Review

Observing bees and wasps: Why surveys and monitoring programs are critical and how they can improve our understanding of these beneficial hymenopterans

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Abstract—Flower-visiting bees and wasps (Hymenoptera: Apoidea, Pompiloidea, Scolioidea, Tiphioidea, and Vespoidea) provide essential services in agricultural and urban systems, and ecological functions in natural ecosystems. Understanding the population trends, resource requirements and preferences, ecological challenges, and how to manage these species better requires increased surveys and standardized monitoring efforts for both groups. A monitoring program performed at various scales that provides ecological data is a prerequisite to managing either bees or wasps for conservation or crop pollination purposes. Methods to survey and monitor bees and wasps can be accomplished by a variety of means, depending on the researchers' aims and goals. Herein, we discuss the importance of 1) evaluating populations of threatened and endangered bee and wasp species, 2) detecting and identifying pollinators of crops, 3) identifying and managing wasp species for use as biological control agents, 4) surveying the ranges of non-native bees and wasps, and 5) utilizing bees and wasps as biological indicators. We also discuss strategies for the selection of surveying and monitoring tools and methodologies best suited to specific goals and situations in beneficial Hymenoptera research. Our hope is that this review will lead to additional bee/wasp survey and monitoring programs and assist researchers with selecting tools and methodologies for the purpose of better understanding these beneficial insects.

Keywords—Bees, Wasps, Hymenoptera, Monitoring Programs, Pollinators, Biological Control

Bees and Wasps

The insect order Hymenoptera, which includes sawflies, ants, wasps, and bees, consists of nearly 150,000 species that fill numerous ecological niches (Huber 2009). The Hymenoptera comprise a wide breadth of feeding habits ranging from phytophagous to parasitic/parasitoid and predators. They are important as plant pollinators, pest control agents, and seed dispersers, thus providing food for humans (e.g., honey) and other organisms. They can even act as pest species of various plants.

Bees (Hymenoptera: Apoidea) are efficient and important pollinators. They survive on a diet of pollen and nectar and have developed morphological and behavioural adaptations to facilitate the collection and transfer of pollen (Thorp 1979, 2000). Flowers attract bees with rewards of nectar, pollen, essential oils, and plant resins. Bees use pollen as their primary source of protein, particularly during the larval growth phase, while nectar is their source of carbohydrates. Some bees use oils during mating and for larval food, and others use plant resins as building materials for their nests (Michener 2007).

As bees forage for these necessities, they transfer pollen from plant to plant, thus increasing fruit set, seed set, and genetic diversity (Crane 1990; Neff & Simpson; 1993; Delaplane & Mayer 2000; Abrol 2012). Many fruit, vegetable, and seed crops, as well as crops providing human medicines, fibres, fuels, and livestock forage, are directly dependent on the pollination services bees provide (Delaplane & Mayer 2000; Allen-Perkins et al. 2022).

Flower-visiting wasps (Hymenoptera: Apoidea, Pompiloidea, Scolioidea, Tiphioidea, and Vespoidea) primarily visit flowers to gather nectar and hunt for prey, sometimes leading to plant pollination (Shuttleworth & Johnson 2009). Many wasps are also beneficial biological control agents as parasitoids or predators of arthropods (Evans & Eberhard, 1970). Parasitoid wasps oviposit on a host arthropod, and development of the parasitoid offspring into an adult is fatal to the host (Gauld & Bolton 1988). Predatory social wasps collect, masticate, and deliver small arthropods to the developing larvae in their colonies. Solitary wasps paralyze and collect small arthropods that they place into a preexisting tunnel that they have selected for a nest; they then oviposit on the motionless arthropod and seal the nest as their final act of parental care (Evans & Eberhard 1970). Prey foraging and parasitic behaviours exhibited by wasps are natural ecological services that can help to control herbivorous insect pests (Gould & Jeanne 1984; Shaw & Hochberg 2001; Rogers & Potter 2003; Frank & McCoy 2007; Brock et al. 2021).

Under these circumstances, bees and wasps contribute to the function of natural and agricultural ecosystems. Unfortunately, not enough information is known about many of these beneficial insects to predict their population trajectories (Meiners et al. 2019). This is a critical knowledge gap given that this information can be used to identify endangered populations of bees and wasps, develop conservation programs for them, determine their contributions to agriculture, etc. For example, scientists have a good sense of the size of the managed population of western honey bees (*Apis mellifera* L., 1758) in the United States. Annual surveys conducted by The Bee Informed Partnership (http://beeinformed.org) and the United States Department of Agriculture (USDA) National Agricultural Statistics Service (https://www.nass.usda.gov/) help us understand the high loss rates of managed honey bee colonies and their overall population trajectory. These data allow researchers to identify trends in colony losses and this helps direct further research into identifying problems and developing solutions. Most other bee species are not managed by beekeepers who otherwise would act as stewards, tracking and supporting their populations when necessary. Instead, the research community often learns about a particular species only after its population has declined to the point where its existence is in jeopardy.

In this review, we discuss the importance of surveys and monitoring programs for 1) evaluating populations of imperilled bee and wasp species, 2) documenting and finding bee and wasp crop pollinators, 3) identifying and utilizing wasps for biological control agents, 4) evaluating the ranges of non-native bees and wasps, and 5) employing bees and wasps as biological indicators of habitat quality. Furthermore, we identified bees and wasps that have been evaluated as imperilled species or for which there were unsatisfactory data to make a conservation status determination. We note beneficial hymenoptera that have been documented to pollinate crops and could serve as commercially managed pollinators. We also review a wide range of literature from various pollinator studies and compiled a series of methodologies and tools for researchers to consider when developing their own projects. We hope this review will spark and support future research efforts for observing these beneficial hymenopterans, tracking their population trends, and noting any challenges that we may help them overcome.

REASONS FOR SURVEYS AND MONITORING PROGRAMS

The terms 'survey' and 'monitoring' are often erroneously used interchangeably but do have different meanings. A survey is a set of observations made in a set time period typically by following a standardized protocol (Goldsmith 2012). Surveys of bees and wasps are usually done to document the presence/absence of species within a given area or visitors to specific plant species (e.g., flower visitors). Alternatively, monitoring generally refers to a set of surveys accomplished periodically to ascertain changes over time (e.g., population trends, variability of bee and wasp species in given locations, etc.) (Goldsmith 2012).

Monitoring programs are established for a variety of reasons, all of which are applicable to bees and wasps. Often, they are established in response to a crisis as a method of tracking the progress of natural resource conservation or restoration efforts, as well as evaluating the outcomes of these efforts. If a population or natural community is determined to be threatened or in decline, then monitoring is key to developing and executing a conservation plan. Monitoring is also helpful when comparing long-term population trends in response to environmental or ecological variables. Monitoring programs are most often initiated when the resource of concern is highly valued economically, socially, or intrinsically (McComb et al. 2010). They are often designed to help policy makers and managers make informed, fact-based decisions. That said, long-term monitoring programs require investments of time, money, and effort which must be justified prior to the initiation of the program and validated after the program begins. Alternatively, making observational surveys about bees and wasps can provide some important information regarding ranges, natural histories, and interations with crops and other plants.

In this section, we discuss why bee/wasp surveys and monitoring programs are important, including for (1) the conservation of threatened and endangered bees and wasps, (2) identifying and managing bees and wasps as beneficial insects in agricultural settings, and (3) tracking the spread of introduced bees and wasps.

Threatened and Endangered Bees and Wasps

During the 1990's, researchers worldwide became increasingly concerned about pollinator diversity (Batra 1995; Byrne & Fitzpatrick 2009). Following a series of meetings, the International Pollinator Initiative (IPI) was created in 2000. The IPI's Plan of Action outlined several objectives, including the monitoring of pollinator decline, its causes, and its impact on pollination services, the resulting increase of taxonomic information, an economic valuation, and conservation promotion (Byrne & Fitzpatrick 2009). Brown & Paxton (2009) state that the greatest obstacle to advancing pollinator conservation is the dearth of good data on species distributions and abundance. Possibly the most data deficient area is Africa, where very little collecting activity has occurred, in part due to political and infrastructural problems (Eardley et al. 2009); however, data are lacking even in North America (Berenbaum et al. 2007; Woodard et al. 2020; Vigueira et al. 2023).

European researchers outlined the status of all European bees (Nieto et al. 2014). By summarizing existing data, they found that an alarming 9.2% of 1,942 European bee species are considered endangered. Even more troublesome, this does not account for the 56.7% of European species for which data are deficient, making assessment of their status impossible.

It seems obvious that conservation of bee species around the globe is necessary. However, there are several impediments to invertebrate conservation, most of which are related to a lack of data on the life history, population dynamics, and ecological importance of invertebrate species (Cardoso et al. 2011). Furthermore, monitoring pollinators beyond the bloom period of crops is an important, but often-overlooked, necessity. For example, crops that need insects for pollination services rely on healthy pollinator populations that depend on resources outside the blooming period. To conserve populations of bees and wasps, it is necessary to identify all of their resource requirements during all seasons, not just their food requirements during crop bloom (Patrício-Roberto & Campos 2014). This is especially important because the basic biology of some bees and wasps predisposes them to endangered status because of their specific requirements for a particular host, food source, nesting situation, etc. (Box 1). For instance, solitary and parasitic bees and predatory wasps are at higher trophic levels than their prey and will be reliant on unpredictable resources or have consistently limited populations if their prey abundance fluctuates (La Salle & Gauld 1993). Pollination ecologists have noted declines in bee abundance and species richness since the 1980s (Williams 1986; Buchmann & Nabhan 1996; Matheson et al. 1996; Allen-Wardell et al. 1998; Kearns et al. 1998; Mola et al. 2021), including many documented declines among non-managed bees and wasps (Day 1991; Banaszak 1995; Buchmann & Nabhan 1996; Shaw & Hochberg 2001; Biesmeijer et al. 2006; Ellis et al. 2006;

Box 1

YELLOW-FACED BEES (*HYLAEUS* SPP. FABRICIUS, 1793), A CASE STUDY

Through monitoring efforts, threats to endangered Hawaiian yellow-faced bees (*Hylaeus* spp.) have been identified and work is underway to mitigate these challenges. While monitoring the bees in artificial nest blocks, researchers determined that the yellow-faced bees are often invaded by ants (none of which are native to the Hawaiian Islands) (Magnacca & King 2013; Graham et al. 2021). The artificial nest blocks were then protected using a sticky ant-proofing barrier (Tanglefoot) which has helped provide ant-free nesting opportunities for the endangered, native pollinators (Graham et al. 2021). Through monitoring, it was also discovered that introduced bees are potentially competing for resources with the native bees, by utilizing the same size holes in the same coastal plants for nesting and foraging on the same flowers (Magnacca & King 2013; Graham et al. 2021). Citizen science projects are now being implemented to help identify populations of endangered Hawaiian yellow-faced bees (https://www.inaturalist.org/projects/pollinators-in-paradise) and the rusty patched bumble bee (https://www.bumblebeewatch.org/). These citizen science projects have the potential to increase our understanding of known populations of these endangered species and help to drive conservation efforts where most needed.

Fitzpatrick et al. 2007; Magnacca 2007; Cameron et al. 2011; Magnacca & King 2013; Graham et al. 2021; among many others). The summary of European data only drives this point home, with one of the major gaps in knowledge being identified as a shortage of data provided by long-term surveys (Nieto et al. 2014). Additionally, how conservation actions affect biodiversity trends is largely unknown and little research exists that connects local conservation efforts with large-scale biodiversity trends (Kleijn et al. 2011). Despite the enormity of the project, bee and wasp species need to be surveyed and monitored regionally, nationally, and globally for decisions to be made about their conservation management needs.

The high gross loss rate of colonies of managed honey bees in parts of the world was easily detectable by the network of beekeepers who monitor their own colonies closely. However, comparatively fewer individuals currently monitor populations of native bees or wasps. For many years, the only data collected were by entomologists who studied a particular species or group of bees or wasps, thus potentially skewing the existing population data with collector, location, and species biases (New 2012). Independent studies show declines of specific bees and wasps in specific locations detected by focused research over a given time (Box 2), representing a snapshot of the status of the bee and wasp species under investigation. However, the conservation needs of most bees and wasps are unknown due to insufficient monitoring (La Salle & Gauld 1993; Kearns et al. 1998; Shaw & Hochberg 2001, Meiners et al. 2019), and additional data are urgently needed. Long-term monitoring programs can help identify challenges to species success and population trends that can be used to assess and direct conservation efforts.

Box 2

THREATENED BEES AND WASPS

Museum records of insect collection data have provided insight into bee species of concern that are candidates for conservation assessment. For instance, the species richness of northeastern *Bombus* Latreille, 1802 was found to have decreased by 30% over a 140-year timeframe, with three species: *B. affinis* Cresson, 1863, *B. pensylvanicus* (De Geer, 1773), and *B. ashtoni* (Cresson, 1864) showing a "rapid, recent, population collapse" (Bartomeus et al. 2013). In another study, voucher specimens from museum and personal collections revealed that since the early 1990's the majority of 770 eastern North American bee species had been detected at least once, while 37 species had not been detected at all (Colla et al. 2012). These findings were qualitative and do not provide evidence against declines of these detected species, nor do they imply that extinctions among the 37 undetected species did or did not occur. However, this study does provide a short list of eastern North American bee species on which to focus when assessing conservation needs (Colla et al. 2012). Alternatively, Koh et al. (2016) used a spatial habitat model and land-cover data to show that modeled wild bee abundance declined across 23% of area in the United States between 2008-2013. This study also highlighted that most of the modeled wild bee declines occurred in response to changing land-use; row crops taking the place of natural habitats.

Like most insects, bees and wasps are underrepresented in red lists and conservation plans (Byrne & Fitzpatrick 2009; Zamin et al. 2010; Cardoso et al. 2011). Among the 84 insect species listed as threatened or endangered under the United States Endangered Species Act, there are only eight bee species which include seven endangered Hawaiian yellow-faced bees: *Hylaeus anthracinus* (Smith, 1853), *H. longiceps* (Perkins, 1899), *H. assimulans* (Perkins, 1899), *H. facilis* (Smith, 1879), *H. hilaris* (Smith, 1879), *H. kuakea* Magnacca & Daly, 2003, *and H. mana* Magnacca & Daly, 2003, all listed in 2016; and the Rusty Patched Bumble Bee: *Bombus affinis*, listed in 2017. No additional bee or any wasp species are currently listed, even though many other bee and wasp species are known to be very rare, declining, or likely extinct (Shepherd et al. 2005; USFWS 2016, 2017, 2017a). Many regions, countries, and even entire continents are not well represented in the red lists reviewed. For instance, red listed bees or wasps of Africa, Central America, South America, and parts of Asia are underrepresented or not represented at all compared to those listed for Europe and North America. This anomaly is probably due to a lack of sampling and monitoring effort within these regions.

Figure 1 presents the current review (2023) of red listed bees from the International Union for Conservation of Nature (IUCN) database. The IUCN assesses the conservation status of species on a global scale. Using the IUCN database (https://www.iucnredlist.org/), hundreds of bees are listed as endangered, threatened or data deficient (Figure 1). However, only two wasp species were listed as endangered (Ichneumonidae: *Syrphoctonus morio* (Hellén, 1949); Aphelinidae: *Encarsia estrellae* Manzari & Polaszek, 2002 and two listed as near threatened (Sphecidae: *Tachysphex pechumani* Krombein, 1938; Braconidae: *Phaedrotoma sanmiguelensis* (Fischer, 2001)); exemplifying the lack of information on wasps. Despite the IUCN attempt at documenting rare bees and wasps, many rare/endangered species are not listed and, thus, much more work must be done before an accurate global list can be generated (e.g., the 7 *Hylaeus* species are not listed in the IUCN). Additionally, the majority of bees listed in the IUCN database are classified as data deficient, exemplifying the need for increased and better monitoring systems. Despite the IUCN assessing species on a global scale, the information their database contains is dependent on researchers. Thus, taxa in some areas (e.g., Europe) are well documented whereas other areas are largely unknown.

Bees for Crop Pollination Purposes

Observing bee species that pollinate crops will help identify potential species that could be used as a managed pollinator. Approximately 75% of food crops rely on animals (e.g., bees) for pollination services (Klein et al. 2007), thus, exemplifying the need to understand population trends for honey bees and other animal pollinators. Pollination has become an industry unto itself, with beekeepers and commercial bee suppliers selling or leasing honey bees to growers whose pollination needs are more than can be satisfied by the local wild bee population (Delaplane & Mayer 2000). The western honey bee is the most commonly managed pollinator (Delaplane & Mayer 2000), but its North American and European managed populations experience sporadic high gross loss rates due to pests, pathogens, pesticides, queen quality, and nutrition (vanEngelsdorp et al. 2009; Potts et al. 2010). The number of managed honey bee colonies in North America has declined to 2.7 million as of 2021, down from nearly 6 million hives in the 1940s (Pettis & Delaplane 2010; NASS 2022). The many problems facing managed honey bees underscore the importance of native bee communities, only a fraction of which are currently managed as crop pollinators despite the fact that alternative bees are often more efficient pollinators than honey bees (Sedivy & Dorn 2014; Campbell et al. 2018a). Kleijn et al. (2015) found that a few wild bee species were common in agricultural systems. Thus, survey efforts can be developed to help identify pollinator species that might be manageable for crop pollination purposes or to help develop population management programs for common pollinator species. This is especially important given that crop production in some areas (such as the United States – Reilly et al. 2020) is frequently limited by a lack of pollinators.

There are many examples in which managed alternative bees have provided pollination services along with or instead of honey bees. Some recognized examples include several bumble bee species (*Bombus* spp.) (Velthuis & van Doorn 2006; Vergara 2008; Campbell et al. 2017a; Abbate et al. 2023), several mason bees (*Osmia* Panzer, 1806) (Batra 1978; Maeta & Kitamura 1981; Yoshida & Maeta 1988; Maeta et al. 1990; Torchio 1990; Torchio 1991; Sekita et al. 1996; Da-Yong & Long-Shi 2007; Lee et al. 2008; Matsumoto & Maejima 2010; Boyle et al. 2020), and two bees used for pollination of alfalfa for seed, the alfalfa leafcutting bee (*Megachile rotundata* (Fabricus, 1787)) (Bohart 1972; Pitts-Singer & Cane 2011) and the alkalki bee (*Nomia melanderi* Cockerell, 1906) (Rauf et al. 2021). The latter is also the only intensively managed ground-nesting solitary bee in the world (Cane 1997, 2008). Over 100 other potentially manageable bees have been found visiting crops and some have been tested globally on a variety of crops (Supplementary Table S1). Of these, over 25% are tunnel-nesting solitary bees, which are well suited for management because their nests can be moved

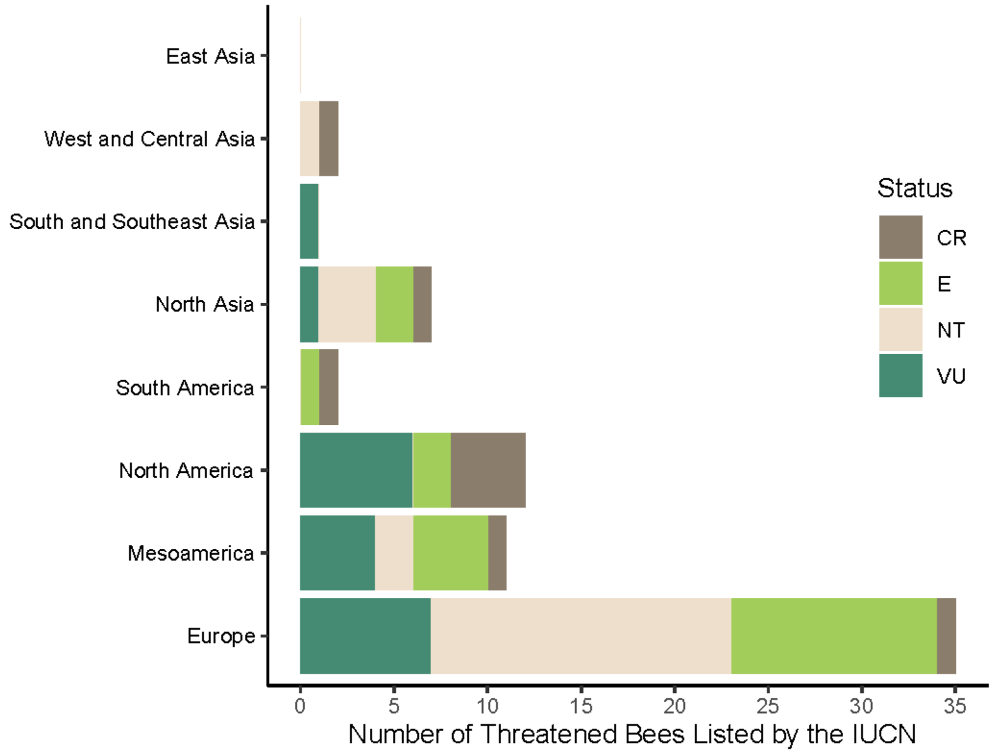

Figure 1. Number of bee species that are listed by the International Union for Conservation of Nature (IUCN) as vulnerable (VU), near threatened (NT), endangered (EN), and critically endangered (CR) in 2023.

East Asia: China, Japan, North Korea, South Korea, Mongolia, Taiwan, Hong Kong, Macao

South & Southeast Asia: Bangladesh, Bhutan, Brunei, Myanmar, Cambodia, India, Indonesia, Laos, Malaysia, Maldives, Nepal, Philippines, Singapore, Sri Lanka, Thailand, Timor-Leste, Vietnam, British Indian Ocean Territory, Disputed Territory

North Asia: Russia, Belarus, Moldova, Ukraine

West & Central Asia: Afghanistan, Armenia, Azerbaijan, Bahrain, Cyprus, Georgia, Iran, Iraq, Israel, Jordan, Kazakhstan, Kuwait, Kyrgyzstan, Lebanon, Oman, Pakistan, Palestine, Qatar, Saudi Arabia, Syrian Arab Republic, Tajikistan, Turkey, Turkmenistan, United Arab Emirates, Uzbekistan, Yemen

and manipulated much more easily than can the nests of ground-nesting species.

In general, monitoring for possible crop pollinators should aim to 1) determine species composition for a given area, 2) evaluate the status and health of pollinator species and populations over time, and 3) determine pollinator species' pollination efficiency for crops and native plants. Bosch & Kemp (2002) emphasize the importance of monitoring in the form of field surveys when seeking pollinator species with potential for management. Not only does monitoring help identify potential pollinators, but it also provides information about the pollinators' phenology and pollination efficiency. This information is vital to determining if a particular pollinator will be a good match to the crop of interest and also how easily the pollinator might be managed (Bosch & Kemp 2002: Sedivy & Dorn 2014).

A good example of how valuable monitoring can be when seeking to augment pollination is presented by Sheffield et al. (2008), who, along with comparing habitats for suitability for tunnel-nesting bees, sought to identify native bee species that could possibly be managed for pollination. The authors monitored 23 sites in Nova Scotia, Canada for tunnel-nesting bees for three years using trap-nests (artificial nest sites for cavity/tunnel nesting bees/wasps). Of the 18 native tunnel-nesting bee species that were trapped, *Osmia tersula* Cockerell, 1912 showed great promise as a pollinator of apple orchards due to its commonality during apple bloom and its attractiveness to apple flowers for pollen. This example highlights one way of addressing pollination deficiencies through the identification of pollinator species, via observational surveys and monitoring programs, that are candidates for management.

Wasps as Biological Control Agents

Monitoring programs can also be useful for discovering and managing wasp species for biological control purposes. Van Driesche & Bellows (1996) define biological control as "the use of parasitoid, predator, pathogen, antagonist, or competitor populations to suppress a pest population, making it less abundant and thus less damaging than it would otherwise be." Three primary methods of biological control are used: conservation, augmentation, and introduction. It is possible that the infested area already contains natural enemies in sufficient numbers, in which case the biological control plan would implement appropriate conservation strategies (Van Driesche & Bellows 1996; Riley & Ciomperlik 1997; Shepard & Braun 1998; Semeão et al. 2012). If numbers are insufficient, augmentation of these enemies should be considered. In this case, the biological control plan then includes determining how to mass rear, release, and manage populations of the most effective natural enemies (Van Driesche & Bellows 1996; Dias et al. 2014). However, if the pest's natural enemies are not present or not known, the biological control program centers on the discovery and introduction of useful natural enemies (Van Driesche & Bellows 1996). Of the three approaches, introduction has been the most successful (Hajek and Eilenberg 2018) and is commonly used against non-native, invasive pests (Kenis et al. 2017).

There are several methods used for monitoring predatory and parasitic wasps in the context of biological control. This could lead to the discovery of new biological control agents. Typically, the method for developing a biological control program begins with accurate identification of the pest species, either weed or insect. Following this, its natural enemies need to be ascertained (Van Driesche and Bellows 1996), at which point monitoring becomes important.

Predatory and parasitic wasps rely on other arthropods as prey or hosts for their offspring, and many of these relationships could potentially be utilized for biological control of pest species. Nearly all of the known solitary wasps are highly host-specific and very few attack beneficial insects (Evans & Eberhard 1970). In many cases, the prey choice is specific to each wasp species or particular genera, in which case the wasp can be used as a biological control agent (De Bach & Rosen 1991). Many social wasps prey upon insects of economic importance and in some agricultural regions, these wasps are considered valuable control agents (Evans & Eberhard 1970). Parasitic wasps were reported as the biocontrol agent in over 65% of all successful cases of biological control of pest insect species due to their host specificity and the ease with which they are incorporated into biological control programs (De Bach & Rosen 1991). Nevertheless, many parasitic Hymenoptera remain undescribed (La Salle & Gauld 1992), but possibly could be identified in well-structured surveys and monitoring programs, leading to their use in the control of agricultural pests or invasive species.

A few monitoring strategies can be helpful for the discovery of wasps that can be used as biological control agents. One strategy is to collect specimens of an insect pest species and its eggs from its native range and rear them in the laboratory in hopes of discovering parasitoids that emerge (Legner & Bellows 1999). A second strategy is surveying the pest's native range or another infested area (Legner & Bellows 1999) for potential natural enemies using sweep nets or using a trapping method such as sticky cards or bowl traps.

Monitoring strategies are also useful after the development of biological control programs. It is important to monitor the dispersal, distribution, and abundance of parasitoids after their release as biological control agents (Fraser et al. 2008; Zappalà et al. 2012; Böckmann et al. 2015), sometimes both before and after parasitoid release (Purcell & Messing 1996; Bruck & Lewis 1998; Ayalew & Hopkins 2013), to ensure program success. It can also be important to monitor phenological traits such as seasonal population levels (Jewett & Carpenter 2001), which can help assess synchronicity with the host (Bąkowski et al. 2013) and assist with the timing of pesticide sprayings (Udayagiri et al. 1997). Monitoring parasitoid populations is also useful following pesticide treatments (Longley et al. 1997; Frost et al. 2015) or ecological disturbances (Maeto et al.

2009). Lewis & Martin (1990) discuss the importance of continued monitoring of parasitoid populations to ensure that desirable traits are maintained and suggest the development of semiochemicals, which parasitoids often use for locating their hosts, to enhance the monitoring component of biological control programs.

The practice of collecting pests in the field and rearing them in the lab is not used only during natural enemy discovery. A similar strategy has been used to monitor pest and naturally occurring parasitoid populations when deciding if parasitoid augmentation or introduction is necessary, or if conservation will be sufficient (Riley & Ciomperlik 1997; Shepard & Braun 1998; Semeão et al. 2012). This method has also been used after the decision was made to augment the parasitoid population. Larvae have been gathered in the field and lab reared as a way to monitor parasitism rates before and after parasitoid release (Ayalew & Hopkins 2013).

Monitoring to Track Non-Native Bees and Wasps

Invasive species are among the greatest threats to local biodiversity (Wilson 1999; Brown & Paxton 2009). Introductions can happen naturally or due to the actions of humans, both purposefully and accidentally. The most common entrance points for introduced species are major ports and these are monitored for incidental transportation of exotic species; however, solitary bees and wasps can be unseen while nesting in small tunnels (Cane 2003). Bees and wasps are beneficial insects in agricultural and natural ecosystems. In fact, some managed bees (e.g., *Apis mellifera*) in the United States are introduced species. Honey bees and bumble bees, as well as social wasps (*e.g. Vespa velutina* Lepeletier, 1836, the Asian hornet), tend to be successful in non-native lands, presumably because of their sociality and associated traits (Moller 1996; Chapman & Bourke 2001; Goulson 2003; Beggs et al. 2011). However, more than half of the introduced bee species in the United States are tunnel-nesting bees, mostly Megachilidae (Russo 2016). This may be attributed to the fact that these bees nest in tunnels in plants, wood, and other common materials which are easily distributed compared to ground-nesters, lending them to both purposeful and accidental introduction. Geslin et al. (2017) provides a useful review of some of the effects commonly employed pollinating bees (e.g., honey bees, bumble bees, tunnel-nesting bees, etc.) have on plant-pollinator interactions. However, outside of their native ranges, introduced species can negatively impact local ecosystems. In these cases, monitoring is critical for detecting and tracking non-native species of bees and wasps.

Monitoring programs for introduced bee and wasp species are important for multiple reasons. First, introduced bees and wasps may outcompete native species for food and nesting habitat. Second, introduced species may spread pathogens to alternative hosts. Third, introduced bees and wasps may aid in the spread of invasive plants via pollination. Finally, invasive wasps may shift host/prey species and cause unintended changes to native food webs. Thus, knowledge of when and where non-native bees and wasps are found is paramount avoiding deleterious ecological consequences.

Introduced bees may compete for food with native pollinators such as butterflies, hummingbirds, and other bees (Kearns et al. 1998; Goulson 2003; Roubik & Villanueva-Gutierrez 2009; Brockerhoff et al. 2010; Inoue & Yokoyama 2010). Furthermore, many introduced bees that are able to establish successfully and spread are polylectic, putting native oligolectic bee species at a disadvantage (Gross 2001; Goulson 2003). Other sources of competition for food include size differences, with larger bees often foraging earlier than and flying farther for resources than smaller bees (Gathmann and Tscharntke 2002; Greenleaf et al. 2007). Smaller bees, in turn, may have the advantage when resources are scarce or when the landscape is dominated by plants with small flower morphologies. Introduced social species, such as honey bees, may also have an advantage because they can communicate resource locations, whilst solitary bees and wasps have no assistance with foraging (Moller 1996; Goulson 2003). However, it is not always clear how introduced species interact with native fauna due to the many behavioural and biological differences that may exist among species (Minckley et al. 2003).

Introduced wasps can have impacts similar to those of introduced bees. At high densities, invasive arthropod generalist predators such as the common wasp, *Vespula vulgaris* (L., 1758), have very significant impacts, including reducing native prey species, preying on nestling birds, competing with native arthropods for honeydew, and causing other ecosystem disruptions (Matthews et al. 2000; Brockerhoff et al. 2010; Gardner-Gee & Beggs 2013; Burne et al. 2015). There is also the potential for introduced wasps to shift or broaden prey or host choice to native or beneficial arthropods (Brockerhoff et al. 2010; Choi et al. 2012; Monceau et al. 2013; Couto et al. 2014). There are many reports of invasive wasps outcompeting native wasps for food resources (Gamboa et al. 2002; Wilson & Holway 2010; Downing 2012). Improved monitoring systems are needed to help quell the increase of invasive wasps such as the many Vespidae species (e.g., northern giant hornet (*Vespa mandarinia* Smith, 1852) that continue spreading worldwide (Beggs et al. 2011, Zhu et al. 2020). Competition for nesting resources can also be an issue between introduced and native bees/wasps (Chapman & Bourke 2001; Goulson 2003). This has been shown to be the case in Japan where an introduced species of bumblebee has the same nest requirements as those of the native bumblebees (Inoue et al. 2008; Inoue & Yokoyama 2010). In the United States, *Megachile sculpturalis* Smith, 1853 has been shown to compete with native carpenter bees (*Xylocopa virginica* (L., 1771)) for their nesting sites (Laport & Minckley 2012, Roulston & Malfi 2012). Introduced small carpenter bees (*Ceratina* Latreille, 1802) and yellow-faced bees (*Hylaeus*) have been found using the same size nest in the same coastal plants as native Hawaiian yellow-faced bees and may be contributing to the decline of some species of endangered Hawaiian yellow-faced bees (Magnacca & King 2013; Graham et al. 2021). In these cases, monitoring programs may benefit the native bees by exposing potential population declines early and allow for timely conservation efforts.

Bee/wasp introductions may also spread pests/pathogens to alternative hosts. As more knowledge is acquired about pathogen and pest spread between both congenerics and heterogenerics, there is particular concern for wild bees (Chapman & Bourke 2001; Goulson 2003; Brown & Paxton 2009; Williams & Osborne 2009). For example, introduced bumble bees have introduced parasites and pathogens to native bee populations in many areas (Goka 2010; Goulson 2010). Furthermore, the spread of honey bees globally has led to the widespread distribution of honey bee pests and pathogens (Boncristiani et al. 2021), many of which are now found to be associated with other bees (Mallinger et al. 2017).

Exotic bees can also affect native plant populations, either increasing or decreasing seed set (Kearns et al. 1998; Chapman & Bourke 2001; Gross 2001; Goulson 2003; Stokes et al. 2006; Dohzono et al. 2008; Goka 2010; Roubik & Villanueva-Gutierrez 2009; Hermansen et al. 2014). Furthermore, exotic bees, including intentionally introduced honey bees and bumble bees, pollinate exotic plants more often or more efficiently than do native wild bees, potentially leading to or exacerbating weed problems (Kearns et al. 1998; Chapman & Bourke 2001; Stout et al. 2002; Goulson 2003; Magnum & Sumner 2003; Simpson et al. 2005, Morales & Aizen 2006; Abe et al. 2011). Some non-native plants, such as introduced figs, did not become weedy until their pollinators, in this case, fig wasps, were introduced as well (Kearns et al., 1998). Alternatively, surveys have shown exotic bee species aiding in the pollination of endangered plants (Campbell et al. 2016a) and, thus, may provide some beneficial services. Monitoring areas with exotic bees present as well as areas with high potential for exotic bee spread/introduction would help to conserve ecosystems by allowing appropriate control measures and conservation efforts.

Despite all of this, sharing habitat does not necessarily mean that species share resources. Niche overlap, and even more so competition, may be hard to demonstrate (Pickett & Wenzel 2000; Goulson 2003; Minckley et al. 2003), but possibly could be shown in monitoring programs. Experimental approaches can provide some of the most convincing evidence of competition (Moller 1996; Thomson 2004, 2006), but few experimental studies have been conducted, perhaps due to a lack of feasibility or the need for preliminary evidence in the form of survey data. Monitoring co-existing species and the spread of non-native species can help researchers and conservationists determine when an overlap may be occurring and help ascertain what the impact is on native species (Pickett & Wenzel 2000; Gross 2001; Ishii et al. 2008; Inoue & Yokoyama 2010; Kato & Kawakita 2004). Often, it is not obvious if competition is occurring, either due to fluctuations in resources or populations, making more long-term monitoring of introduced species and co-existing natives necessary (Moller 1996; Kearns et al. 1998; Minckley et al. 2003; Magnacca & King 2013; Graham et al. 2021). Additionally, short-term monitoring may not accurately represent species competition. For example, in a ten-year study of the invasive paper wasp *Polistes dominulus* (Christ, 1791) and the native *P. fuscatus* (Fabricius, 1793), early monitoring indicated that the exotic wasp would displace the native wasp, but after several years, the displacement decreased (Miller et al. 2013).

Monitoring the presence and establishment of non-native insects and tracking the population spread is critical for understanding the impact of these species, whether beneficial or detrimental (Cane 2003; Brown & Paxton 2009; Roubik & Villanueva-Gutierrez 2009; Sheffield et al. 2010). Indeed, some make the argument that introduced species have conservation potential to fill the roles of the ecological services that are lost with declining, extinct, or endangered species (Schlaepfer et al. 2011; Sanguinetti & Singer 2014). Nevertheless, long term monitoring of exotic species is important, as often there is a lag between the introduction of a species and the growth of its population to problematic levels (Brockerhoff et al. 2010). Additionally, long term monitoring affords researchers the ability to differentiate between weather-influenced and other population fluctuations. Shorter studies could arrive at vastly different conclusions, simply based on the period of time in which they were conducted. Due to the lack of basic knowledge of many native bee and wasp species, baseline data including basic biology, distributions, and abundance for native bees and wasps are necessary if the impacts of exotics are to be measured accurately (Moller 1996; Kearns et al. 1998; Minckley et al. 2003; Brown & Paxton 2009; Perrard et al. 2009) and if control programs are to be successful (Ishii et al. 2008; Kadoya et al. 2009).

BEES AND WASPS AS BIOINDICATORS

Bees and wasps are being increasingly used as bioindicators and sentinel species, thus necessitating monitoring programs to ascertain species' presence and abundance in an area. Many studies that examine land-use changes or habitat quality inspect the overall bee or wasp community or a certain bee guild (e.g., tunnel/cavity nesting bees) within an ecosystem. For example, cavity nesting bee and wasp abundance and diversity measures have been utilized as bioindicators for ecological change or habitat quality in agricultural and forested landscapes (Tylianakis et al. 2004) with species richness declines occurring in fragmented landscapes (Tscharntke et al. 1998). Cavity nesting bee and wasp communities have also been monitored to determine whether wildflower plots planted within agricultural land can potentially augment beneficial bee and wasp abundance and diversity (Campbell et al. 2017b). Additionally, cavity nesting bee and wasp species richness have been examined within grasslands that had varying livestock grazing pressures, with ungrazed pastures containing significantly more bee and wasp species (Kruess and Tscharntke 2002). Most cavity nesting wasps are predators of many agricultural pests and may act as biological control agents and can be used as an indicator of predator/prey interactions (Tscharntke et al. 1998).

Overall bee and wasp communities have been successfully used for monitoring ecological change. For example, bee and wasp communities can act as a bioindicator for forest health by documenting how forest management techniques affect bee and wasp biodiversities (Campbell et al. 2007; Rubene et al. 2015; Campbell et al. 2018b). Bee and wasp diversity and abundance have also been monitored after removal of invasive shrubs within forested habitats (Hanula and Horn 2011). Additionally, bee and wasp communities have been utilized to examine forest fragmentation (Brosi et al. 2008) and row-cropping switchgrass within large monocultures of pine (Campbell et al. 2016b). Alternatively, habitat loss, grazing, logging, and changes in agriculture caused by anthropogenic activities can also be monitored by using bees as an indicator group (Winfree et al. 2009).

Instead of examining the overall bee or wasp communities, many studies utilize specific bee or wasp species (indicator species) to make inferences about habitat quality. Bee and wasp abundances or health of particular species can be used to detect environmental pollution (Celli & Maccagnani 2003), issues with genetically modified plants, and the spread of invasive plants and animals (Kearns et al. 1998). Honey bees have been used for environmental monitoring since the early 1980's, where they have been implemented to monitor pesticides, heavy metal pollution, and radioactive contamination (Porrini et al. 2002). Bumble bees and other managed bees have been increasingly used as indicator species for insecticide risks (Scott-Dupree et al. 2009; Laycock et al. 2012, 2014). Alternatively, wasps have not been utilized as indicator species as frequently as bees. However, many social wasp species (Vespidae) have also been shown to be good potential ecological indicators (Urbini et al. 2006; de Souza et al.2010; Brock et al. 2021). Other wasps, such as some sphecids, have been suggested as having potential to be good biodiversity indicators (Gayubo et al. 2005). Thus, utilizing bee and wasp species for biomonitoring has many potential and promising applications. Most species are readily identifiable, and many correlations can be made regarding ecological health based on abundances and species richness.

MONITORING METHODS

Many tools and programs are available for studying bees and wasps, and the researcher's choice is dictated by the purpose of monitoring (Table 1). Ideally, monitoring methods should be selected for the collection of unbiased data that can be widely replicated over space and time. For example, some methods favour general or specific types of bees and wasps while excluding others, thus leading to spurious results. Methods may also generate incidental collection of non-target bees or wasps. Variable methods used at the same location and time of day or season will often lead to dissimilar results as many bees and wasps are either more or less detectable depending on the method used. Ultimately, many factors may be important when choosing a monitoring method, factors such as cost, labour intensiveness, etc.

One common goal of monitoring programs is to catalogue the abundance and diversity of bees or wasps within a given locale or on a particular crop. Many tools and methods should be used in tandem in order to maximize the potential of collecting data on all the representative species within a given area and minimize the potential of missing cryptic or rare species (Silveira 2004). The use of multiple trap types will allow for a more comprehensive representation of the bee fauna (Geroff et al. 2014; Campbell et al. 2023). Whether using a passive or non-passive trapping method, the study site should also be monitored in variable conditions (e.g., varying temporal and climatic conditions) to ensure adequate, unbiased sampling. The initial dataset collected may provide a benchmark for future studies but is essentially a snapshot of the bees and wasps in a given place at a given time and detected with a given set of tools (Magurran et al. 2010). By monitoring the same location or crop over multiple seasons and with replicated methods, the collector may be able to interpret the data as changes in the population dynamics of the pollinator community.

Alternatively, the goal may be to find and learn more about a particular bee or wasp species. Verifying the existence of a species in a given area may be important when tracking endangered or non-native species. Studying the natural history of a particular species may be important when developing conservation or management plans. Monitoring can be useful for learning about a species' nesting, foraging, or host preferences, its associations with conspecifics and heterospecifics, its predators and parasites, and many other life-history traits. In such cases, it is helpful to use a method best suited to detecting the particular bee or wasp of interest, in order to increase the likelihood of encountering the target species in the wild. For instance, if the bee or wasp is known to nest in tunnels in wood or hollow stems, trap nesting or the use of artificial nest sites may be the best monitoring method (e.g., Roubik & Villanueva-Gutierrez 2009; Graham et al. 2021). Droege (2015) provides an excellent overview of bee collecting techniques and how to manage a bee collection properly. Overall, the monitoring method is dependent on the goals of the project, but the use of multiple monitoring methods over long periods of time will provide the most accurate survey of bees and wasps within an ecosystem.

We list in Table 1 a summary of the many tools and methods useful for monitoring bees and wasps. It serves as a helpful reference for the selection of monitoring strategies and the pros/cons associated with each. The purpose of Table 1 and this portion of the review is to give researchers an introduction to the wide breadth of bee and wasp monitoring methods and sources to seek additional details related to experimental

Table 1. A summary of the many tools and methods useful for monitoring bees and wasps. "Collector Variability" refers to the likelihood that the data quality may vary by collector.

Method	Summary	Mode of Capture	Primarily Collects	Collector Variability	Considerations	Cons	Benefits	Selected References
Aspirators/ vacuum collector	collector inhales or vacuums live specimen into a container	collected into container	bees or wasps; social or gregarious; small adults	medium	avoid using inhalation aspirators where pesticides may have been sprayed	some individuals may be too fast or evasive	mark-release-recapture; avoids handling specimen	Paulson 2005 Stephen & Rao 2007
Bait stations	a station containing an attractive resource is observed for visitation	attracted to bait station	bees but may be used for wasps	low	stations need to be more attractive than local resources	may not be visited by some species	attracts local foragers to a predetermined observable area	Spurr 1995 1996; Vaudo et al. 2012; Human et al. 2013
Baited traps/ sticky trap	trap with airborne volatile as the attraction method	fall into or is stuck to trap	bees or wasps; adults attracted to a particular pheromone or volatile	low	attractants can be designed to be target specific or to replicate a specific odour	may be messy and difficult to curate specimens i.e. sticky traps	olfactory attractiveness studies; social bees and wasps	Caron & Morse 1972; Meagher & Mitchell 1999; Landolt et al. 2000
Bee-lining	a specimen is followed to a nest	leads collector to nest	social bees but may be used for wasps or gregarious nonsocial species	high	establishing a beeline may require the use of a bait station or bee box	may be difficult with fast flying or small specimens	allows for the discovery of nest sites in the field	Visscher & Seeley 1989; Breed et al. 1999; Vaudo et al. 2012; Human et al. 2013
Bowl/ dish/ pan/ Moericke trap	coloured vessel partially filled with soapy water	drown in soapy water	mostly bees some wasps; foraging adults	low	evaporation; specimens must be carefully washed and dried post collection	potential for species bias; potential for over collection	standard method with low collector bias; low cost; easy set up	De Souza & Campos 2008; Leong & Thorp 1999; Cane et al. 2000; Silveira 2004; Bartholomew & Prowell 2005; Campbell & Hanula 2007; Wilson et al. 2008
Digital macro-photos/ video capture	photos or video	photos or video collected and analyzed	bees or wasps in any lifestage	medium	image quality and resolution can vary greatly	some defining ID features not visible in most images	allows for review and ID remotely and at a later time	Gaglianone 2000; Steen et al. 2011; Deguines et al. 2012; Campbell et al. 2014

Tab.1 continued

Method	Summary	Mode of Capture	Primarily Collects	Collector Variability	Considerations	Cons	Benefits	Selected References
Flight intercept trap	vertical wall of black terylene into which insects fly and fall into kill jars	hit wall and fall into kill jar	mostly wasps, some bees; flying adults	low	those sprayed with insecticide reported to increase results	not suitable for most bees; may be damaged or blown over in unfavourable weather	collects a wide variety of flying adults; good for detecting parasitoid wasps	Masner & Goulet 1981; Noyes 1989; Ulyshen et al. 2010
Fluorescent pigment	dyes are used to track flower visitation	data collected via dyes spread from flower to flower	can be used for both bees or wasps	low	some dyes transferred at different rates depending on visitation	dye can over-estimate or under-estimate	allows for studies on pollen depositions and transfer as well as movement	Johansson 1959; Stockhouse 1976; Adler & Irwin 2005; Van Rossum et al. 2011
Fumigation/ fogger	Insecticide sprayed	Insecticide sprayed	mostly wasps in collection reviewed	low	potentially negative effects including non-target kills and over collection	non-targets killed	samples obtained are expected to correlate abundance and diversity	Erwin 1989; Noyes 1989; Simandl 1993
Harmonic radar/ radio telemetry	a trans-ponder is attached	Movement data captured via radar	can be used for both bees or wasps; potential size limits	low	varying degrees of detectability and strength	may limit flight ability	tracks bee or wasp movement throughout environment from nest to forage and back	Osborne et al. 1999; Pasquet et al. 2008; Wikelski et al. 2010; Hagen et al. 2011
Insect net	net swept through the air or vegetation	swept into net	bees or wasps; flying or foraging adults	medium	various net types available (i.e. mesh, canvas, canopy, etc.)	may be too fast or evasive	mark-release-recapture; targeted or random	Paulson 2005; Stephen & Rao 2007
Light trap	mercury vapor, UV, broad spectrum or any number of light sources	attracted to light and captured	mostly wasps, some bees; nocturnal	medium	different light sources will have variable results; best used in complete darkness	potentially expensive; requires power source; bulbs can get very hot	detecting nocturnal wasps and bees	Wolda and Roubik 1986; Roubik and Wolda 2001; Kelber et al. 2006

Tab.1 continued

Method	Summary	Mode of Capture	Primarily Collects	Collector Variability	Considerations	Cons	Benefits	Selected References
Linear transects	Collector travels along a route or for a time	photos or data	bees or wasps flying or on flowers or nests	high	can be standardize, random or variable	variable walking speeds, detecting abilities of collectors	economic and allows division of area into smaller portions	Drummond & Stubbs 1996; Nielsen et al. 2011; Campbell et al. 2018a
Malaise trap	net trap designed to collect flying insects	fly into net climb to the top into a funnelled container	mostly wasps, some bees; flying adults	low	many styles and types available; different color mesh may produce variable results	not suitable for most bees; damaged or blown over in bad weather	collects a variety of flying adults; good for detecting parasitoid wasps	Bartholomew & Prowell 2005; Campbell & Hanula 2007; Fraser et al. 2008
Quadrat/ visual plot	specimens/ data collected from within a set area	photos or data	bees or wasps flying or on flowers or nests	high	can be standardized, random or variable	can be difficult to adequately sample all visitors in a vegetation rich habitat	inexpensive and allows for the division of an area into smaller portions	Drummond & Stubbs 1996; Nielson et al. 2011
Sensor/ pass monitor	sensor that tracks specimens crossing a set point	monitors motion activity	used mainly for bees but could be used for wasps	low	wide range of electrically, optically or mechanically controlled movement sensors	accuracy variable between instruments and specimens, need set point of entry/exit	some instruments record size and velocity; correlate activity with environmental and temporal data	Buckley et al. 1978; Morandin et al. 2001; Campbell et al. 2005
Trap nest/ artificial nest site	holes drilled in wood, clay; pithy or hollow stems, tubes, straws, etc.	collected from or observed in nesting material	mostly wasps, some bees; all lifestages	low	potential nest site variables such as height, size hole, material	unattractive to certain species	central hub of activity; provides habitat	Krombein 1967; Frankie et al. 2002; Silveira 2004; Campbell et al. 2017b
Vane trap	coloured hanging funnel trap	fall into funnelled container	mostly bees, some wasps; foraging adults	low	non-destructive if checked often; wide range of shapes, sizes, opaqueness and colour	unattractive or ineffective for some species, can be expensive	baited or unbaited; easy set up and transport	Caron & Morse 1972; Stephen & Rao 2005 2007; Prendergast et al. 2020 Campbell et al. 2023

Tab.1 continued

Method	Summary	Mode of Capture	Primarily Collects	Collector Variability	Considerations	Cons	Benefits	Selected References
Visual counts/ sight ID	collector observes and records visitation	observed on flowers	bees or wasps; foraging adults	high	potential bias towards large or colourful individuals; time of day, weather variables	unable to identify certain species without preserved specimen	low cost; non-invasive; potential for pollination observation	Frankie et al. 2002; Silveira 2004
Wing morphology	wing venation is used to identify specimen	wing venation data is linked to GIS data	primarily bees, however system could be expanded to include wasps	medium	images must be captured in a specific way to be usable; provides results only for species of which wing data is inputted	emerging technology that is not fully developed	potential for both automated ID and monitoring	Steinhagen et al. 1997, 2001; Arbuckle et al. 2001; Hall 2011; Eimanifar et al. 2018

design. However, we do caution that the majority of literature in this area has been accomplished in Europe and North America (but see Prendergast et al. 2020) and we can only assume that these same methods would be efficient in other areas that may contain different genera. In general, monitoring methods can be classified into a few broad categories: (1) observational and direct bee/wasp sampling, (2) utilizing passive traps, and (3) monitoring with citizen science programs. Below are some details on a few of the more commonly used methods for monitoring bees and wasps.

OBSERVATIONAL AND DIRECT BEE/WASP SAMPLING

Some monitoring methods lend themselves particularly well to certain monitoring objectives and situations. Observational data have been collected visually by researchers in the field, using nets, photos, or video to determine the primary pollinators of a particular plant of interest (e.g., Gross 2001; Stout et al. 2002; Minckley et al. 2003; Simpson et al. 2005, Abbate & Campbell 2013; Campbell et al. 2014; Hermansen et al. 2014; Campbell and Morphew 2022), to examine plant-pollinator interactions, to evaluate niche overlap (Gardner-Gee & Beggs 2013), to determine non-native species populations, and to investigate interspecies competition (Pickett & Wenzel 2000; Minckley et al. 2003; Kato & Kawakita 2004; Morales & Aizen 2006; Dohzono et al. 2008; Ishii et al. 2008; Kadoya et al. 2009; Perrard et al. 2009; Abe et al. 2011; Downing 2012). Data can be collected through observations on a specific flowering plant, a community of plants, or throughout an entire habitat or ecosystem. Observing flowering plants is helpful for collecting foraging, resource use, predator interactions, and sometimes mating or nesting data. Areas where nesting is occurring or via natural or artificial nest sites can provide a focal point to gain observational data on nest provisioning, immature development, and nest success. We do caution that sweep netting of insects can have a large collector bias if careful training is not accomplished prior to implementation. Additionally, the method of sweep netting can be done in many different ways (e.g., specific number of sweeps, targeted sweep netting of plants, etc.) and little research has been done to determine best methods for various hymenopteran groups (Pei et al. 2022).

A common practice in biological control scenarios is the employment of sentinel eggs to monitor parasitism and dispersal rates (Abell et al. 2014; Jennings et al. 2014). Eggs from the target pest are strategically spaced throughout the area of interest. Depending on the pest species, the eggs may be monitored in the field visually for signs of parasitism or may have to be retrieved after a few days and reared in the lab.

Other predatory wasps are often monitored by using baited traps. Baits used can include beer (Porporato et al. 2014), fermented brown sugar (Brown et al. 2014), fruit juice (Monceau et al. 2015), fish or meat (Masciocchi et al. 2013; Monceau et al. 2015) or a combination of these ingredients. Targeted insects that land on the baits are usually collected directly with sweep nets. Other direct collection methods include insect vacuums (Riley & Ciomperlik 1997; Stephen and Rao 2007) and canopy fogging/fumigation (Potts et al. 2005).

PASSIVE TRAPS

Passive trapping involves setting up traps and collecting the contents after a certain amount of time. Depending on the goal of the research, passive traps can be active for short amounts of time (e.g., hours) or utilized for long periods (e.g., weeks). Although some passive traps may be more 'passive' than others (McCravy 2018), all attempt to collect a subset of the bee or wasp fauna from a given area. Some of the more common passive traps used for bee and wasp collection are yellow sticky cards, coloured pan traps, vane traps, Malaise traps, and trap-nests. Below are additional details for some of the commonly used passive traps.

Yellow sticky cards are often chosen for monitoring both naturally occurring and released parasitoid populations or other predators like syrphid flies, and occasionally bees (Longley et al. 1997; Udayagiri et al. 1997; Bruck & Lewis 1998; Burgio and Sommaggio 2007; Zappalà et al. 2012; Larsen et al. 2014; Böckmann et al. 2015; Biella et al. 2022). There are several advantages to using yellow sticky cards for monitoring. Sticky cards are inexpensive, easy to use, and do not require a large time investment for deployment or processing (Larsen et al. 2014). They enable monitoring of multiple species simultaneously (Bruck & Lewis 1998; Udayagiri et al. 1997) and allow for concurrent monitoring of both pest and control species (Bruck & Lewis 1998). The effectiveness of sticky cards and other styles of traps can often be enhanced using lures such as sex pheromones (Zappalà et al. 2012) and other infochemicals (Dias et al. 2014). Although sticky cards catch insects indiscriminately, it is fairly easy to focus on only the wasps that are caught without an increase in processing time. Yellow sticky cards, as opposed to other coloured cards, are particularly attractive to many species of hymenopterans (Udayagiri et al. 1997; Larsen et al. 2014). However, bees and wasps collected with yellow sticky cards can be damaged when removed making identification more difficult (Gill and O'neal 2021).

Coloured pan traps, often called bowl traps, are another commonly used tool to monitor released and naturally occurring bee and wasp populations (e.g., Purcell & Messing 1996; Campbell & Hanula 2007; Bąkowski et al. 2013; Larsen et al. 2014). Pan traps can be made in a variety of sizes and are filled with a liquid such as soapy water that breaks surface tension and drowns attracted insects. Some colours have been shown to be more successful in certain environments; therefore, pan traps are usually deployed in an assortment of colours to maximize the diversity of insects captured (Campbell & Hanula 2007). Yellow, blue, and white are the primary colours that have been used in previous studies (Campbell & Hanula 2007; Geroff et al. 2014). Coloured pan traps have also been utilized within forest canopies; allowing for spatial differences in bee and wasp diversity/abundance to be detected (Nuttman et al. 2011; Campbell et al. 2018b). Like sticky cards, pan traps are inexpensive and can be used in conjunction with lures to enhance detection of the target species while decreasing non-target bycatch. One potential drawback using pan traps is that they are biased towards collecting smaller bees (e.g., *Lasioglossum* Curtis, 1833) and may under sample larger bodied bees (Campbell et al. 2023).

Blue and yellow vane traps are becoming more popular and have been used to monitor bees and wasps (Stephen and Rao 2007; Kimoto et al. 2012; Geroff et al. 2014; Campbell et al. 2023). These traps are advantageous because they are sturdy and can be easily hung at different heights and, in general, can be left for longer periods of time because they withstand weather events better than other passive traps. However, unlike coloured pan and sticky traps, they are expensive, especially if many traps are desired for a project.

Other commonly used tools for monitoring bees and wasps are Malaise traps (Matthews et al. 2000; Campbell and Hanula 2007, Fraser et al. 2008; Frost et al. 2015) which are basically flight intercept traps. Malaise traps are primarily used without any attractant (e.g., color, scent, etc.) and generally collect fewer bees and wasps compared with pan traps (Campbell and Hanula 2007; Bartholomew and Prowell 2005). Additionally, because Malaise traps usually contain no attractant, they are generally considered a more passive trap compared to other passive trapping methods. However, Malaise traps are indiscriminate and higher bycatches can be expected Malaise traps are also not known to collect large numbers of bees or wasps (Campbell and Hanula 2007) and, thus, having the traps active for long periods of time may be necessary to assess hymenopteran communities.

Artificial nest sites (also referred to as trap-nests) are often used to monitor populations of non-native and native wasps and bees (Krombein 1967; Tscharntke et al. 1998; Gamboa et al. 2002; Miller et al. 2013; Graham et al. 2021). They work by providing nesting sites for local bees and/or wasps, sites that can be monitored visually or using traps. Artificial nest sites can be constructed from various materials depending on the objective of the project. Commonly used materials include cut reeds (e.g., bamboo), clay or 'cob' structures, and wooden blocks with pre-drilled holes of varying diameters (Graham et al. 2014; 2015). Artificial nests can be constructed incorporating transparent or translucent materials to allow the researcher to view the developing bees or wasps without opening the nest. For instance, using tubing as 'sleeves' or 'inserts' in holes drilled into wood allows the researcher to remove the tube and view the bee or wasp nest developing within it. It is important to recognize that bees or wasps may show a preference for or avoidance of a particular material; likewise, some materials may cause unintended effects that could impact the bee or wasp development success rate. Bees and wasps have varying developmental times, and it is possible to have multiple generations in a single season. Correspondingly, it is best to monitor these on a weekly or biweekly basis in order to avoid missing data points regarding when the nest was created and when developing bees emerge. However, some bees or wasps may overwinter or go into a longer diapause than others depending on species and climate. The nests containing them may seem inactive or even the individuals dead. Yet, given enough time and the right conditions, individuals may still emerge from the nests. Additionally, tunnel diameter can be a determining factor for many wasps and artificial nest sites could be designed to monitor certain species and with proper guidance can be monitored by citizen scientists (Graham et al. 2014; Campbell et al. 2017b). An obvious bias with trap nests is that they cannot be used to collect ground-nesting bees or wasps and should be used in concert with additional monitoring methods if a complete assessment of hymenopteran communities is desired.

Citizen Science Programs

Citizen science and public surveys have also been used as interesting monitoring approaches and can result in the collection of a large amount of useful data (Masciocchi & Corley 2012). Projects involving volunteers who collect data are becoming more common and allow researchers to collect data over large areas and time (Cohn 2008). Additionally, utilizing citizen scientists allows researchers to reduce costs but also boosts educational and recreational benefits for volunteers (Bonney et al. 2009). Data generated by volunteers have generated a wealth of knowledge allowing researchers to construct species distributions and seasonal cycles (Dickinson et al. 2012). Many of the monitoring methods discussed earlier and in Table 1 can be utilized by volunteers or citizen scientists to assist with survey efforts.

Monitoring programs that involve volunteers have been used to track invasive bumble bee (*Bombus terrestris* (L., 1758)) spread in Japan (Kadoya et al. 2009), to assist with bee surveys (Kremen et al. 2011), and to measure pollination success by weighing fruit and counting seeds from garden crops (Kleinke et al. 2018). Additionally, conservation efforts can also be enhanced with the use of volunteers. For example, Graham et al. (2014) utilized hundreds of volunteers to construct and monitor artificial nesting habitats (e.g., trap-nests) throughout Florida and beyond. This project contributed over 10,000 potential nest sites for bees and wasps, thus, illustrating the potential for gaining conservation benefits with the use of volunteers.

Despite these citizen science successes, there are limitations. For example, in one monitoring program, trained volunteers identified fewer than half of the bees identified by professional researchers, and thus, the utility of bee observational data may be restricted to the detection of community level changes rather than abundance of specific bee species (Kremen et al. 2011). Roy et al. (2016) used 13,000 school children (ages 7-11) to monitor diversity and abundance of bumblebees and received over 26,000 bumblebee sightings but also had a high rate of misidentifications. However, correct insect identifications can increase over time for volunteers if citizen science projects interject collaboration and communication with other volunteers (Deguines et al. 2012, 2018). Thus, citizen science projects can be useful when examining community level patterns (Kremen et al. 2011; Ratnieks et al. 2016). Despite any drawbacks, volunteers involved with bee-related citizen science projects have been greatly motivated to assist simply to learn about bees (Domroese & Johnson 2017; Mason and Arathi 2019). The accuracy and dependability of citizen science data may be enhanced by training volunteers more thoroughly and utilizing high quality photographs or some other line of evidence for observational records to be verified (Roy et al. 2016). Websites and online keys devoted to bee and wasp species' ranges and identifications such as 'Discover Life'(https://www.discoverlife.org/20/q?search=Apoidea) and 'Canadian Journal of Arthropod Identification' (https://cjai.biologicalsurvey.ca/) have utilized many photographs of bees, wasps, and other insects - which are verified by taxonomists and can readily be used by citizen scientists. Although this type of citizen science is not always an organized monitoring effort, these data have elucidated many bee ranges and distributions.

CONCLUSION

Bees and wasps provide critical ecological services within agriculture and urban environments and ecological functions in natural ecosystems. Both bees and wasps contribute to the pollination of the majority of flowering plants and parasitoid/predatory wasps can help control unwanted insect pests. Accurate and replicable monitoring of these beneficial hymenopterans has not been attempted in many areas around the globe and for most bee and wasp species. Nevertheless, monitoring efforts should be a priority due to the potential of declining bee and wasp abundances or ranges in many areas. Not only can population trends over time be detected with solid monitoring efforts, but the extent of non-native bee and wasp dispersal and the potential development of other managed pollinators and biological control agents would be enhanced with monitoring programs. Multiple monitoring methods exist for bees and wasps and can be tailored to the species of interest or the overall goals or research questions of the project. For example, sweep netting bees and wasps off flowering plants and crops can give insight into which insects provide pollination services whereas utilizing passive trapping can allow relative measures of abundance and richness among areas over time. All monitoring methods have biases (e.g., pan traps collect more smaller bees than large bodied bees). Additionally, other certain collecting or monitoring methods may be more appropriate for certain habitats or questions that are being asked. Thus, in many cases, utilizing multiple monitoring/collecting methods will minimize biases and allow for more accurate assessments of hymenopteran statuses. Another criterion that may dictate how hymenopterans are monitored is whether researchers are asking questions that have a regional or specifc scope rather than a broader goal. For instance, if specific questions regarding plant and hymenopteran interactions are of interest, utilizing some sort of sweep netting or direct observational method should be used rather than a passive collecting method. In summary, collecting and/or assessing hymenopterans can be accomplished with a variety of means and with some forethought, a researcher can design a rigorous assessment of hymenopterans based on the research questions.

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AUTHOR CONTRIBUTION

Concept and design JRG, JDE, & JWC, data collection JRG, JWC, AT, & CSS, writing JRG & JWC, contributed edits and approval for publication JDE, CSS, & AT.

DISCLOSURE STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data used to write portions of this article are available as a supplement to this article, see below.

APPENDICES

Additional supporting information may be found in the online version of this article:

Table S1. Literature compilation of wild bees that have been shown to pollinate crops.

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