrix", similar to the hypothetical example in Table 3, is constructed which reflects the *changes* in cost or benefit factors likely to occur through different management options compared with current management, and these are scored between -3 to +3. For example, biological control of pests is considered to be unaffected when using rented honeybee hives (0 score), and to change positively under low (+2) or high (+3) level pollinator conservation. These scores are then multiplied by a value weight (0-3), depending on their relative value to the farmer or group, and the overall service change values are aggregated to provide an overall score for each management type. The scores and value weights can be assessed using different valuation methods. Table 4 also presents the same hypothetical example where economic values are known and the monetary value of the change (the additional cost or income of the project) replaces the scores. Overall, if the "value of change" is negative, the project should be rejected. If it is positive it can be accepted, and the project with the highest value of change should be adopted in theory. This process should be repeated throughout the life of the project, and values and weights adjusted as appropriate.

Table 2.

Ecosystem service valuation methods and the cost/benefit factors for which they can be used

TECHNIQUE	DETAILS OF METHOD	USEFUL FOR
Market prices	Values are prices of goods or services that are traded on markets (extendable to non-market goods based on effects on prices of market goods)	• Changes in yield/revenue • Production, labour and management costs • Alternative crop revenue • Costs of weed control • Government subsidies
Replacement cost	Cost of replacing or restoring an ecosystem service, e.g. replacing pollination	• Honeybee hive rental • Valuing the improvement in wildlife conservation, water quality or soil fertility • Benefit of improving other ecosystem services
Defensive expenditure or avoidance cost	Costs incurred in avoiding unwanted events or reduced ecological function	• Cost of controlling pests/disease/weeds • Benefit in avoiding pest control: reduction in pesticide use
Contingent valuation	Stated preferences of individuals as described through questionnaires and interviews; usually assesses willingness to pay (WTP) for benefits or willingness to accept (WTA) costs	• Aesthetic value of improved landscape • Price premium or subsidy on environmentally friendly produce • Community benefits beyond farm boundary

Adapted from Gillespie and Wratten, 2012.

SUCCESSFUL EXAMPLES OF APPLICATION

The best available study exploring the potential economic benefit of uncultivated area for pollinators was conducted in a typical Canadian canola agro-ecosystem. This project calculated the average seed set as 18.1 ± 0.2 seeds/pod, an average yield of 1 335 kg/ha and an average profit of USD 112 per ha. It was calculated that if a central section of 64 ha in a 4 km^2 agricultural landscape was left to revert to semi-natural habitat, the bee abundance index would increase from 30.1 to 63.9

in each field, with a corresponding seed set increase of 1.8 seeds/pod. Yield would increase to 1 467 kg/ha and profit would increase to USD 130 per ha (Morandin and Winston, 2005).

This study uses a number of factors that farmers in different parts of the world are unlikely to have access to: calculations of average seed set, the bee abundance index and the pollination deficit change, which may be meaningless to farmers and landowners but are nonetheless important factors in determining the true net cost or benefit of encouraging pollinators benefitting from habitat management. We therefore recommend that farmers attempt, with guidance, pollinator conservation measures on small, affordable scales and monitor the results to gain information about the positive or negative effects.

An additional example demonstrates the use of simple experiments to calculate the amount of yield attributable to pollinators. Bommarco *et al.* (2012) used ten fields of oil seed rape in Sweden, five of which were treated as "controls", i.e. they were treated normally, and five of which had ten rape flower stalks in a small plot enclosed in net bags to prevent insect pollination, but allow wind pollination. The difference in the yield from ten plants from the five control fields and the yield from these netted flowers was then taken to represent the contribution to yield of insect pollination of oil seed rape. They also collected information about the quality of the seed from the two treatments, and incorporated this into the monetary value of wild pollination. Overall, insect pollination contributed 18 percent to yield and 20 percent of revenue from oilseed rape in Sweden.

GENERAL DO's AND DON'Ts

- Consider as many hidden and secondary benefits as possible.
- Use direct, scientific information where possible. Use proxies such as replacement cost where necessary.
- Where local or regional detailed information about important pollinators and crops is not available, consider conducting your own experiments.
- Alternatively, conduct pollinator habitat enhancements on a small scale with guidance and monitor the results throughout the year over a number of growing seasons.
- Consider using a "service matrix" decision-making method, as described above and by Farber *et al., (2006).*

Table 3.

A service matrix adapted from Farber *et al.* (2006) for a hypothetical pollinator conservation project

In the example of Table 3, there are three different projects to improve crop pollination under consideration: 1) Honey bee hive rental, 2) low wild pollinator conservation (minor habitat provision) and 3) high level wild pollinator conservation (major habitat provision). The change in each cost or benefit, e.g., the additional cost or benefit occurring from the project, is estimated and scored (-3 to 3) and then multiplied by a "value weight" reflecting the importance placed on the factor by the farmer. The resulting "value of cost/benefit change" figures are summed for each project. In this example, renting honey bee hives results in a net cost compared to current operations. Both pollinator conservation projects should be considered for adoption though, due to positive scores.

COST OR BENEFIT	ANTICIPATED CHANGE IN COST OR BENEFIT (C): -3 TO +3				VALUE OF COST/BENEFIT CHANGE (C x V)		
	RENT HONEY BEE HIVES	LOW WILD POLLINATOR CONSERVATION	HIGH WILD POLLINATOR CONSERVATION	VALUE WEIGHT (V): 0-3	RENT HONEY BEE HIVES	LOW WILD POLLINATOR CONSERVATION	HIGH WILD POLLINATOR CONSERVATION
YIELD	1	1	3	3	3	3	9
QUALITY OF PRODUCE	1	2	3	3	3	6	9
PRODUCTION COSTS	-3	-1	-2	1	-3	-1	-2
MANAGEMENT COSTS	-1	-2	-3	2	-2	-4	-6
SUBSIDIES (IN CONTEXTS WHERE SUBSIDIES ARE PROVIDED)	0	1	3	2	0	2	3
IMPROVED BIOLOGICAL CONTROL	0	2	3	1	0	2	3
OPTIMIZED PESTICIDES	0	1	2	1	0	1	2
INCREASED WEEDS	-1	-1	-3	3	-3	-3	-9
AESTHETIC VALUE	0	1	2	0	0	0	0
OTHER WILDLIFE BENEFITS	0	1	3	1	0	1	3
TOTAL VALUE					**-2**	**7**	12

Table 4.

A service matrix adapted from Farber *et al.* (2006) for a hypothetical pollinator conservation project

In the example of Table 4, there are three different projects to improve crop pollination under consideration: 1) Honey bee hive rental, 2) low wild pollinator conservation and 3) high level wild pollinator conservation. The change in each cost or benefit, e.g. the additional cost or benefit occurring from the project, is estimated in USD per ha and then multiplied by a "value weight" reflecting the importance placed on the factor by the farmer. The resulting "value of cost/benefit change" figures are summed for each project. In this example, all projects should be considered, but the high wild pollinator conservation project is likely to be most profitable.

COST OR BENEFIT	ANTICIPATED CHANGE IN COST OR BENEFIT (C): USD VALUE PER HA				VALUE OF COST/BENEFIT CHANGE (C x V)		
	RENT HONEY BEE HIVES	LOW WILD POLLINATOR CONSERVATION	HIGH WILD POLLINATOR IMPROVEMENT	VALUE WEIGHT (V): 0-3	RENT HONEY BEE HIVES	LOW WILD POLLINATOR CONSERVATION	HIGH WILD POLLINATOR CONSERVATION
YIELD	+USD10	+ USD 11	+ USD 23	3	USD 30	USD 33	USD 69
QUALITY OF PRODUCE	+ USD 7	+ USD 5	+ USD 8	3	USD 21	USD 15	USD 24
PRODUCTION COSTS	- USD 8	- USD 10	- USD 15	1	- USD 8	- USD 10	- USD 15
MANAGEMENT COSTS	- USD 2	- USD 10	- USD 12	2	- USD 4	- USD 20	- USD 4
SUBSIDIES (IN CONTEXTS WHERE SUBSIDIES ARE PROVIDED)	USD 0	USD 5	USD 7	2	USD 0	USD 10	USD 14
IMPROVED BIOLOGICAL CONTROL	USD 0	USD 2	USD 3	1	USD 0	USD 2	USD 3
REDUCED PESTICIDES	USD 0	USD 4	USD 5	1	USD 0	USD 4	USD 5
INCREASED WEEDS	- USD 2	-USD 3	- USD 5	3	- USD 6	- USD 9	- USD 15
AESTHETIC VALUE	USD 0	USD 1	USD 2	0	USD 0	USD 0	USD 0
OTHER WILDLIFE BENEFITS	USD 0	USD 1	USD 3	1	USD 0	USD 1	USD 3
TOTAL VALUE					USD 33	USD 26	USD 64

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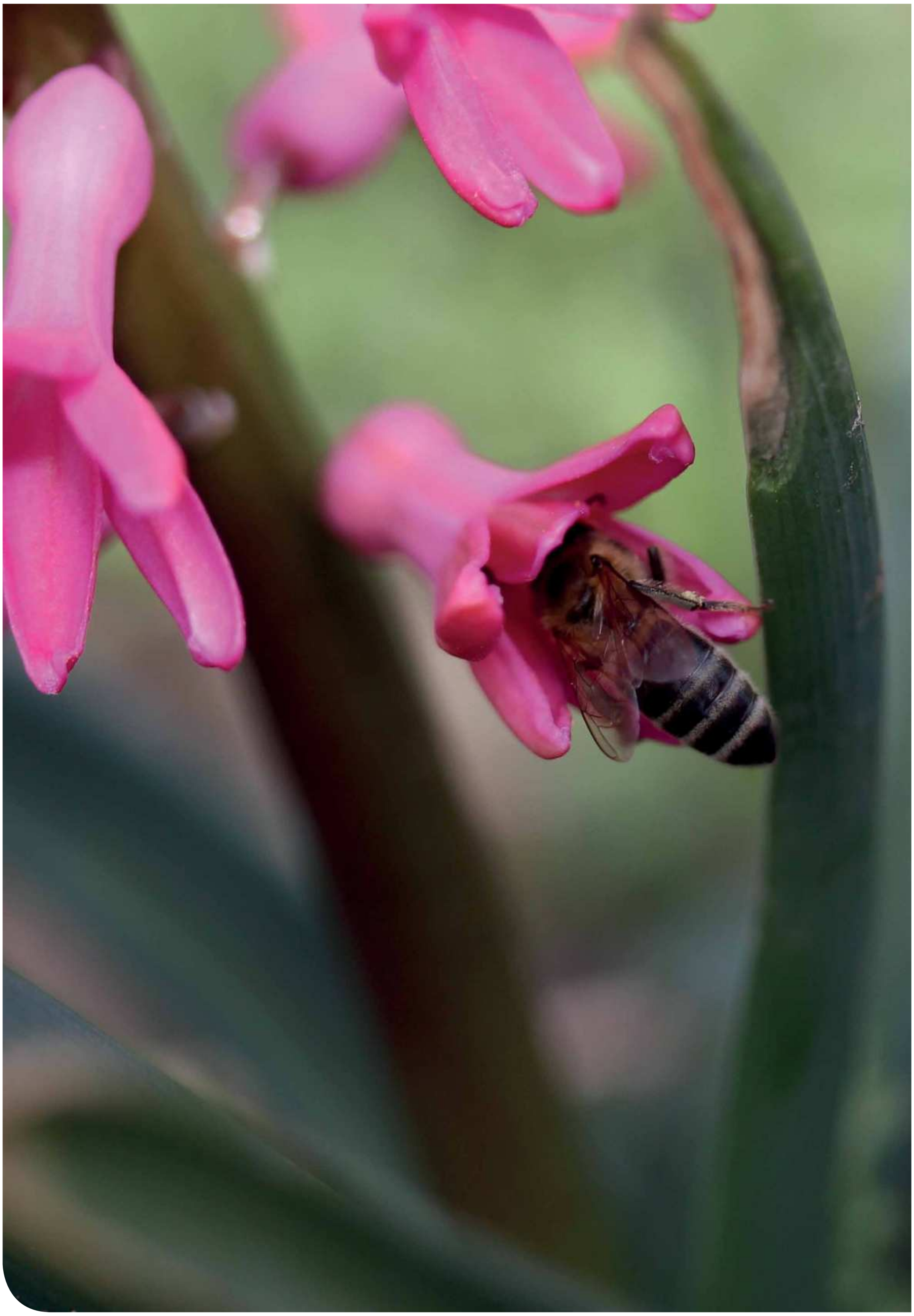

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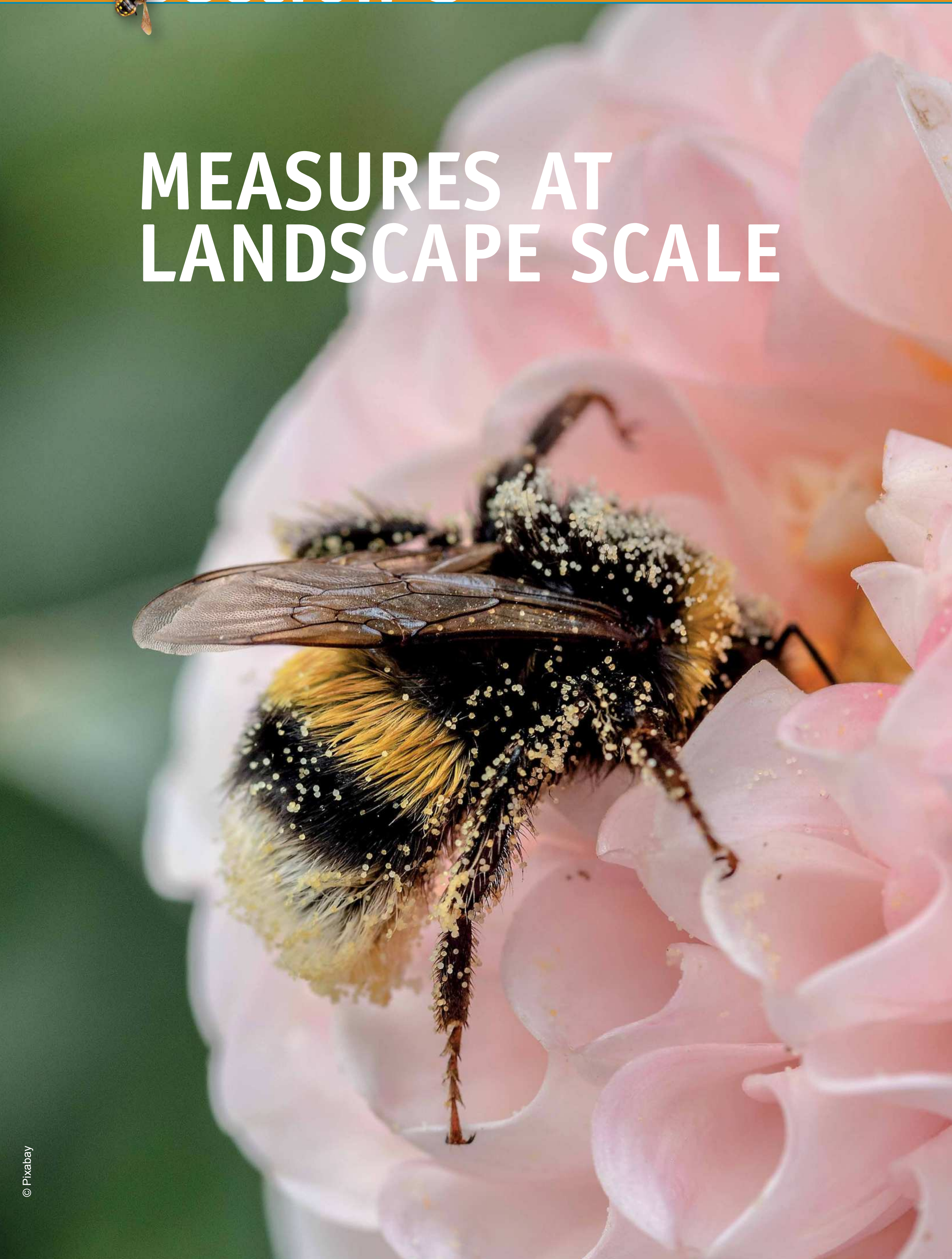
Section 3

MEASURES AT LANDSCAPE SCALE



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Chapter 12

Securing forage resources for indigenous managed honey bees – thoughts from South Africa

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REASON FOR THE PRACTICE

In South Africa where honey bees (*Apis mellifera*) are native, they are important for pollination processes that sustain numerous indigenous plants and as managed pollinators of pollinator-dependent agricultural crops. Two subspecies, *Apis mellifera capensis* and *Apis mellifera scutellata*, are actively managed by beekeepers and provide pollination services to the majority of pollination-dependent crops in the country by moving their colonies to farms during the pollination season (Johannsmeier, 2001; Mouton, 2011). Outside the pollination season, beekeepers undertake practices that provide a honey flow, ensure colony build-up, or trap swarms to replace bees that abscond or die (Allsopp and Cherry, 2004).

These practices require a diverse quality and quantity of good forage resources for the honey bees – i.e. flowering plants supplying pollen (protein) and nectar (carbohydrates). In a study undertaken in South Africa from 2011 to 2014, various forage resources important to beekeepers were investigated (Hutton-Squire, 2014; Masehela, 2017). It emerged that different regions in the country had a dissimilar reliance on certain forage resources, but forage resources could be roughly divided into: indigenous forage (sub-divided into natural and semi-natural habitats and vegetation types); and exotic forage, sub-divided into *Eucalyptus* spp. (formal forestry and other stands), agricultural crops and urban plantings (garden plants, tree lanes, etc.) (Masehela, 2017). These forage resources are all important for their complementary preferred uses (honey flow, colony build-up, or swarm trapping), availability (varied flowering times) and accessibility (localities of occurrence and access to localities). Therefore, an overarching strategy for managing forage resources has to consider the importance of both indigenous and exotic plants, as well as use, availability and accessibility.

Honey bee forage resources (and, therefore, the sustainability of the managed pollination service) are seriously threatened in South Africa. These threats do not only limit honey bee forage availability or accessibility, but also directly affect beekeeper livelihoods, pollination services, and put both wild and managed honey- bee populations at risk. The threats include, but are not limited to:

- **Changes in land use and landscape management.** The changes in land use and agricultural practices concomitant with an increasing and mobile human population are a threat to natural habitats and good forage sites for honey bee populations. In the past, particularly in small-scale farming, natural habitats adjacent to crops could easily provide habitat for honey bees (and other insect pollinators) and thus, lessen the need to bring in managed honey bee colonies for crop pollination (Veldtman, 2018). Today, however, farmers are expanding or intensifying their operations, often at the cost of the remnant natural areas, and thereby limit habitats for honey bees and other native pollinators (Steffan-Dewenter *et al.*, 2006). Monoculture farming practices further limit the quantity and quality of nectar and pollen resources. Market trends or climatic conditions may encourage farmers of important forage crops to change the crops they farm, perhaps opting for crops that provide little to no forage. The expansion in housing, roads and infrastructure development around towns and cities further exerts pressure on already diminishing forage resources.
- **Unconsidered removal of invasive alien plant species that are important forage resources.** Globally, biological invasions have been well documented regarding the threat they pose to ecosystems and economic productivity. Honey bee forage can be comprised of both alien and invasive alien plants, and many studies emphasise the fact that honey bee forage needs to have a diversity of reliable flowering plants, irrespective of their status (Vaughan *et al.*, 2007; Decourtye *et al.*, 2010; Levy, 2011). Eucalypts in South Africa are a good example: several eucalypts are important for honey flow, colony build-up and swarm trapping activities (Figure 1). These trees are also said to have given rise to commercial beekeeping in South Africa, due to their reliable nectar and pollen flows. Since the late 1990s, eucalypts are being removed in many areas because of their invasiveness. Six of the *Eucalyptus* spp., important as honey bee forage, are listed in the regulations of the National Environmental Management:

Biodiversity Act, 2004 (NEMBA) as Category 1b invaders, which requires that they be removed in most circumstances, but allows for them to be retained in demarcated areas subject to certain conditions that place responsibility on the landowner to control spread. Although currently most removals occur in the Western Cape Province, beekeepers have raised concerns due to the potential spillover effect such removal programmes might have for other provinces (Allsopp and Cherry, 2004).

- **Accessibility to important and secure forage resources.** There is immense pressure on South African beekeepers to find forage sites for their honey bees. Most beekeepers do not own or have control over land that provides adequate forage resources, but instead rely on formal or informal access to important forage sites on both public and private land. Land owners or managers might not allow beekeepers access to sites. For example, beekeepers are not allowed to place their managed colonies in most protected areas in South Africa, as visitor safety and the competition for floral resources with other flower visitors are concerns – both issues probably warranting further investigation (Brand, 2009). Forage sites on privately-owned land are usually a beekeeper's best option and the rights to

Figure 1.

***Eucalyptus sideroxylon* (left) and *Eucalyptus cladocalyx* (right), two of the most important eucalyptus species in terms of honey bee forage in South Africa**

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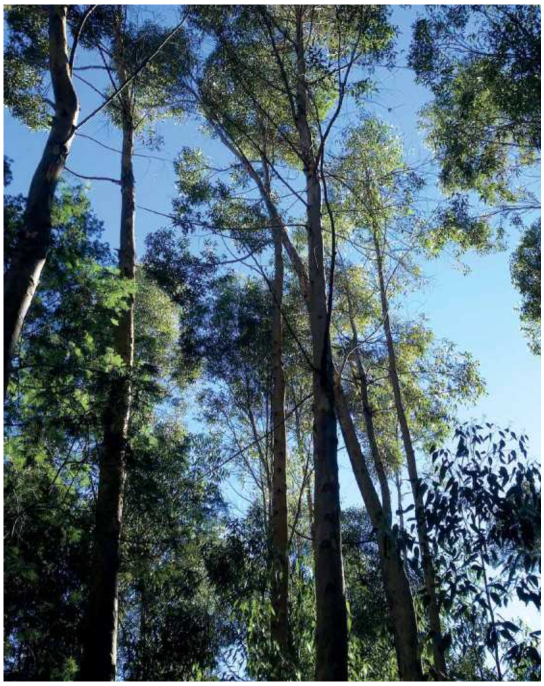

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such forage sites are sacrosanct and may be inherited or even traded between beekeepers. Good interpersonal relationships between beekeepers and landowners are a vital part of a beekeeping business in South Africa.

In essence, managed honey bees are transported to desired forage areas to ensure these forage resources are accessible (within bee flying distance). Beekeepers may also be forced to place their colonies on unsecured land where the colonies are prone to vandalism and theft. The latter factors may be some of the reasons hindering beekeeping activities in certain areas in South Africa that have good forage, simply because damage to hives and honey harvest creates an unsustainable beekeeping business.

- **Inappropriate crop chemical regimes that impact the viability of crops as important forage resources.** Agro-chemicals have been labeled by some studies to be one of the leading causes of honey bee deaths across the Northern Hemisphere. Common insecticides, such as neonicotinoids and pyrethroids, have been shown to affect learning, foraging activities, and nest site orientation by honey bees at sub-lethal doses (Aliouane *et al.*, 2009; Spivak, 2011). In South Africa, reports and studies on agro-chemical impact on honey bee health are limited – although the subject is receiving the much needed attention. Also, pesticide use is a widespread farm management practice and has been of great concern in recent years in relation to bee deaths. Many beekeepers in South Africa rely on the farmers of important honey bee forage crops (e.g. canola, lucerne, sunflowers and citrus); agreeing to let them place colonies on their farms for the nectar and pollen resources. Such farmers, who do not necessarily need or pay for pollination services from beekeepers, may not understand how important the colonies are to other farmers and may feel that there is no benefit from having these colonies on their farms. Poor communication or lack of understanding can result in the beekeeper not being contacted when spraying is to take place, and the colonies' search for food in these farming landscapes can end fatally for the bees.
- **Impacts of climate change on forage resources.** There is increasing evidence globally highlighting the fundamental threats that climate change poses to the environment, various animal and plant species, resources and ecosystem services as well as people's livelihoods. In terms of honey bee forage, looking into the phenology of plants important to bees is critical to providing clues around any major changes in flowering seasons/times, and nectar and pollen provision by the different plants in terms of quality and quantity. Further correlations in this regard can account for needs of bees at different stages of their lifecycles or hive productivity. In South Africa, some of the current major impacts of climate change include extreme, but not consistent, high temperatures and prolonged drought conditions. For the

Figure 2.

Hives on canola are very susceptible to inappropriate chemical regimes

Left photo shows typical position of a canola field in the landscape. Right photo shows placement of managed *Apis mellifera* hives

Western Cape Province in particular, drought conditions have persisted for at least three years (2015 to mid-2018). This has resulted in very dry vegetation that is prone to not only an increased fire frequency, but the intensity of these fires (Midgley, 2017). In essence, increased fire frequencies are not ideal for various ecosystem functions and the services they support. It was reported that over 120 000 hectares of vegetation was lost in the fires seasons between 2016 and 2018, adding more pressure to the already depleting forage resources. As a direct consequence, beekeepers have had to spend more money on supplementary feeding to ensure hive health and productivity. It remains difficult to predict where the exact impact(s) associated with climate change will be, and the level thereof – not only for honey bees, but for other insect pollinators.

HOW TO IMPLEMENT IT

Understanding the need for honey bee forage resources, documenting the contribution of various plant species as honey bee forage, and identifying the threats to these forage resources are the prerequisites for formulating and testing management practices. South Africa is now at the stage where various management recommendations have been framed, a few developed for implementation, while others still need to be verified. As such, the practices described below detail some of the current experiences, while others still require further investigation and piloting.

1. Raising awareness and building understanding

For any change in practice to occur, the first priority should be to create awareness about the issues and explain why current practices need to change. To secure forage resources for South Africa's indigenous managed honey bees, this entails building understanding about: the loss of forage as a threat to managed honey bees; and the link between managed honey bees and food production (thereby creating a link between the intangible issue of honey bee forage with the tangible issue of food production). Target audiences for these messages are private landowners (including farmers), public land managers, state departments, policy-makers, the general public, agricultural and conservation extension officers, input suppliers and educational programmes and institutions. Mechanisms through which each of these audiences could be influenced include popular articles, policy briefings, educational materials, etc. The messages these convey should be specific to each audience. Building understanding is a long-term practice that should be ongoing and regularly monitored to ensure effectiveness.

2. Practices that protect existing forage resources

When linking the findings of the 2011-2014 honey bee forage use study into conservation and agriculture recommendations, it will be important to consider the conservation of indigenous forage species, agricultural practices that affect honey bee forage resources, as well as trade-offs between the benefits of the removal (control) of certain alien species and their value to beekeepers. At the center of all these is the desire to ensure a viable and sustainable honey bee population – both wild and managed. The South African project has achieved the following, while some new prospects and initiatives by various institutions have also drawn from the project outcomes:

- **Influence policy-makers to incorporate forage protection issues into spatial and economic instruments and land-use planning policies.** South Africa has a strong conservation ethic with several important conservation policies that are applicable to the preservation of indigenous honey bee forage resources (e.g. tax incentives linked to biodiversity stewardship agreements). While the actual issue of honey bee forage might not need to be mentioned explicitly in all policies, there may be scope to bring the issue to the fore in some policies. Recent examples for this aspect include the incorporation of some of the findings into the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) report on the assessment of pollinators, pollination and food production. At provincial level within South Africa, the Western Cape Government (through the Department of Agriculture and the Department of Environment and Planning) funded the development of a strategy for the sustainability of beekeeping in the province, while other studies and reports explored the conservation of honey bees as well as the economic aspects in relation to the biodiversity economy.

- **Inform landowners, as well as the agricultural extension officers and conservation professionals who advise them, of issues important to beekeepers.** Relevant materials have been developed to promote this aspect, although further engagement is necessary. These cover topics on helping beekeepers to obtain access to forage areas, planting indigenous honey bee forage protecting existing honey bee forage (perhaps through stewardship programmes, or the demarcation of eucalypt stands), and creating awareness regarding hive vandalism and theft.
- **Encourage researchers, policy-makers and conservation agencies to invest in long-term research that investigates ecosystem services/benefits from certain alien plant species.** Such research could inform decision-making and management of alien species that have a value, and may result in amendments to some policies relating to useful alien, invasive species.
- **Encourage management of eucalypt plantations or stands in ecologically non-sensitive areas for honey bee forage purposes.** The 2011-2014 study described above showed formal, feral and demarcated eucalypt plantations or stands to be the most important honey bee forage resources in South Africa; and similarly, in countries such as India, Israel and recently, Ethiopia (Thomas *et al.*, 2002; Keasar and Shmida, 2009). Many of the feral or small-scale stands of eucalyptus in South Africa have been targeted for clearing, due to alien invasive species regulations. Removals are conducted by invasive species clearing programmes or by private contractors who offer the landowner the benefit of removing the invasive species and then selling the harvested wood. *Eucalyptus* spp. in formal plantations can either have restricted access for beekeeping purposes, or can be compromised due to a change in late-to-non-flowering cultivars, causing significant loss of honey bee forage. Extensive research and discussion is needed on the cultivar issue and accessibility into formal plantation areas, and the South African forestry industry should be approached in this regard. The benefits and costs of feral and demarcated eucalypt stands also require an in-depth analysis. The management of eucalypt stands for the purposes of honey bee forage may always be a secondary aim for landowners (timber, windbreaks or shade perhaps being the primary aim). However, the benefits of this secondary aim may outweigh the benefits the landowner may obtain from the removal of the stands. Such cost/benefit analyses may need to be undertaken on a case-by-case basis.

- **Encourage the correct management of crop chemicals in relation to honey bee forage:** In South Africa, pesticides are regulated under the Fertilizers, Farm Feeds, Seeds and Remedies Act 36 of 1947. In addition, CropLife South Africa represents the plant science industry, including the majority of manufacturers and suppliers of crop protection products, and its members are registered holders of various categories of pesticides (Crop Life South Africa, 2013). The association and its members are said to be fully committed to an environment that is safe for bees and other pollinators. Although CropLife South Africa stepped in during poisoning incidents across the country, there is still a need for a practical research approach, as well as thorough communication and agreements between farmers and beekeepers regarding safe and compatible spraying regimes to ensure the safety of the colonies during spraying times. Education and awareness concerning chemical application and safety is needed amongst farmers, farm workers and extension officers as off-label use is at times, the biggest problem. Policy-makers are also revising some of the registration and labeling requirements to address incompatible spraying regimes and ensure enforcement. On 22 May 2014, an Agro-Chemical and Honey Bee Technical Committee was established to deal with specific issues relating to the use of pesticides on honey bees and was to ensure specific and ongoing honey bee pesticide impacts are addressed.

Practices that promote planting of honey bee forage

In promoting the health of honey bees, awareness campaigns involving the general public have begun internationally and similar campaigns are beginning to take shape in South Africa. An issue that the general public can easily become involved in is the need to plant and maintain good honey bee forage resources. The awareness around planting good honey bee forage needs to distinguish between the public land and the private land platforms:

- **Public land:** government nurseries, public land managers and urban greening programmers are suitable to promote the responsible planting of indigenous and possibly non-invasive exotic honey bee forage in public spaces. Such spaces may include urban streets, spaces beneath power lines, public parks and road verges, and the practice could be applied to areas requiring rehabilitation. All managers of public spaces, including protected areas, should be aware that they are stewards of land that is important for honey bee forage resources.
- **Private land:** farm owners (and the extension officers who advise them), gardeners (and nursery associations) and the public are strongly encouraged to plant indigenous or non-invasive exotic honey bee forage plants. There is potential for certain farmers to obtain approval for the planting of eucalypts in approved demarcated areas.

Figure 3.

***Aloe greatheadii* subsp. *davyana* is an important indigenous honey bee forage plant in some northern regions of South Africa**

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Noting trends internationally, these activities may lead to a rise in urban beekeeping in South Africa – a feature already common in most cities/metros across the country. Safety aspects should remain a priority and general awareness around South Africa's honey bees and their needs is vital should urban beekeeping become a popular practice.

SUCCESSFUL EXAMPLES OF APPLICATION

South Africa has been lucky in protecting its wild and managed honey bee population, with threats such as diseases and pests having had little impact to date (Strauss *et al.*, 2013). However, occasional American Foulbrood (AFB) outbreaks in the Western Cape Province are worrying, having led to the deaths of many colonies. Similarly, the Capensis problem[1] in the northern summer rainfall regions remains a challenge for beekeepers (Pirk *et al.*, 2014). A collapse - although unlikely in significant colony numbers - could impact severely on beekeeping practices (i.e. honey production) and pollination services. The issue of securing forage resources for managed honey bees is, however, a man-made challenge and, as such, few examples of application exist. Most of the practices mentioned above are currently being explored, with a few small-scale success stories, and a general willingness to engage on the issue has emerged. The South African project has concluded, and provided some insight into future plans. These include:

- Honey bee forage "'farms/sanctuaries/havens' are emerging – land farmed for the specific purpose of keeping honey bees (with secondary income from the timber species, crops species, or wildflowers that are planted). A beekeeper attempting such a farm has been profiled and several other beekeepers have mentioned forage farms as potential job creation projects. The economics of such farms are yet to be truly tested.
- Discussion regarding the impact of alien invasive species-clearing programmes on the availability of eucalypt species is already occurring. South Africa's leading alien invasive species management programme (the Working for Water Programme) recognised the need to engage on the eucalyptus issue and provided funding for South Africa's Honey bee Forage Project. While much momentum is in place for the removal of invasive species, there is potential to adapt the approach regarding eucalyptus species in certain areas. The 2014 update of the alien and invasive species regulations under the National Environmental Management: Biodiversity Act 2004 (NEMBA) now includes several provisions for eucalypts because of their value to beekeepers. In addition, a supplementary booklet Gums & Bees: a roadmap for landowners in South Africa was developed to provide guidance to landowners on how to protect and grow forage resources for honey bees. In this booklet, Eucalyptus importance, status and positioning within the landscape were outlined.

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1 Establishes when a Cape worker bee (*Apis mellifera capensis*) parasitizes nests of other honey bee subspecies (*A. mellifera scutellata*) by producing pseudo queens which eventually achieve reproductive dominance and cause the demise of colonies.

- Several nursery associations and urban greening programmes have already expressed interest in favoring important indigenous (and possibly non-invasive exotic) honey bee plants in their initiatives. The bee-friendly plant lists, and a book titled: Beeplants of South Africa: sources of nectar, pollen, honeydew and propolis for honeybees, have since been published, and it is envisaged that these organisations will play a big role in the 'plant honey bee-friendly plants' campaign. The Western Cape Bee Industry Association (WCBA) has also begun facilitating a programme that will see the development of a Bee Forage Working Group. This group will be tasked with the responsibility of forage provision for honey bees in the Western Cape Province of South Africa.
- As the South African project has concluded, awareness about threats to honey bees has grown – possibly due to the large colony losses in parts of the world and the media giving the issue a high profile. This has been fortuitous, as capacity building and awareness drives pollinator importance and their habitat requirements have been well-received. Education institutions, the media, policy-makers and others continue to approach the project management unit for more information.
- Despite the complexities of some of the messaging on South African honey bee forage issues, the project has had a large impact on awareness. We hope that enough momentum will be gained so that the building of capacity, the practices to protect existing honey bee forage and the practices to promote the planting of honey bee forage can all continue into the future and make a substantial difference to securing honey bee forage resources in South Africa.
- Addressing inappropriate chemical regimes through various agricultural, beekeeping and research platforms is starting to yield some positive results in South Africa. In 2015, the Pollination Services Charter was developed in partnership with the crop growers, the crop protection industry and beekeepers. The Charter presents best practices and guidelines towards the preservation and protection of bees during crop pollination. The different provincial beekeeper associations also host frequent workshops and information sessions with the growers to discuss poisoning issues – and how to address the incidents. The Academy of Science of South Africa (ASSAf) has also made great strides in creating a scientific-based dialogue and documentation around pesticides and their impact on pollinators. The primary focus has been on neonicotinoids, with the scope and coverage on the topic inclusive of all African countries. Workshops were held in Pretoria, South Africa (2018) and Nairobi, Kenya (2019) in an attempt to gather more information and assess the level, as well as extent, in both use and impacts of neonicotinoids in African agricultural systems. Through

these respective platforms, enough awareness on the subject matter will hopefully reach the relevant authorities and policy-makers tasked with safeguarding the various environmental legislative instruments.

GENERAL DO's AND DON'Ts

The following are suggestions to other countries/regions looking to secure forage resources for indigenous managed pollinators, although this also applies in general for countries where managed honey bees are exotic:

- Research and understand the forage needs of the pollinator and its managers, including the threats to these forage resources.
- Investigate which parties should be influenced and what practices can be initiated to mitigate these threats in order to plan plan an awareness campaign. Consider the entire chain: from high-level policy-makers to landowners because they all have a role to play.
- Consider the role that the general public can plan in advocacy and small-scale planting programmes – while the physical hectares they may contribute are likely to be small, the value of their advocacy is immeasurable.
- Note that communication and formal agreements between beekeepers and landowners are vital where access to private land for forage and pollination matters are concerned.

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Chapter 13

Conservation of natural and semi-natural habitat providing resources for pollinators

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REASON FOR THE PRACTICE

Pollination is one of the classic, and most-cited ecosystem services, defined as the "benefits people obtain from ecosystems". Many recent studies have documented the impacts on the numbers, composition and behavior of wild pollinators as natural ecosystems decline or degrade (Viana *et al*., 2012). From these studies, it seems quite certain that the spatial organization and quality of natural areas in a landscape influences the survival and dispersal capacity of pollinators. Many pollinator-dependent crops provide pollen and sometimes nectar to their pollinators during the period of bloom. However, most pollinators will need other foraging resources before, after and even during crop bloom, to provide sufficient and diverse food to sustain their populations at the levels needed by the crop. In addition, pollinators need adequate sites for nesting and reproduction. As agriculture becomes more pollinator-dependent over time (a trend that is even more pronounced in the developing world (Aizen *et al*., 2009), there is good reason for farming communities to consider the importance of any adjacent natural and semi-natural areas in sustaining pollinator communities for their crops.

HOW TO IMPLEMENT IT

Considerations across space: The entire landscape

Foraging bees are quite capable of visiting crops far from where they nest, even up to five kilometers distant. Thus, it can be beneficial for farmer communities to consider the availability of habitat far beyond their farm boundaries, into the larger landscape. Larger bees such as carpenter bees, bumble bees and honey bees will readily fly over such long distances, if a crop or habitat patch is particularly inviting to them. Small habitat patches on farm – such as flowering strips – may not only encourage more local pollinators, but also the visits of larger bees that nest in natural or semi-natural areas at some distance from the farm.

Smaller pollinators and ground-nesting bees, on the other hand, do not forage far from their nesting sites. However, their choice of nesting grounds may show strong preference for certain structural elements in the landscape such as sandy banks, roadside verges, livestock holding grounds and even roadways.

Consider corridors/connectivity

Being highly mobile, pollinators are likely to make use of different patches of natural and semi-natural habitat. The more "connected" these patches are, by relatively hospitable habitat such as trails, riparian areas or roadways with flowering plants, the more likely that pollinators will pass through and make use of multiple patches.

Considerations across time: Pollinator needs that change with seasons

Because pollinators are quite mobile and opportunistic, their use of natural and semi-natural habitat may change seasonally. For example, in the Nguruman area of southwestern Kenya, eggplants are being grown in fields cleared from riverine *Acacia* forest, for the export horticultural market. Since eggplant provides only pollen and no nectar, visiting bees must visit nectar-bearing flowering plants for food. For most of the year, the pollinating bees could fulfill their needs for alternative forage from the many flowers of indigenous herbs growing as arable weeds along field edges and paths. But, in the height of the dry season, these herbs dry up. During this time, the eggplant pollinators forage among those riverine *Acacia* forests that have not yet been cleared for crops; here, understory flowers benefit from the coolness and moisture of the umbrella *Acacias* above. Even if critical for only one month out of the year, this resource is nonetheless essential if pollinator populations are to be sustained and active year-round. The value of the *Acacia* forest to crop production – because of the needs of pollinators – has protected several forest stands from being cleared (Gemmill-Herren and Ochieng, 2008).

Consider different types of protected areas

As best measures are identified in terms of conserving pollinator communities in agricultural landscapes, we may need to think of protected areas in a different sense than the conventional large park areas. For bees, and perhaps other insect taxa, the kind and size of protected areas they may need are quite different. This is perhaps best illustrated by the findings from long-term studies of the bee fauna around a town in the Mid-West of the United States of America.

The bee fauna around Carlinville, Illinois (near St. Louis, Missouri) was meticulously recorded by Charles Robertson between 1884 and 1916. Bee specialists revisited this site in 1970 and 1972 (Marlin and LaBerge, 2001), giving an indication of the trends in pollinator populations over more than a century in an agricultural landscape where row crop cultivation has vastly intensified, including greater use of pesticides and other agricultural chemicals. Despite this intensification, the bee diversity remained remarkably persistent over time; generalist bees fared better than specialist bees, but a few bee species went extinct.

Marlin and LaBerge (2001) suggest that the bees survived because small, protected areas occurred throughout the landscape: riparian areas dissecting the farmland, hedgerows and fencerows on the edges of fields, and slight hilly areas that could neither be cultivated nor developed. All such areas may provide habitat for bees because they are unploughed, not unduly exposed to pesticides, and harbour plants that provide pollen and nectar sources. Thus, as depicted in Figure 1, the standard categories of land under protected area management might be re-tooled to create a pollinator-friendly landscape.

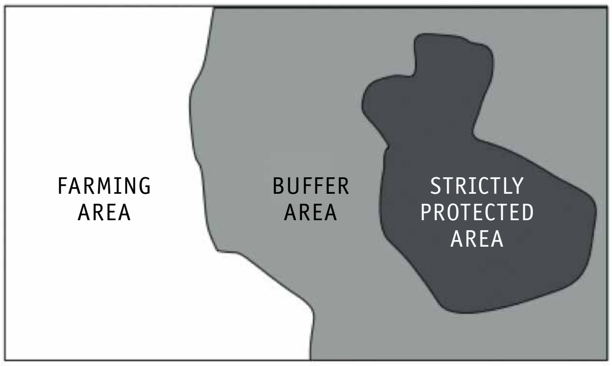
Recognise the importance of a variety of habitats, including small woody areas and early successional fields

Many social and solitary bees live in trees or woods, or nest in plant stems (Roubik 1989; Pitts-Singer and Cane, 2011). Particularly in tropical zones, habitats with trees and woody cover are thus vitally important to sustaining pollinator populations. Farmland, when devoted to annual and row crops, is often quite devoid of tree cover and thus, small patches of forest – occurring often where forests previously were the predominant vegetation – are of great importance to conserve pollinators in agricultural land.

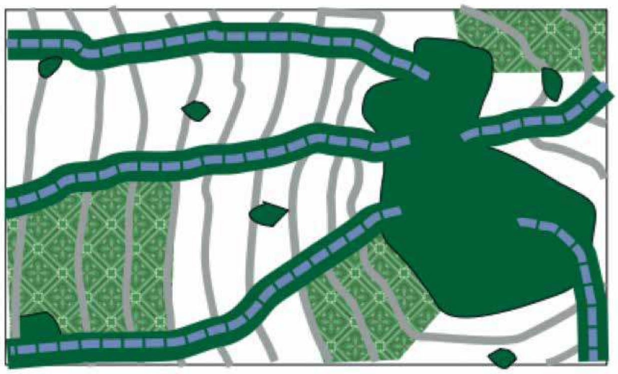
Figure 1.

Land under protected area management re-tooled to create a pollinator-friendly landscape

STANDARD CATEGORIES OF LAND UNDER DIFFERENT FORMS OF SUSTAINABLE NATURAL RESOURCE MANAGEMENT



POSSIBLE LAND USES IN A POLLINATOR-FRIENDLY LANDSCAPE



- Protected areas, including parks, sacred forests, and small pollinator habitats
- Fruit orchards or shade-tree cocoa of coffee plantations
- Arable crops, with flowering intercrops where appropriate
- Countour strips and hedgerows with erosion, pollination and pest control value
- Riparian strips with indigenous vegetation lining waterways

Many pollinators thrive in early successional habitats, such as meadows or abandoned fields with a diversity of flowering plants. Such habitats often benefit from being periodically mown, to keep a sunny, lower-successional proliferation of flowering herbs and grasses. In some ecoregions, fire may also be a natural process that helps maintain open habitat favorable for pollinators. But while fire may be a useful management tool, managers are well advised to only burn a portion of a habitat each year, thus leaving refugia for pollinators and other wildlife in the remaining areas.

Redundancy is good

As Daniel Janzen famously noted thirty years ago: "What escapes the eye ... is a much more insidious kind of extinction: the extinction of ecological interactions." This certainly has great applicability to managing pollination services. Long ago, pollination was thought to be a sort of "lock and key" operation, with specific pollinators having evolved to pollinate different kinds of blossoms. While some of these "pollination syndromes" are quite evident – such as flowers that smell like rotting meat to attract flies – they do not characterize the majority of plant-pollinator interactions, and certainly not those relevant to crops. In fact, generalization rather than specialization, is more the norm in plant-pollinator interactions. It is clear that healthy pollination services are, indeed, best ensured by an abundance and diversity of pollinators, most of which are not highly specialized.

Nonetheless, this does not mean that there is no need to be concerned about diversity. In fact, diversity is key to effective pollination services. No pollinator lives in isolation, servicing one particular flower plant or crop; they exist as part of an ecological web. While the complexity of pollinator webs are still being unraveled, there a few points that are well understood:

- The interaction between bees – whether native bees or introduced or managed bees – is often highly beneficial to crop pollination, resulting in a higher level of service from the visitation of one group alone. Thus, when managed bees are placed in crop fields, the visitation of wild bees from nearby habitats may contribute substantially to the effectiveness of managed bees.
- The complex ecological webs that sustain a diversity of pollinators are not easily restored. It is, however, normal for the community of pollinators to have many species that visit the same flowers, and for each species to readily visit a diversity of flowers.

When degraded land is being restored, pollinators may be highly important to the long-term functioning of restored habitats. Natural ecosystems may show more "robustness" in their pollination functions, with seemingly many more redundant species than newly restored habitats (Williams, 2011). However, it is this redundancy that provides stability; in different years, under different climatic regimes, the species mix changes in abundance but the level of service remains more or less the same. A degree of redundancy may be taken as a desirable element, in habitat restoration.

SUCCESSFUL EXAMPLES OF APPLICATION

Kenya: Restoration of pollinator-friendly plants in national park near Kilimambogo

In the Kyeleni Location of Kenya, the Kimanza Youth Group (a self-help group formed in 2008) works together on a 5-acre (approximately 2.2 ha) farm owned by five households located on the degraded northwest slopes of Kilimambogo in Kyeleni Location, Kyanzave Division (Figure 2). Working together, the youth group grows French beans, tomatoes and sweet peppers for sale in the local markets.

A joint effort between Kenya Wildlife Service and Sustainable Agriculture Conservation and Development Programme (SACDEP-Kenya) and the United Nations Environment Programme, the Global Environment Facility, and the Food and Agriculture Organization of the United Nations, (GEF/UNEP/FAO) has created the Global Pollination Project in Kenya. Through this, the youth group has come to appreciate the importance of pollination for optimal production of the crops they grow.

Among other measures, they have undertaken to help restore the degraded tree cover in the adjacent national park. They have developed a tree nursery, growing Croton and Acacia seedlings. The flowers of the indigenous Acacia are known to provide a rich source of nectar while the pods provide good forage for livestock. The restoration of the Kilimambogo vegetation is also important in providing nesting and foraging habitats for the wild, solitary carpenter bees, a group that is important for the pollination of the bean crop, pigeon peas and other wild legumes. Together with the Kenya Wildlife Service, this youth group is planting and protecting trees, and restoring habitat in the adjacent national park, of benefit to their crops and to the environment.

Nepal: Restoration of community forests with Chiuri (Nepali Butter Tree) in Jutpani Location, Chitwan

In Nepal, the GEF/UNEP/FAO Global Pollination Project has worked with farmers in a number of locations in Chitwan District. One of these is the Jutpani location, which is a resettlement location area where farming has been underway for 35 years. In the beginning, this location was famous for production of potatoes and mustard, as well as traditional staples (i.e. maize and rice). But few farmers grow mustard now, because of declining yields. The farmers' general feeling has been that they are producing less and less, with more and more inputs and costs (Figure 3). Through the pollination project, as farmers have understood the importance of pollination services, they have

Figure 2.

The Kimanza Youth Group working in Kyeleni Location, Kenya

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Figure 3.

A farmer in Chitwan District, Nepal

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developed nurseries of an important bee forage tree, the Chiuri (Nepali Butter Tree, Diploknema butyracea). Their nursery is adjacent to a community forest and the farmers group is replanting the tree seedlings into the degraded community-managed forest.

GENERAL DO's AND DON'Ts

- Small areas of natural or semi-natural habitat may benefit pollinators; consider what can be done to enhance pollinator habitat along field edges and fence rows.
- If important crop pollinators are large bees, such as carpenter bees, they may benefit from natural or semi-natural habitat at some distance; but smaller bees need habitat nearby crops.
- Crops provide resources for pollinators only for short periods; thus, any enhancement of habitat that provides floral resources and nesting sites for a longer period than crop bloom will be advantageous.

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Chapter 14

Common approach for socio-economic valuation of pollinator-friendly practices

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REASON FOR THE PRACTICE

Rationale

With increasing recognition of the centrality of ecosystem services in agricultural production, the need for placing a value on these services has also increased in order to provide a value- or "evidence"-based argument for their maintenance and enhancement. There are different ways to define and measure value, of which monetary is only one. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) notes that: "in keeping with the general anthropocentric notion of 'nature's benefits to people', one might consider a benefit to be an ecosystem's contribution to some aspect of a good quality of life, where a benefit is a perceived thing or experience of value," (IPBES, 2013).

In the definition provided by the IPBES Conceptual Framework, the "value" is multi-dimensional and cannot be properly estimated with only one variable. This is one of the bases of the multi-dimensional aspect of the protocol for socio-economic valuation of pollination-friendly landscapes presented here.

Commonly, valuation estimates have focused on the benefits of pollination to crop production and do not include all the benefits that pollinators provide to the economy. A region´s wealth includes the financial, physical, natural, human and social capital that enhances development and sustainable rural livelihoods. Therefore, comparing the influence of practices (or landscapes) that are pollinator-friendly versus practices that are unfriendly, using all of these measures of capital would be a more robust approach to putting a value on pollinator changes, and allows quantification of the synergies and trade-offs associated to pollinator enhancement.

This chapter presents a protocol for determining the socio-economic value of pollinator-friendly versus -unfriendly practices that can be implemented at different spatial levels (for example, farms or landscapes). The scope is comprehensive and includes both small- and large-scale farming systems; indeed, the comparison between these systems can be of great interest. The results of the application of this protocol may interest both producers and decision-makers wishing to answer, for example, questions such as: are differences in the socioeconomic assets of the producers associated with friendly or unfriendly practices? Can a group of socioeconomic variables predict the number of pollinator-friendly practices applied by producers? Which assets should be promoted to enhance the number of pollinator-friendly practices? Are there trade-offs or synergies among different assets (for example, biodiversity and crop production)?

Context

The valuation of ecosystem services is an increasingly important issue at international, national and regional levels. Some examples of global initiatives that address this issue at an international level are The Economics of Ecosystems and Biodiversity (TEEB) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). At the national level, countries are interested in valuing ecosystem services to provide financially based evidence for the conservation and management of services that are important not only for humans, but also for the wider environment. Initiatives such as Payments for Environmental Services (PES) are in place to address this matter. At the regional level, in 2012 a regional workshop was held on "Mainstreaming Ecosystem Services Approaches into Development: Application of Economic Valuation for Designing Innovative Response Policies" for senior level decision-makers from regions of South and Southeast Asia. This workshop was organized by the United Nations Environment Programme (UNEP), in close cooperation with the ASEAN Centre for Biodiversity (ACB).

Insect pollination has been shown to improve fruit and vegetable yields, as well as oil, seed and nut crops (Klein *et al.*, 2007). Gallai *et al.* (2009) estimated that, for 2005, the global economic value of pollination was USD 215 billion or 9.5 percent of global food production value. Clearly, a convincing argument for the monetary value of pollination services exists; however, it needs to be further supported.

Addressing the economic valuation of pollination services – essential for crop production – has been undertaken through different perspectives and at different levels (local to global). For example, the Handbook for Participatory Socio-Economic Valuation of Pollinator-Friendly Practices (FAO, 2012)[1] looks at valuation at the local level; it is a guide to help farmers evaluate the benefits and costs of applying pollinator-friendly practices. It looks not only at the economic, but also at the social value of these practices. FAO's Tool for Valuation of Pollination Services at National Level, using producer price and crop production data, is supported by the Guidelines for the Economic Valuation of Pollination Services at National Scale[2] (Gallai and Vaissière, 2009).

HOW TO IMPLEMENT IT

There are five basic steps to implement this protocol:

Summary of the steps for valuation of agricultural landscapes

1. Experimental design: define a contrast;
2. Multiple dimensions of socio-economic value: define at least three variables per asset;
3. Define the method (feasibility) for obtaining information for each variable (questionnaires, Geographic Information System (GIS), databases);
4. Statistical analyses;
5. Inform decision-makers.

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1 http://www.fao.org/3/a-i2442e.pdf
2 http://www.fao.org/3/a-at523e.pdf

Step 1. Experimental design: Define a contrast

Based on satellite images and landscape features, characterization of the experimental plots will help to identify and select contrasting study sites (Table 1). For example, these can be landscapes dominated by crop monocultures (pollinator-unfriendly) versus those planted with several crop species (friendly); or low (unfriendly) versus high (friendly) habitat diversity (Garibaldi *et al.*, 2011; Kennedy *et al.*, 2013). An aspect to bear in mind is that areas providing resources for wild bees usually also provide them for managed pollinators (e.g. honeybees). In general, the following aspects define a pollinator-friendly site (i.e. higher species richness of flower visitors):

- high complexity (diversity, heterogeneity) of habitats (different types of habitats)
- high habitat quality (not only natural)
- low or no use of pesticides
- high within-field plant biodiversity (e.g. ruderal plants)

Table 1.

Example of site general characterization in order to select contrasting study sites

Main primary activity	i.e., Main crop grown.
General characteristics of the landscape	e.g. What are the other crops grown? What is the typology of the natural habitat surrounding the landscape? Is there livestock present? If so, what kind? What are the primary pollinators (e.g. Africanized honeybees, stingless bees, midges).
Scale	Describe the landscape and scale (e.g. each landscape is a drainage basin of approximately 5 x 5 km^2).
Scope	Describe the scope, e.g. rural landscapes with more than 10 percent of "x" crop and less than 10 percent of urban area.
Friendly versus unfriendly	Complexity of habitats, agricultural practices.

In statistical terms, there are at least two treatments (friendly versus unfriendly) with several replicates each. The number of replicates depends on the desired precision, selected confidence, and the variability among landscapes (Anderson *et al.*, 2008). Replicate numbers can be determined through standard statistical procedures (Anderson *et al.*, 2008); based on our experience, we recommend at least 10 replicates per treatment (i.e. at least 20 landscapes as a minimum for the assessment).

> This section provides a framework to value different practices; therefore, the user needs to choose the most useful (relevant) contrast for their specific objectives (e.g. landscapes providing resources for honeybees versus those that do not provide resources).

The design implies an observational experiment in contrast to manipulative experiments (Hulbert, 1984). In manipulative experiments, the treatments (pollinator-friendly versus -unfriendly designs) are randomly assigned to the experimental units (e.g. farms or landscapes). These experiments have the ability to establish causal relations (i.e. the effects of treatments on response variables); however, they are usually not feasible (nor ethical) in many circumstances, such as in our case. Manipulative studies, therefore, are rarely employed in socio-economic valuations. On the other hand, observational experiments can be set up in real-world rural landscapes, through the evaluation of statistical associations between treatment and response variables (not necessarily causal). Our design allows evaluation if the socio-economic value of pollinator-friendly practices is different from that of the pollinator-unfriendly practices. The design does not, however, tell us if higher socio-economic value is a result of the agroecological design (e.g. pollinator-friendly practice); or the reverse (e.g. a higher socio-economic value determines a higher capacity to implement a pollinator-friendly design); or a win-win scenario (e.g. positive feedback between agroecological design and socio-economic value). The information provided by this protocol is of great importance for policy implementation. For example, it will allow us to detect if landscapes with more natural capital share less financial capital and, therefore, correct the financial deficit by payment for ecosystem services programmes (Zheng *et al.*, 2013).

> The general idea is to choose farms (or landscapes) that differ greatly in the degree to which they support pollinator richness, based on *a priori* knowledge and GIS information (Step 1). This information can be updated with field data and questionnaires (Steps 2 and 3) to create a quantitative index of the number of pollinator-friendly practices applied in each farm (or landscape). This index is usually more informative in analysis (Step 4) and in guiding decision-making (Step 5).

Step 2. Multiple dimensions of socio-economic value: Define at least three variables per asset

The sustainable livelihoods (SL) framework (also known as the "rural livelihoods" framework) has been implemented for many years in rural areas (DFID, 1999; Nelson *et al.*, 2010), including FAO assessments (Baumann, 2002; Cleary *et al.*, 2003; Seshia and Scoones, 2003; Tayyib *et al.*, 2007). The SL framework accounts for the multi-dimensional socio-economic value of agricultural practices by considering five livelihoods assets:

- **Human capital**: individuals' skills, health (including mental health), nutrition and education that contribute to the productivity of labour and capacity to manage land (Nelson *et al.*, 2010).

- **Natural capital:** land productivity counting climate, water and biological resources that contribute to current and future agricultural productivity, including wildlife, wild foods and fibers, biodiversity and environmental services.
- **Financial capital:** stocks of financial resources to which households have access, including cash, incomes, access to other financial resources (credit and savings) and overall wealth that influences the ability to generate income.
- **Physical capital:** infrastructure, transport, roads, vehicles, secure shelter and buildings, water supply and sanitation, energy, communications, tools and technology, equipment for production, seeds, fertilizers, pesticides, traditional technology.
- **Social capital:** reciprocal claims on others by virtue of social relationships, social bonds that facilitate cooperative action, and social bridging and linking together; and which ideas and resources are accessible (networks and connections, relations of trust and mutual support, formal and informal groups, common rules and sanctions, collective representation, mechanisms for participation in decision-making, leadership).

The SL provides a general framework that must be modified, adapted and made appropriate to local circumstances and priorities (objectives).

Step 3. Define the method (feasibility) to obtain information for each variable (questionnaires, GIS, databases)

Once the contrast has been defined, the relevant variables must be selected, data sources must be identified and instruments for the collection of data must be prepared and administered. Gathered data will conform the database to be analysed (see Step 4: Statistical analyses).

a) Variables selection: Adapt the framework to the specific conditions of your system

Choose at least three variables per asset. In particular, we are looking for variables with a direct relation to pollinator-friendly practices (whether they are a result of the agroecological design or determinants of practices adoption; see Step 1: Experimental design). Different variables may be selected for different regions and socio-economic conditions. Researcher judgment and previous knowledge of the study context are important for selecting which variables are considered the most important within each asset, and to determine how to measure them. Below is a non-exhaustive list of variables and examples of elements for each asset described in the SL framework that you can include in the questions. New variables should be added to the list and the unit of analysis should be adapted to best fit your assessment.

Table 2.

List of non-exhaustive variables of human capital, which can be included in the questions

CAPITAL	SAMPLE QUESTIONS
Educational level	What is the highest level of education reached? Responses will be measured using ordinal variable with the following values: (1) primary school completed or attended; (2) 1-4 years high school completed; (3) 5-6 years high school completed; (4) trade apprenticeship or technical qualification completed; and (5) university or other tertiary completed (Tayyib *et al.*, 2007; Nelson *et al.*, 2010; Antwi-Agyei *et al.*, 2012). To measure this variable at the landscape level, calculate the percentage of each value or select the percentage of the value considered most relevant (for example, the percentage of the producers that have attained levels 4 or 5).
Health status	Has any member of this household been ill (i.e. in need of hospital treatment) in the last six months? Do you have local medical assistance (i.e. within the landscape)? (Antwi-Agyei *et al.*, 2012). (*Prediction: pollinator-friendly landscapes may increase health because of lower agrochemical use. This may be measured directly by other methods, e.g, irritation, report of illness because of pesticide use.*) To measure this variable at the landscape level, calculate the percentage of households with ill members and the aggregate access to health care.
Nutritional outcome	Yearly energetic value of primary and secondary production.
Dietary diversity	Vitamins, antioxidants, minerals, essential amino acids and nutrients of primary and secondary production (e.g. using USDA data for nutritional composition of crops) (Eilers *et al.*, 2011).
Number of households	Record the number of households present in the site.
Labour status	Percentages of employed, unemployed and/or inactive inhabitants (Tayyib *et al.*, 2007).
Status in employment (A)	Percentages of self-employed or employed persons.
Status in employment (B)	Percentages of full- or part-time employment (Plagányi *et al.*, 2013).
Livelihood diversification	Main livelihood activities in terms of their contribution to household income.
Pollination knowledge	Percentage of farmers that know: which insects visit the production area; what a pollinator is; the importance of pollinating insects for crops.
Beekeeping experience	Percentage of farmers that have beekeeping experience. Average number of years of beekeeping experience.

Table 3.

List of non-exhaustive variables of natural capital, which can be included in the questions

CAPITAL	SAMPLE QUESTIONS
Number of pollinator-friendly practices	Compose an index that measures the number of pollinator-friendly practices applied in the landscape. The index will have positive values for the pollinator-friendly practices (e.g. holdings having beehives for pollination services in the productive area; having forage in the form of native bush or other crops or conservation areas; increasing pollinator accessibility to crops through, for example, presence of water containers). It will have negative values for practices that are detrimental to pollinators (e.g. use of chemical products; destroying wild pollinator colonies in the productive area; monoculture systems).
Landscape complexity	Several standard indices are available for land-use composition (richness, evenness and diversity of landscapes) and configuration (patch area and edge, patch shape complexity, core area, contrast, aggregation, subdivision, isolation). “Patch-based metrics (i.e. for categorical map patterns or patch mosaics) fall into two general categories: (1) those that quantify the composition of the map without reference to spatial attributes; and (2) those that quantify the spatial configuration of the map, requiring spatial information for their calculation. “Each category contains a variety of metrics for quantifying different aspects of the pattern. It is incumbent upon the investigator or manager to choose the appropriate metrics for the question under consideration” (Mcgarigal, 2013; see also Kennedy *et al.*, 2013). It is important to define the range in which the complexity is measured, because the effect of the variables is scale-dependent.

CAPITAL	SAMPLE QUESTIONS
Wildlife	Proportion of natural (or semi-natural) habitat, and their diversity. Possibly highly correlated with complexity (depends on the index).
Crop biodiversity	Number of crops.
Ecosystem services	Services provided by agricultural landscapes not necessarily related to primary or secondary production (e.g. aquifer recharge, water quality improvement, carbon fixation, reduction of soil erosion). It is suggested that two "key" ecosystem services should be chosen. There should be a relation between the chosen service and pollination provision.

Table 4.

List of non-exhaustive variables of financial capital, which can be included in the questions

CAPITAL	SAMPLE QUESTIONS
Profit per crop per hectare	Income versus costs. Kg ha^{-1} produced per crop, kg ha^{-1} sold per crop (produced - sold = consumed), main costs (fertilizers, etc.), price at which it is sold (Grieg-Gran and Gemmill-Herren, 2012).
Access to credit	Percentage of farmers that have access to credit for their agricultural activities (Antwi-Agyei *et al.*, 2012).
Ownership of livestock	Percentage of farmers that have livestock or poultry. List the types and number of livestock (Antwi-Agyei *et al.*, 2012).
Remittances received	Percentage of farmers that received remittances from family or friends in the last year (Antwi-Agyei *et al.*, 2012); or average (median) value of remittances received.
Abroad work	Percentage of farmers that work abroad from their farms. Percentage of the aggregate income generated in the landscape represented by the work abroad the farms.
Income from tourism	Current or potential income on farms that include these activities (e.g. farm hotel, agro-ecotourism). Indicators can include data from farms or municipalities, e.g. tourist flow; number of hotels; number of restaurants; number of tourist agencies; number of rental car companies; number of events (congresses, meetings, symposiums) per year; currency revenues from tourism; presence of thematic and/or ecological parks and natural reserves.

Table 5.

List of non-exhaustive variables of physical capital, which can be included in the questions

CAPITAL	SAMPLE QUESTIONS
Ownership of honeybee hives	Percentage of holdings that own beehives or numbers of hives relative to the number of farms.
Irrigation facilities	Percentage of farms that have access to irrigation facilities.
Agricultural machinery	Percentage of farms that use machinery in the productive cycle. Average expenditure on machinery.
Fertilizers	Average expenditure in the use of fertilizers.
Pesticides	Average expenditure in the use of pesticides (Tayyib *et al.*, 2007). Percentage of farmers that apply pesticides.
Economically active population	Percentage of people of working age in the landscape, disaggregated by gender.
Workers	Average or median number of working days per year and percentage of holdings with family/hired workers (Grieg-Gran and Gemmill-Herren, 2012).
Infrastructure	Availability of roads, ports.

Table 6.

List of non-exhaustive variables of social capital, which can be included in the questions

CAPITAL	SAMPLE QUESTIONS
Number of groups or associations present in the landscape (relative to the number of farms)	Membership of a group provides an indication of a linking form of social capital, the horizontal connections between socially similar groups through which ideas, resources and opportunities flow (Nelson *et al.*, 2010; Antwi-Agyei *et al.*, 2012).
Tenure system	Percentage of farmers by type of arrangements for access to farming activities (e.g. owner, partner, occupant, employee).
Partners	Average number of non-family partners running farm business. This variable provides an indicator of the linking form of social capital, the kind of local social capital that provides support in difficult times and enables individuals to take advantage of opportunities (Nelson *et al.*, 2010).
Services from outside	Percentage of farmers that hire services from outside the landscape (e.g. for harvesting). Cost of hiring services from outside the landscape.
Availability of extension service	Number of days per year that a professional from an extension service is available in the landscape for technical assistance or other activities.
Access to Internet	Internet access availability. Internet access is an indicator of the linking form of social capital – vertical connections that provide access to ideas and resources between economically and socially differentiated groups (Nelson *et al.*, 2010).
Production and commercialization organization	Percentage of farmers that produce/commercialize in a collective way.

b) Data sources

Data can be obtained from regular questionnaires performed by governmental agencies, GIS databases and questionnaires specially prepared for this purpose. Bear in mind that when preparing your questionnaire, questions will need to be formulated in an inquisitive but polite fashion. Responses that have ranges instead of details of exact values are recommended to reduce non-response. Additionally, a pilot sampling is very important to refine the questions, trying to implement it in heterogeneous sites (i.e. pollinator-friendly and pollinator-unfriendly sites). Asking more (but not too many) questions than those you are going to analyse is a good practice, in order to later select the best variables. Administering the questionnaire should not take more than 30 minutes per farmer. Remember human ethics.

c) Data collection

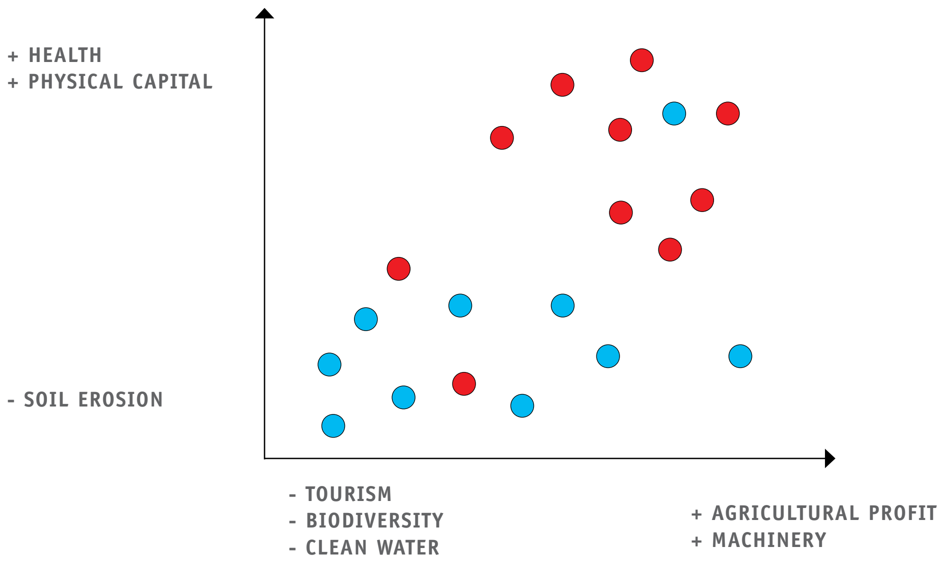
The sample of survey respondents should be selected randomly from GIS data (this data needs to be gathered and assembled) and should allow aggregate statistics (mean, variance, skewness, equity, etc.). Questionnaires should be applied to the decision-maker or person with knowledge of how the farm operates. Ideally, half of the responses should come from women to allow for gender comparisons or, when this is not possible, through community organization (i.e. women not related directly to farm activities). Here the researchers may find different groups within the community to compare (i.e. beekeepers and farmers). Face to face interviews are recommended in order to reduce non-response. Researcher trustfulness and empathy are also important in collecting answers that are more reliable; in many places, some local governmental professionals advise the farmers and already know them. They should be involved and can be of help in contacting the farmers. The information gathered can be useful for future programmes – for example, to pay the farmers for ecosystem service delivery, so they can be incentivized to respond the questionnaires (Zheng *et al.*, 2013).

The entire survey process should take as much as one month in total, considering the selection of conceptually relevant variables and the 20 sites and data analyses in GIS.

Step 4. Statistical analyses

Information gathered from the different variables (in Step 3) should be integrated through standard multivariate statistics (e.g. principal component analyses, correspondence analyses). Multivariate statistics are powerful and provide useful information for socio-economic analysis, instead of a general index. In this way, the co-variation among different conceptually relevant variables can be understood (Figure 1). It is important to note that, for example, if one asset has very low values it can limit sustainable livelihoods even when the other assets have very high values. Therefore, the balance among all assets is important.

Figure 1.
Example of a possible result from a principal component analysis



Step 5. Inform decision-makers

Knowing the socioeconomic value of agricultural practices can make an important contribution to decision-making processes and the design of subsequent interventions. For example, this value can indicate which type of asset (human, social, physical, financial or natural) should be strengthened in order to enhance pollinator-friendly practices in a region.

It could also provide a solid argument for conservation in cases where no negative relation between natural capital and economic revenue of the producers is found. That suggests that it is possible to conserve and promote nature and pollinators without losing economic benefits (i.e. absence of trade-offs between natural and financial capital). Moreover, pollination could even support the productivity of some crops (i.e. synergies between natural and financial capital may exist). Thus, the assessment results can provide solid arguments for conservation in both cases: that is, in the absence of trade-offs and the presence of synergies between natural and financial capital.

SUCCESSFUL EXAMPLES OF APPLICATION

Example 1: Coffee

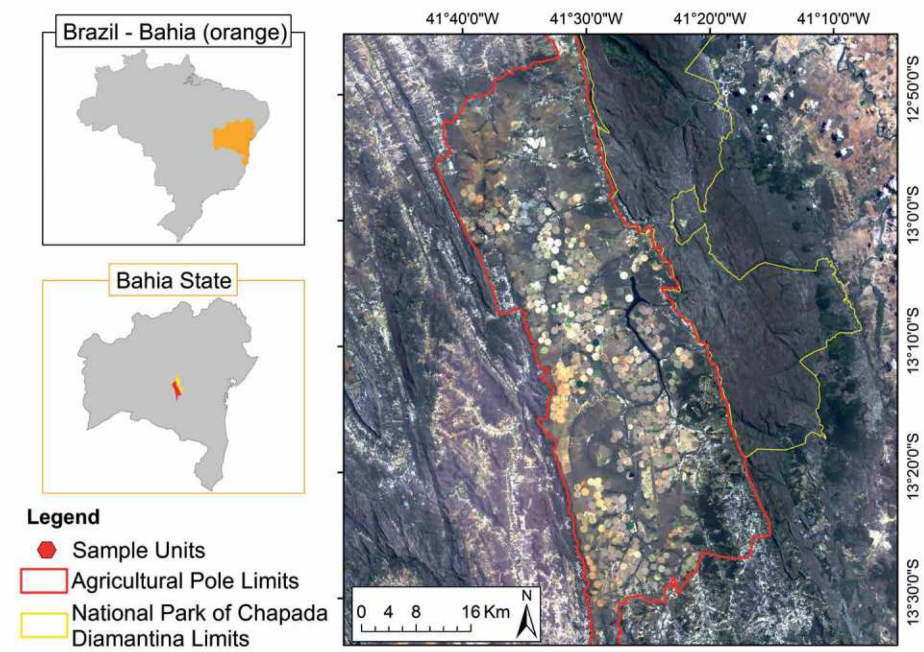
The protocol for assessing the socio-economic value of pollination at the landscape scale was applied on coffee farms in Bahia, Brazil. Assessing this value can enable the identification of opportunities, risks and threats in order to propose actions that lead to more sustainable and "pollinator-friendly farms", i.e. farms that use practices that intend to increase the abundance and diversity of natural pollinators through the enhancement of diverse floral resources, farm land heterogeneity, reduced- or non-use of synthetic insecticides, among others (Garibaldi *et al.*, 2014; Hipólito *et al.*, 2016).

Step 1: Experimental design

Study sites included areas of intense agriculture and production of coffee, potatoes, tomatoes and strawberry, among others, but also bordered one of the National Parks of Chapada Diamantina in Brazil (Figure 2). The region is markedly dominated (80 percent) by small (< 20 ha) coffee farms, but there are also medium (20 - 200 ha) and large farms (> 500 ha) corresponding, in total, to over 2 000 farmers (Seagri, 2002) on 11 250 ha of cultivated coffee (IBGE, 2013).

Figure 2.

Map of the agricultural area of Chapada Diamantina in Bahia, Brazil



The yellow and red lines demonstrate the borders of the National Park of Chapada Diamantina (yellow) and the agricultural region (red)

Table 7.

Characterization of friendly and unfriendly coffee landscapes in Chapada Diamantina, Bahia, Brazil

Main primary activity	Coffee
General characteristics of the land-scape	Potato and coffee are the main crops in the region, although others such as tomato and passionflower can be found; semi-natural habitats, many streams, some livestock, wild and Africanized honeybees, etc.
Scale	Each landscape is an area of 2 000 m ratio.
Scope	In each landscape coffee farms varies from 1 to 110 ha, and from 15 percent to 93 percent of natural areas.

Characteristics that define landscape	**Pollinator friendly**	**Pollinator unfriendly**
Beehives	Native or *Apis mellifera*	No
Pesticide use	No use or only when necessary (low use)	High
Weed control	Partial manual weeding	Total weeding
Organic certificated	Yes	No
Hedges	Present	Absent
Crop richness	Presence of non-coffee crops (product diversification)	Only coffee present, i.e. monoculture

Steps 2 and 3:
Selecting variables and defining the method for obtaining information of each variable

A standardized questionnaire was elaborated and tested face-to-face with 12 of the 29 farmers who responded to the final questionnaire. Some questions that were too general or inadequate were excluded. The final questionnaire included approximately five questions per type of capital. For statistical analyses, variables included not only those from the questionnaires, but also variables obtained by GIS, such as the percentage of natural areas around the farms (Table 3). This allowed more reliable data given that, sometimes, producers that own more than one farm don't have all the information for each one, or do not know the percentage of natural areas around the farms (small farmers).

Table 8.

Selected variables for coffee landscapes analysis

VARIABLES	HOW TO MEASURE IT?	WHY MEASURE IT?/ SOME IMPORTANT CONSIDERATIONS
HUMAN CAPITAL		
Education level	What is your highest educational level?	More formally educated farmers could practice more friendly practices.
Management capacity	What are your functions on the land?	Undoubtedly this is a difficult variable to measure, but it should assess and respect that farmers have different managing capacities, some of which may derive not just from their formal education (as noted above) but how they apply it; equally, farmers with no formal education often have high capacity to manage and innovate on their farms.
Family structure	How many people in your family work on activities directly related to the farming activities?	Knowing the family structure and number of people contributing to total income may also reveal the number of women working the land, since not many are formally responsible for the farm.
NATURAL CAPITAL		
Conservation	Percentage of natural area in the 200m area around the farm	This is a variable that has been shown to be highly contributory to pollination services. If the farmer does not have the information, it can be easily gathered by GIS.
Conservation	Do you implement the governmental requisite of forest reserve?	To correlate with GIS information and analyse if forest reserves are close to the coffee farm and can maintain ecologic processes (pollination).
FINANCIAL CAPITAL		
Profit per crop per ha	How many crops per hectare? What is the amount of production per hectare?	Some caveats on determining this: in coffee production this is related to the area, however, we do not always found the same number of plants in a given area, so both are important.

VARIABLES	HOW TO MEASURE IT?	WHY MEASURE IT?/ SOME IMPORTANT CONSIDERATIONS
Other income	Is farming your main occupation? Do you have another employment? Receive any other income? (e.g. government benefits, retirement).	To assess the farmer's dependence on the income generated by agricultural activities.
Area	What is the total farm area planted with coffee?	Important to measure production based on the total planted area.
PHYSICAL CAPITAL		
Irrigation	What type of irrigation do you practice (e.g. flooding, drip, sprinkler)?	Knowing the type of irrigation implemented may be important to consider the possible impacts on the environment or production.
Production system	Do you have any machinery? Which fertilizers and how much of these is utilized? Do you use herbicides?	To consider the machinery and technology used in agricultural activities. In addition, certain tools, techniques and/or technologies can affect pollinator activity in the field.
Improvements	What kind of farm improvements do you have to make to increase coffee sales? (e.g. investment in post-harvest equipment such as machines for drying coffee, or for coffee selection)	To consider the equipment that may raise the value of the product and thus, benefit the sales.
SOCIAL CAPITAL		
Associations	Are you a member of any association?	To evaluate social associations that can generate new ideas and opportunities.
Extension	Do you interact with professionals from extension services? If so, which extension services and how many times (per year)?	Extension services may bring benefits to farmers in the form of technical assistance or other activities that lead to higher productivity.
Sales	How do you sell your products? (alone, with partner)	Partners may lead to higher probability of selling the products.

Step 4: Statistical analyses

Generalized Linear Models (GLM, Poisson error distribution) were used in this study, although the data generated for the analysis should be carefully examined in order to properly choose the statistical analysis as well as the data distribution (normal, poison, binomial, among others). Thus, analysis can vary depending on the data. In a general sense (and a suggestions, as multivariate analysis such as the Non-Metrical Multidimensional Scaling techniques can be quite flexible considering its assumptions), the data generated by the components of multivariate analysis can be used in these studies when it is interesting to extract the information of multiple variables in one. The new composed variable can be followed by a GLM (generalized linear model) to identify which variables best explain the use of friendly practices. We suggest that an expert evaluate what is the best analysis for the generated data.

Results

In this study, pollinator-friendly and -unfriendly landscapes were represented by a gradient ranging from no pollinator-friendly practices (value = 0) to a maximum level of pollinator-friendly practices (value = 5; Figure 3).

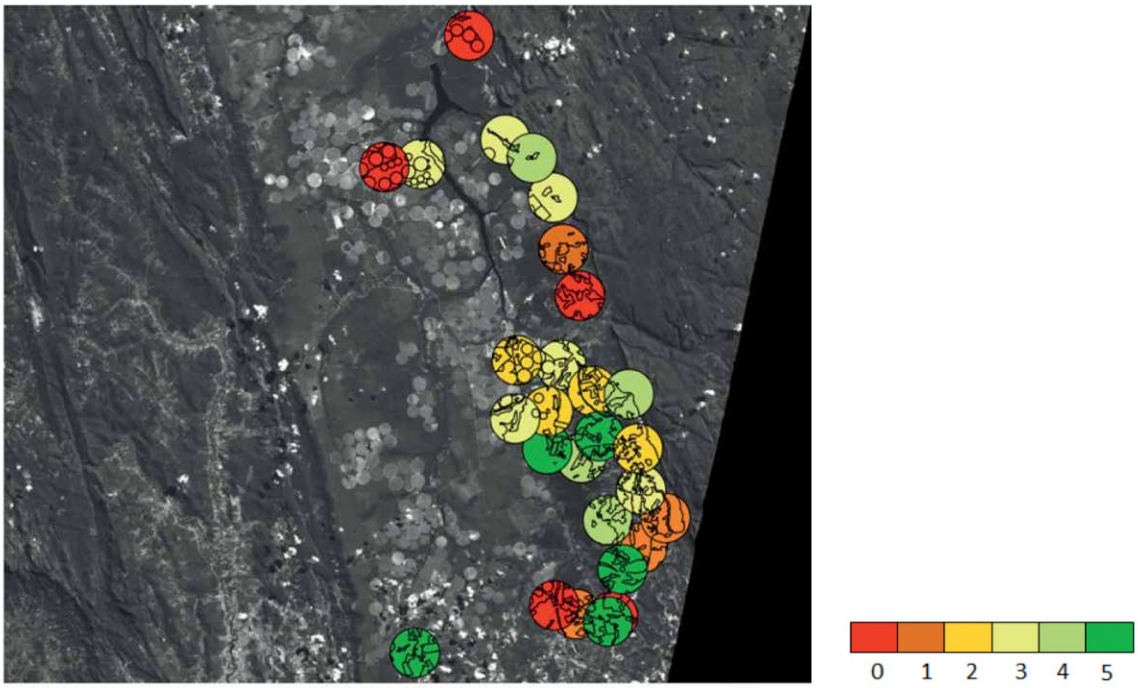
The most important variables to predict the number of pollinator-friendly practices applied by producers were management capacity (human capital), production per hectare (financial), area (financial), conservation (natural), education (human) and commercialization (social).

Pollinator-friendly practices encountered in the different farms were also related to the biodiversity of flower visitors, reinforcing its importance as a variable to consider in order to improve pollination services in coffee farms (Figure 4).

Findings highlight the possibility of generating win-win scenarios between biodiversity, production and producers' profitability.

Figure 3.

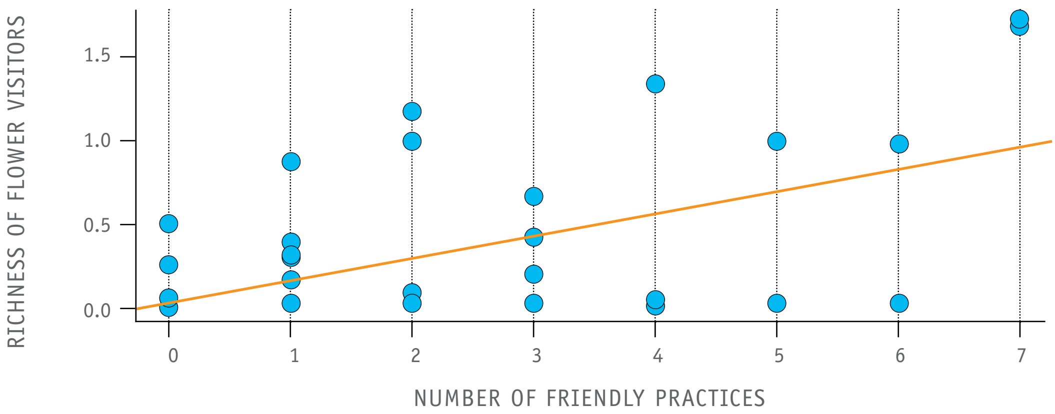
General overview of friendly and unfriendly landscapes of coffee in Chapada Diamantina, Bahia, Brazil



Colors and numbers refer to the number of pollinator-friendly practices from none (zero) to five

Figure 4.

Relationship between the number of friendly practices and visitor's richness in coffee landscapes in Chapada Diamantina, Bahia, Brazil



R=0.3147, p<0.001

Example 2: Cashew

This protocol has also been applied to cashew fields in the States of Ceará, Piauí and Río Grande do Norte in Brazil, between June 2011 and February 2012. The survey targeted 162 producers and the sample was stratified by the area allocated to cashew production (< 5 ha; 5-20 ha; 20-100 ha; >100 ha).

The number of 'pollinator-friendly practices' was a quantitative variable based on producers' responses to the following questions: (a) Do you have managed pollinators in the productive area? (b) Is there any forage available for pollinators (in the form of native bush or other crops)? (c) Do you use chemical products on your farmland? (d) How do you manage beehives and what do you do with the wild colonies in the productive area? and (e) Do you contribute to increasing pollinators' accessibility to crops (for example, through the presence of water containers in the productive area)?

Findings highlight the positive socioeconomic value of pollinator-friendly practices. Results show that the producers' experience in beekeeping is important to enhance the number of pollinator-friendly practices applied, emphasizing the benefits of promoting human capital among producers (Garibaldi and Dondo, 2015).

Example 3: Cotton

The protocol has also been applied to cotton farms in Brazil. The survey targeted 100 producers in three municipalities (Apodi, Janduís and Nova Descoberta).

The number of 'pollinator-friendly practices' was a quantitative discrete variable based on producers' answers to the following questions: (a) Do you have conservation areas on your property? (b) What do you do with wild plants in the productive area? (c) Do you have beehives for pollinator services? (d) Do you use chemicals? (in general; but also in particular for the flowering period); (e) Do you implement any alternative disease control method? and (f) Is your production a monoculture?

Findings highlight the positive socioeconomic value of pollinator-friendly practices (Garibaldi and Dondo, 2015). Results show that landscapes with more pollinator-friendly practices are associated with higher natural, financial, physical and social assets. Additionally, the number of pollinator-friendly practices increased when producers implemented an organic culture system and had beehives for pollination services on their properties (both physical assets). Overall, for this crop, the pollinator-friendly practices were positively related to four of the five assets. These results suggest that the conservation of natural capital is not related to lower financial outputs (i.e. agronomic yields and income can be increased through sustainable pathways that do not destroy the natural capital).

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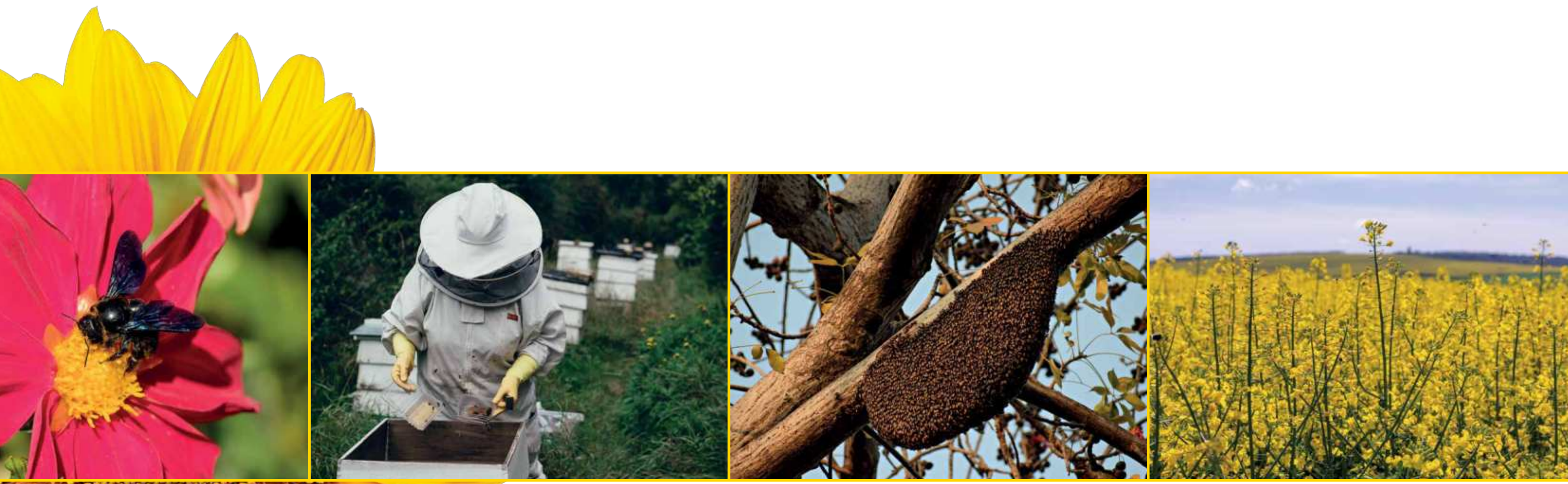
As the discipline of pollination ecology moves from describing the extent of a pollinator crisis to identifying what can be done about it, there is a need to share and highlight very practical measures that will support sustainable crop biotic pollination services. Identifying these practices will require a mix of farmer and natural history knowledge and scientific research. This publication outlines the practices that have so far been identified, and what experiences may contribute to sharing the effectiveness of these measures under different circumstances.



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