Chapter 3
Bees: How and Why to Sample Them

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3.1 Introduction

The enormous scientific, conservation, economic, and policy interest in bees have resulted in explosive growth in fieldwork aimed at assessing bee diversity and abundance. For example, a Google Scholar search for the term "pollinator sampling" yielded 14 citations for 2019 already by mid-April, yet there were no matches for the entire year of 2000. Indeed, 14 citations were exceeded only by searching for the years 2000 through 2008 combined. Similarly, for "bee sampling", there were 18 citations that clearly related to field sampling of bees for ecological research but none in 2000, and 18 is exceeded only by summed returns from 2000 through 2004. Despite this exponential growth in data acquisition and analysis, there is little consistency in sampling methodology in current bee population studies. Whenever and wherever methods are compared (e.g. Westphal et al. 2008, Nielsen et al. 2011, Bashir et al. 2013, and many others, only some of which are cited below), species richness and other biodiversity metric differences are found to be present and large. These are all index sampling techniques and always biased (i.e. they are an unknown reflection of the absolute or relative abundance of the bees present at a sampling location). This does not invalidate their use; rather, it requires cautious interpretation of studies presenting, using, and comparing techniques using both judgement of the capture patterns and their context and understanding of life histories.

Investigations of surveying techniques often suffer from the problems of limited geographic scope. In most studies, one or only a small number of locations were used. An exception is Westphal et al. (2008) who used a range of sampling methods at a continental scale. Given that each bee species has its own life history, floral preferences, and behaviours and that different habitats and even locations in the same field always contain different suites, ratios, and abundances of species, it is not

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J. C. Santos, G. W. Fernandes (eds.), *Measuring Arthropod Biodiversity*,
https://doi.org/10.1007/978-3-030-53226-0_3

surprising to find that results from different locations diverge. Any large-scale survey of bees in an area that has not been sampled extensively previously should, if possible, undergo some preliminary trials of techniques (Hall 2018). Numbers and species of bees can be substantially, and at times completely, altered simply by changing the timing of surveys within a day, month, or year and according to the number and placement of traps or whether netting or observation is used. Results also differ among years even with identical sampling methods and timelines. In general, the most useful techniques will be ones that capture large, representative, and repeatable numbers of the target populations across a region; are relatively inexpensive, minimally impacted by variation among observers or collectors; and minimize sample processing time and variability in results associated with weather, location, and site conditions. As the reader will see, this is a tough set of conditions to meet, yet we must do the best we can and err on the side of larger sample sizes to capture and illuminate population changes in face of time and treatment effects amidst an ocean of naturally occurring statistical variance and bias. We must remember that we are measuring populations of short-lived insects not antelope, and variance in sampled abundance on different dates within and on the same (Julian or calendar) dates among years is great. The situation is magnified when we consider sampling for social bees for which dozens of individuals might be sampled in a field survey which, in reality, may represent no more than the output from a single queen.

In this review we first outline the pros and cons of lethal versus non-lethal methods for sampling bees and suggest times when the latter is necessary. Next, we survey the different methods that have been used to sample bees. Because more studies have demonstrated the benefits of coloured bowls over, or in combination with, other methods and there is seemingly greater variability in approaches using them, we discuss this method in more detail than others. Next, we discuss the reasons researchers might want to use different trapping methods depending on the research question posed. While it might seem sensible to discuss "why sample bees" before outlining the methods available, we found it impossible to describe the reasons for sampling bees without reference to the methods. We discuss the pros and cons of each technique. Finally, we suggest what the most important methodological research needs of the bee conservation and ecology community might be in regard to bee sampling.

We do not cover the specialized methods that might apply to a small taxonomic subsample of the bees in an area—such as the use of bait lures for orchid bees (e.g. Janzen et al. 1982). Note though the great success of application of this method for long-term orchid bee sampling (Roubik 2001; LeBuhn et al. 2012) and finding new taxa (e.g. Nemésio 2010). Vertebrate lures, in the form of flesh or fish skin, have been shown to attract some bees, but the taxonomic representation with such methods is low, and the pleasures of sorting through trap samples substantially diminished for anyone without anoia. The number of bee species known to be attracted to carrion, faeces (Baumgartner and Roubik 1989), or tears (Bänziger 2018) is both too small and geographically restricted for consideration in a review of sampling methods, although there remains the possibility of discovering new species with them and we would be thrilled to see any publication with a title such as "Panda tears as a bee sampling method".

Despite the use of commercial yellow and blue sticky cards (a coloured surface covered in a sticky compound) for sampling insects elsewhere in the world, it is little mentioned as a survey technique for bees but has been used to effectively capture bees in New Zealand (Larsen et al. 2014). Notably, the New Zealand study applied their own Tangle-Trap© layer to specially crafted large cards which may have greater ability to attract and hold bees than sticky cards used for pest detection; of possible note is the very reduced bee fauna found on New Zealand (~40 vs. ~1600 species in Australia). Further investigations are warranted as such traps may have particular usefulness when hung from bushes and trees.

Bees also are by-catch found within other insect surveys. Pitfall traps and light traps used to collect nocturnal insects and coloured pheromone-based Universal Moth Traps all have been shown to capture bees, sometimes in significant numbers. In all cases that we are aware of, these captures likely have their root in the colour of the traps (usually white, yellow, or blue) or direct attraction to bright light and thus function to some extent like the vane and bowl traps presented below. Traps such as these are often widely deployed as surveys of agricultural pests and present opportunities for opportunistic sampling (Hatten et al. 2013; Hung et al. 2015; Spears et al. 2016).

We also do not discuss the methods used to analyse bee sampling data nor recent developments in automated DNA barcoding of malaise trap samples (e.g. Yu et al. 2012), eDNA samples (Shokralla et al. 2012; Critescu and Hebert 2018), or genetic estimates of population sizes for which the reviews of Lozier and Zayed (2017) and Lopez-Uribe et al. (2017) should be consulted. Molecular techniques will likely play a larger role in the future.

3.2 Lethal Versus Non-lethal Sampling

While it is sometimes possible to learn how to identify bee species in a restricted area by sight without killing specimens, unless for a restricted taxonomic group (e.g. bumble bees, Fowler et al. 2016), this takes years of experience (and usually still involves lethal subsampling to verify the sight identifications). This approach always fails to completely assess species as there are complexes that are impossible to separate by eye (indeed, some cannot be identified even with a microscope (e.g. Packer et al. 2016)); new species move into an area, and as is the case with many of the smaller bees, identification is difficult (Gibbs 2017). Field identification issues even apply to some of the common bumble bees (e.g. Fowler et al. 2016). Bees can also be uncooperative, individuals may be hidden by vegetation, sit at such an angle as their field characteristics cannot be completely seen or move too quickly. Research questions that require counting the numbers of individuals of each species will also suffer at least some slight bias from double counting individuals. The primary issue is the considerable interindividual (researcher/technician/volunteer) ability to both see and accurately identify the study organisms to finer taxonomic categories. Studies using visual surveys primarily partition the bees only into large,

multispecies groups based on rough approximations of size or colour (Osborne et al. 2008; Broussard et al. 2011; Oberhauser and LeBuhn 2012). An intermediate approach is to capture and photograph the live specimen in a plastic bag or chamber (Anonymous 2015). Sample sizes, though, suffer because of greatly increased handling time, but identification accuracy is higher; issues of observer bias in netting are relevant and discussed later in this chapter, and identification of small bees or taxonomically complex groups also remains an issue.

Mark-release-recapture methods have been used to assess bee population sizes (e.g. Bischoff 2003; Yamomoto et al. 2014). Larsson and Franzén (2008) found good agreement between population sizes estimated with this method and those obtained from transect surveys with visual identification. However, it is simply logistically impossible to apply such methods to a whole community of bees as the accuracy of the estimates depends strongly on capturing, marking, and recapturing a significant proportion of the population over a short enough period of time in which few emergences and deaths have occurred, a high bar to achieve for most researchers (Bischoff 2003).

Removing bees via lethal collection creates the possibility of impacting subsequent generations and this can be a concern in terms of conservation, moral values, and the validity of further years of sampling if the sampling itself greatly impacts the subsequent year's counts. There is only one published evaluation of the effects of repeated sampling: that study demonstrating no impact (Gezon et al. 2015). Multi-year studies have not generally indicated a consistent decline in numbers of specimens in the year after initial sampling. For example, Grixti and Packer (2006) surveyed bees intensively over 2 years. Of the 11 species for which >100 individuals were collected in the first year, 6 were sampled less frequently in the second, while 5 were found more abundantly. In contrast, in the longest-running lethal trapping study, Onuferko et al. (2018) found that two of the three groups of bees they assessed declined over the course of the 10 years of research. However, they concluded that succession of the study site was the cause of the declines which were most marked for taxa that preferred to nest in patches of bare ground.

Numerous reports exist that fluorescent blue vane traps can capture large numbers of bees. Captures often favour larger species and may be particularly efficient at capturing queen *Bombus*; consequently, deploying these traps needs to be done with caution and perhaps scaled back during early spring when queens are flying, at least until there is an understanding of the population impact, which has not been studied (Kimoto et al. 2012; Gibbs et al. 2017).

There are situations where non-destructive sampling is required—such as very small habitat islands or wherever endangered species are found—as well as cases in which lethal sampling may have a large negative impact or be illegal. The senior author has surveyed bees in two locations in Toronto by excising an antenna from each individual, storing it in ethanol, and then releasing the bee. The antennae were then submitted for DNA barcoding. Almost all antennae yielded DNA barcodes; nearest neighbour identifications averaged over 99.5% similarity, and there was 100% agreement between DNA-based and morphological identifications. While this sounds as if it could be damaging to populations (or cruel), female bees were observed flying around with one antenna missing 2 weeks after initial sampling, and males were observed to resume chasing females on flowers immediately upon

release. Nonetheless, there are drawbacks with this approach: (1) not all bee species have DNA barcodes available, (2) some species have indistinguishable barcodes (Gibbs 2017), (3) handling time for antennectomy is somewhat higher than it is for simply putting a collected bee into a killing tube (this latter issue was relatively minor with an average of 46 compared to 27 s, though the difference likely decreases with experience and confidence), and (4) DNA barcoding is likely prohibitively expensive for large-scale surveys at present (although the relative costs of this method to the less obvious costs involved with the accrual of identification expertise remain to be compared and, as just noted, there remain taxa that are currently indistinguishable without molecular methods). Single antennae have also been used to obtain microsatellite data for population genetic research (Oi et al. 2013).

Photographic documentation of free-flying bees can be effective for the more easily identifiable members of a fauna, and it is not surprising that it has been implemented for bumble bees which are abundant, often readily identifiable by colour pattern, and popular with both researchers and the general public. The application of this methodology to citizen science programmes has proven to successfully generate extremely important data. For example, MacPhail et al. (2019) found that a combination of citizen science and museum specimen data demonstrated that a species thought to be at a relatively low risk of extinction was actually critically endangered. On the negative side of the equation, many bees fly away before they can be photographed, are not positioned in the photograph such that their identification marks can be distinguished, and/or are too far away from the camera for a good photograph. Camera surveys (particularly by inexperienced photographers) are highly biased favouring large, easy to identify bees that sit relatively still on flowers that are easy to access. A middle ground for photographic surveys is to capture bees with a net or other live trapping technique and place them in a vial, plastic bag, or squeeze box (Anonymous 2015) and photograph them from multiple angles for identification work prior to releasing. A great deal of time is needed per specimen for these techniques, requiring an enormous effort to achieve similar statistical power as those of lethal surveys.

Trap nests (covered below) could be used as a non-destructive means of sampling, although it typically involves rearing bees in a central location away from the exact site where the traps were placed and we know of no studies that have returned the emerged bees to their point of origin. Consequently, trap nesting is discussed among destructive sampling methods below.

3.3 Sampling Techniques

3.3.1 Netting

Two forms of surveys use nets: spot netting (Fig. 3.1a), where the net is aimed at an individual (or individuals) that the sampler has seen, and sweep netting, whereby a net is methodically swung (usually through flowering vegetation) and many insects (as well as other organisms, plant parts, etc.) are collected.

Netting surveys proportionally capture larger and more visible bees than bowl traps, particularly when conducted by novice netters (Roulston et al. 2007). Nets also undersample the fastest species which more readily elude capture. Of all the methods discussed herein, spot netting is the most biased and least replicable simply because of the different styles and aptitudes of users (or even the same individual at different hours of the same day). Anyone sampling an area at the same time as other collectors has experienced the enormous interindividual differences in specimens and species collected.

Sweeping of vegetation has sometimes been used to sample bees (e.g. MacKay and Knerer 1979; Grixti and Packer 2006), and while it suffers undercounts of rapidly flying species compared to spot netting as well as increased practitioner fatigue, it has the advantage of constraining netting in space and time and requiring little skill. Papers that contrast netting with bowl collecting document differences in the suite of species captured, total numbers captured, and numbers standardized by effort (e.g. Grundel et al. 2011; Bashir et al. 2013; Popic et al. 2013; Spafford and Lortie 2013; Rhoades et al. 2017; Table 3.1). These papers should be consulted as they will indicate general patterns in capture rates by genus and sometimes species.

Another drawback of both types of netting is that they can only be used where nets can reach. They are extremely difficult to deploy among the flowers of tall trees (e.g. from eucalyptus flowers in Australia), in dense vegetation, or where thorny plants are present. Netting is also problematic under conditions of low light intensities, and crepuscular and nocturnal bees are easier to catch in the traps we now discuss or light traps briefly mentioned above.

3.3.2 Malaise and Flight Intercept Traps

Malaise traps (Fig. 3.1b) have been used for more than 80 years to intercept flying insects (Malaise 1937) and can accumulate large numbers of bees (Darling and Packer 1988; Deyrup et al. 2002). They are rarely deployed as the sole or main method to capture bees (see Ngo et al. 2013 and Veiga 2013 for exceptions) as malaise traps are expensive and there can be high trap loss in the presence of large wildlife, less well-behaved humans, or wildfire (Veiga 2013). And although they can be deployed for long periods of time, obtaining sufficient sample sizes requires maintaining multiple traps. Studies that compared malaise samples to bowl traps indicated that they largely caught the same pool of species, but, as is always the case, the ranking of the abundance of species differed (Campbell and Hanula 2007; Geroff et al. 2014). McCravy et al. (2016) found that five malaise traps, as they deployed them, likely sampled less than 1/3 of the species richness present (predicted based upon Chao1 estimates), suggesting that more complete sampling would require an enormous investment in equipment, not to mention the considerable length of time it takes to separate and identify the bees of interest from the often overwhelming amount of insect by-catch. However, as the authors pointed out, the short sampling period involved (1 week) meant that the same number of

Fig. 3.1 Insect sampling methods. (**a**) Eli Wyman spot netting a fast flying bee from above *Nolana* flowers (photograph by Laurence Packer). (**b**) A malaise trap—note the tautness of the material, which is essential for it to be less visible to flying insects (photograph by Gerome Darla-West). (**c**) A pan trap, note that traps of different colour can be seen beneath the top one (photograph by Sam Droege). (**d**) Deep cup traps—dug into the ground somewhat to avoid displacement by wind, they can be left in the field with an appropriate fluid for weeks (see text for details) (photograph Laurence Packer). (**e**) A pan trap deployed in a flowering tree with ballast in a smaller cup inside the larger one, to prevent tipping (see text for details) (photograph Elsa Youngsteadt). (**f**) Two vane traps raised above the ground surface (they can also be dug partly into the ground) (photograph by Gerome Darla-West). (**g**) The trap nest design used by Scott MacIvor in his research (photograph Caroline Tiegs). (**h**) A tube taken from (**i**) and partly opened to permit study of the brood cell contents inside (photograph by Madison Marshall)

Table 3.1 Capture proportions in netting and bowl trapping studies in the Mid-Atlantic states, USA; ~ 1/4 million specimen captures, all bee genera used that had >50 total captures/genus; 2079 netting and 6840 bowl trapping events

Genus	Netting (%)
Agapostemon	6
Calliopsis	7
Melitoma	11
Peponapis	19
Augochlorella	20
Osmia	20
Ptilothrix	22
Lasioglossum	24
Eucera	25
Nomada	30
Hoplitis	31
Ceratina	38
Andrena	42
Melissodes	47
Halictus	50
Habropoda	52
Sphecodes	60
Stelis	67
Anthidium	71
Anthophora	73
Apis	75
Augochloropsis	76
Augochlora	81
Pseudopanurgus	85
Megachile	86
Epeolus	86
Colletes	88
Triepeolus	90
Panurginus	90
Hylaeus	91
Bombus	91
Coelioxys	91
Florilegus	91
Svastra	92
Perdita	92
Xylocopa	93
Anthidiellum	98
Lithurgus	98
Heriades	99
Dieunomia	99
All bees	**44**

Results presented as percentage of captures/genus (standardized by collection event) that were from netting; 50% would indicate that you had an equal chance of catching a member of that genus using bowl traps or swinging a net. Recall, though, that this does not account for the fact that you may be able to put out many more transects of bowls in a day than successful netting events. Nor does it account for the fact that most of the netting events here were by individuals with years of experience

traps would undoubtedly have given more complete sampling if used over a longer time. Bashir et al. (2013) found that 15 bowls caught slightly more bees than did one malaise trap. Campbell and Hanula (2007) indicated that adding colour panels to malaise traps increased captures, and Darling and Packer (1988) and Russo et al. (2011) suggested that fluid-filled coloured trays that can function both as bowl traps and by treating the malaise trap also as a flight intercept trap (see below) increased catches of insects overall.

Trap type, mesh size, and location choices also impact the numbers of bees captured. Finer meshes or coarser fibres are relatively easier for bees to detect and avoid (Darling and Packer 1988), but larger mesh sizes permit the possible escape of the smallest bees. Trap costs are usually high enough that the total number of malaise traps deployed in any project will be low and consequently more geographically restricted than more extensive surveys using netting, bowl, and vane traps. However, they can be particularly useful in infrequently visited remote sites or in dense vegetation. Two large-scale surveys of insects in Colombia and Thailand (comparatively understudied areas for bees) have yielded numerous new species using malaise traps (e.g. Gonzalez 2004; Pauly 2009; Silva and Packer 2016), and malaise traps may be particularly effective at catching nocturnal and crepuscular bees, which, for obvious reasons, are rarely collected using active sampling methods or those that rely upon visual attraction. Notable may be the type series of *Mexalictus verdazulus* Dumesh comprising over 410 specimens, all captured from a single malaise trap; this is the species with the largest number of known specimens in this rarely collected genus of mostly early morning bees; two other species of which were also collected primarily from malaise traps (Dumesh 2013).

Flight intercept traps (FITs) are similar in some ways to malaise traps in that, as their name suggests, they intercept an insect in flight. Usually lacking a roof, they work best for taxa that drop after hitting an obstruction and thus are not as well suited to collecting bees as they are to some other insects, such as beetles, although some undescribed species have been discovered as a result of their use. An advantage of these traps over malaise traps is that they are smaller, more easily deployed and need less space in the field. Ulyshen et al. (2010) found that FITs placed in the canopy of a deciduous forest in Georgia collected more bees than those placed nearer the ground. In most cases these traps provide opportunities to secondarily sample bees when they are deployed in the capture of other insects, particularly if yellow-, blue-, or white-coloured pans are used to collect the catch.

3.3.3 Moericke Pan-Bowl Traps

Given the bright and novel colours of flowers that usually strongly contrast with the green and/or brown backgrounds of nature, it is not surprising that colour can be used to attract bees to traps. Such traps come in the form of pans (Fig. 3.1c), bowls, bottles, deep cups (Fig. 3.1d), tubes, and tubs. For purposes of simplicity, we will talk about them in aggregation as bowl traps, given that this shape and type now are

most often deployed although, as discussed further below, long-term trap deployment works better with deeper cup traps housing propylene glycol than more standard bowl designs.

Bowl traps have been found to successfully capture bees in all the parts of the world where bees are present (Ortiz-Sanchez and Aguirre-Holds 1993; Westphal et al. 2008; Gollan et al. 2011; Popic et al. 2013; Wang et al. 2017) even under local circumstances where bees might only be dispersing through the habitat, such as in salt pans (T. Griswold, pers. comm.), drought conditions in South Africa where bloom was absent (Mayer and Kuhlmann 2004), or large parking lots (S. Droege pers. comm.).

3.3.3.1 The Role of Colour

Bees have a complex visual physiology with many nuances. For example, bees can differentiate ultraviolet (UV) and even iridescent patterns in flowers (Whitney et al. 2009). As a group, flowers exhibit unending diversity of shape, size, colour, pattern, surface structure, and pigmentation with clear behavioural responses of bees to those visual signals (van der Kooi et al. 2019). Yet there are few publications investigating such factors in trap design. Colour has been the primary reported variable in papers looking at bowl trap capture rates, with those studies almost always simply reporting conventional names such as "white", "blue", and "yellow" with no spectral diagrams.

Honey- and bumble bee vision is trichromatic, with peak sensitivities at around 350, 440, and 520–570 nm (Peitsch et al. 1992; Skorupski et al. 2007). These are colours that we perceive (or fail to perceive) as ultraviolet, blue, and green to yellow-green, respectively. Sensitivity decreases to zero over 650 nm, a wavelength we perceive as red. Bowl traps of different colours are universally found to be differentially attractive to bees (e.g. Ortiz-Sanchez and Aguirre-Holds 1993; Campbell and Hanula 2007; Gollan et al. 2011; Vrdoljak and Samways 2011). Heneberg and Bogusch (2014) found that oligolectic bees were more colour-constrained than generalists, not surprisingly preferring bowls of a similar colour to that of their preferred floral hosts, with intraspecific sexual dimorphism in colour preferences. Sircom et al. (2018) found that eusocial bees (they treated only honey and bumble bees as eusocial) had different colour preferences than did other bees.

Researchers normally deploy a combination of blue, white, and yellow bowls to capture as broad a representation of a region's bees as possible. Red is rarely used in bowl trap surveys as most bees do not see that colour (S. Droege, pers. comm. performed two large colour trials in the Eastern United States and found that red bowls caught only a handful of bees, a similar number to that captured with clear bowls). However, that may not be the case in regions where bees are attracted to red or orange flowers. For example, the lead author caught hundreds of a *Macrotera* species in a few hours in red and dark blue traps but few in white and yellow ones, this was a species that commonly visits red and orange cactus flowers.

Sircom et al. (2018) studied the reflectance spectrum of unpainted white bowls as well as two types of yellow- and two types of blue-painted traps, including one fluorescent version of each. The fluorescent and non-fluorescent paints had similar spectra with both yellow paints having high reflectance (over 60%) at all wavelengths over 490 nm but with the fluorescent version having more reflectance than non-fluorescent at wavelengths below 540 nm. In contrast, the blue paints had very low reflectance (<10%) at relevant wavelengths above 430 nm. Both blue shades had higher reflectance than either of the yellow ones below 485 nm and substantially more reflectance (>40%) in the range to which studied bumble bees are most sensitive (420–430 nm) than the yellows (<20%). Perhaps unexpectedly, the plain white bowls had higher reflectance than any of the others below 490 nm and higher reflectance than the blue paints throughout the spectrum. Noted here is the common conflation of fluorescence with UV reflectance. Fluorescent paints take incoming UV light and shift it into the visible spectrum; thus fluorescent yellow will appear brighter yellow to our eyes but will not reflect the UV portion of the spectrum. We are unaware of anyone experimenting with UV reflecting paint for bowl traps although such paints are available in the proper spectral range at least in white (https://www.twilightcoatings.com/collections/coatings-for-horticulture).

Wilson et al. (2016) found that the addition of nectar guides in the form of black lines running to the centre of the bowls in one location in Utah, USA, significantly increased the capture rate, while unpublished studies by K. Graninger in the Washington DC region, USA, documented significantly decreased rates. S. Droege (pers. comm.) found that adding dots and black spots to the sides and bottoms of bowls had similar negative to neutral impacts on capture rates.

In sum, colour of bowl trap strongly influences both the number and species composition of a trap's catch. Switching trap colour across sites or over time will bias the results, at times, severely. Consequently, study designs need to reflect on the long-term repeatability of practitioner's choices of trap and trap colour as well as the continued commercial availability of the colours in the future. It is unclear how subtle, or not so subtle, shifts in reflectance colour's hue, value, or saturation levels impact capture as traps fade through exposure to the sun (even within a single field season) or bowls are replaced by those of another manufacturer.

3.3.3.2 The Role of Size and Shape

Researchers have successfully used traps ranging in size from buckets to 0.75 oz. spit cups. Associations of capture success with size are little studied. At a single site in late summer in Utah, USA, Wilson et al. (2016) compared fluorescent yellow traps of three sizes (20, 8, and 3.5 oz), the largest catching significantly more bees than the other two. However, per volume, the smallest traps caught 3X as many bees as the largest ones. In an unpublished study, S. Droege (pers. comm.) looked at capture rates across seven trap sizes (0.75, 1, 2, 3.25, 4, 6, and 12 oz) from sites from Maine to Tennessee in the United States and found no significant differences in capture rates with size, but a great increase when pro-rated by volume. However,

it is worth noting that very small traps can be difficult to relocate. Given the need to take a trap fluid into the field, in most cases, it would be easiest to use smaller traps sampling over a greater area with the same volume of liquid. Additionally, sets of smaller traps can be held in one hand and set on the ground without having to put the remaining traps and jug of water down. These small differences scale quickly to large logistical rewards when deploying hundreds of traps a day.

We know of no study that has compared capture rates of bowls across different bowl shapes. However, it is possible that the low incline of the sides of the standard eating bowls often used by researchers enables some bees to struggle out (anecdotally, we have found dead bees around the lips of traps in situations where there had been no rainfall that could have partially flushed the specimens from the trap). The first author has found that some of the taxa typically undersampled with standard bowls turn up more frequently in almost vertical-sided coloured drinking cups with propylene glycol as the trapping fluid. Capture rates with white Styrofoam© cups were only 20% of that with similar-sized white smooth plastic cups when deployed in a paired experimental design (S. Droege, pers. comm.).

One variant of bowl traps is the use of painted funnels placed over collection buckets of glycol. These have been successfully deployed for years to capture bees in Southwestern United States deserts where rainfall levels are low; success in wetter environments is more limited (yellow plastic automotive funnels drilled and wired with baling wire into the top opening of one quart paint cans; S. Buchmann, K. Wright pers. comm.).

3.3.3.3 The Role of Preservatives

Soapy water using soap that is odour-free (or as odour-free as possible) is the most commonly used liquid placed in bowl traps. The soap breaks the water's surface tension, such that the bees are more likely to sink as well as hastening the bee's death. Traps without soap capture almost no bees. Additionally, an unpublished paired trap study (S. Droege, pers. comm.), comparing citrus-based dish detergents to those with low or no odour, such as Blue Dawn© or lab detergent, found significantly fewer bees in the citrus-based traps. Adding salt to the water solution is required in instances where osmosis will result in undesirable swelling, particularly of the metasomas of bees, when traps are run for multiple days especially in warm weather, and strong salt solution may be used as a preservative in larger traps left out for longer periods or in instances when rain is likely. It is notable that bees have been successfully processed and identified from traps using only soapy water after two weeks in summer conditions despite the strong smell of decomposition.

Propylene glycol is a useful fluid for long-term passive trap use, largely because of its very low evaporation rates, non-toxicity, and preservative nature (Thomas 2008). Ethylene glycol—standard antifreeze—is also used but is poisonous to vertebrates and difficult to find in unadulterated forms. Propylene glycol is a common food additive and can be obtained through chemical companies, veterinary supply houses, plumbing supply houses (often dyed blue), and food grade from apothecary

and food supply distributors or in dilute form as RV or non-toxic antifreeze (note, these mixes are often of unknown dilution, containing other additives, and usually coloured red). Thomas et al. (2001) found that a solution of 10% propylene glycol in water worked well when traps were serviced weekly (albeit for surveying fruit flies) and a 50:50 mixture worked well in rainy areas with periodic topping off with 100% (S. Droege, pers. comm.). In dry environments the water fraction will often quickly evaporate, and pure to nearly pure glycol needs to be used if longer periods between checks are expected. In all cases a small amount of non-citrus detergent is needed to cut down surface tension (water and propylene glycol have roughly the same surface tension, although the senior author has found pure propylene glycol to work perfectly well without soap in desert habitats). Other researchers have used saturated salt or sodium benzoate as preservatives in water, though these solutions are uncommonly used.

The effect of different trapping fluids has been little studied, but significant differences in capture rates were found in a New Zealand study (Larsen et al. 2014) as well as one from Canada (Deville and Wheeler 1998). Notably, both studies used commercial engine coolant mixes as well as commercial detergents both containing multiple compounds that could also impact capture rates beyond the primary fluid. As mentioned previously, citrus-based dish detergents added to water were found to significantly impact capture rates compared to laboratory detergents.

The darker the pan trap colour, the hotter the fluid gets and the greater the rate of evaporation. But even traps that have lost all their glycol have yielded identifiable material, albeit not in the best condition, even in windy places where the dried insects have been blown around inside the trap. For example, during a field trip in 2015, the senior author placed numerous bowl traps with propylene glycol along roadsides in northern Chile and left them out for months. Even a trap left out 6 months, run over by a vehicle, with all glycol gone, yielded 50 bees of 5 species, including one extremely rare one.

Following Frank Parker's discovery of large numbers of bees flying around vegetation where bus passengers made restroom stops, he developed a technique of spraying urine over vegetation as an attractant for bees. Upon learning this both authors have compared bowl trap catches with soapy water compared to soapy urine. Fortunately, the latter collected somewhat fewer bees than the former, and further use of bodily fluids seems unwarranted.

3.3.3.4 The Role of Height

Floral height, flight patterns of bees, vegetation density, size and sex of bee, and whether an individual is foraging, nest site searching, or dispersing through a habitat all likely influence the numbers and species composition of bees captured in traps at different heights. Canopy and tree or shrub feeding species are intuitively less likely to be caught in ground-level traps (Gonçalves and Brandão 2008; Gonçalves et al. 2012). Thick ground-level vegetation density also decreases capture rates (Geroff et al. 2014; see also Sheffield et al. 2013). An unpublished study

by B. Goggins (S. Droege, pers. comm.) found that in fields with thick vegetation, bowls placed on the ground surrounded by this undisturbed vegetation captured significantly fewer bees when paired with traps in either 0.5-m-wide mown strips or bowls elevated to nestle even with the tops of the vegetation (~0.5 m). Given similar widespread anecdotal evidence, it is clear that moving bowl traps to the canopy level of thick vegetation or creating openings or paths for bowl placement is important. If you can't see the bowls, then bees can't either.

No standards have emerged on how to suspend traps within trees or above vegetation; sometimes elevated traps have a greater number of bees compared to ground traps, other times, the opposite. For some examples, in Ghana, bowl traps raised high into jungle canopy openings were successful in collecting large numbers of mostly meliponine bees (Nuttman et al. 2011). Dave Roubik (pers. comm.) found that bowl traps elevated in Panama along the superstructure of a canopy crane did not catch any of the orchid and stingless bees that were commonly found foraging in the canopy in that region's tropical forests. Suspended open white buckets with clear vanes above them caught large numbers of bees in the canopy of a US, Georgia, bottomland forest, throughout the season, even when flowering had ceased (Ulyshen et al. 2010). Bowl traps suspended from trees in the mid-story of oak-hickory forests in western North Carolina, USA, also showed higher capture rates in the elevated traps than ground traps when sampled throughout the year (Campbell et al. 2018). However, when blue vane traps were used rather than bowl type traps, in the interior of deciduous forests in Massachusetts, USA, and deployed continuously from early spring before trees flowered through the fall, the reverse was found to be the case with more bees caught on the forest floor (J. Milam 2018, unpublished report). Painted open cups suspended in deciduous forests and apple trees in New York, USA, in the spring captured similar numbers of bees in the canopy when compared to the ground (K. Urban-Mead, pers. comm.).

Declining catch rates also have been observed when bowl traps were elevated significantly above the surrounding vegetation. When traps are placed below blooming trees, they can capture almost nothing, as in most closed canopy tropical forests (Gonçalves and Brandão 2008; Gonçalves et al. 2012) and, similarly, in closed canopy deciduous forests after spring canopy closure (Ulyshen et al. 2010; S. Droege, pers. comm.); or traps will capture bee species associated with the blooming herbaceous cover rather than the canopy (Cane et al. 2000). However, K. Urban-Mead (pers. comm.) noted that species composition in New York, USA, deciduous forests was similar between traps in canopy, subcanopy, and on the ground. Finally, there is some evidence that the species composition of bees caught in blooming *Acer* and *Cercis* trees, in North Carolina, USA, in traps is similar to those collected directly from those same flowers using a net (E. Youngsteadt, pers. comm.).

Physically, individual traps (buckets, bowls, cups) can be hung from their rims either singly or in sets immediately below each other (Ulyshen et al. 2010; K. Urban-Mead, pers. comm.), from a platform of stiff construction wire (Campbell et al. 2018), or from both ends of a string that is draped through the branches (E. Youngsteadt, pers. comm.). E. Youngsteadt (pers. comm.) created a stable trap that works when suspended from above by placing a coloured soufflé cup inside a

snuggly fitting drinking cup that had damp sand lining the bottom of the drinking cup for trap stability in high wind (Fig. 3.1e). There appears to be a general trend that elevated traps, no matter what the type, capture, on average, larger bees.

3.3.3.5 Context

The number and species composition of flowers have biasing impacts on abundance and species composition of bees captured in bowl trap setups. Published and casual observations indicate that locally abundant and attractive floral resources appear to decrease captures in bowls, with capture rates potentially increasing during periods of drought, following cutting of blooming plants or following a decrease or cessation of seasonal flowering (Cane et al. 2000; Baum and Wallen 2011). Nonetheless, bowl use in unusually densely flowering periods in some deserts and bottomland forests (S. Droege, pers. comm.) has still yielded large numbers of interesting species (e.g. Praz and Packer 2014). Much of the impact of capture rates and degree of bloom may simply have to do with bowls either being placed or not being placed at the level of the flowers.

Narrowly oligolectic bees are often caught in low numbers in bowls (Heneberg and Bogusch 2014), though there are notable exceptions to this [e.g. *Andrena erigeniae* Robertson, *A. violae* Robertson, and *Ptilothrix bombiformis* (Cresson) in eastern North America]. It may be that narrowly specific floral cues are missing from existing traps, or again, it may be that bowls are not placed at the flowering level of the plants, which for oligolectic species in North America tends to be high because they are associated most often with perennials and shrubs (Fowler 2016).

One issue that seems not to have been assessed is the difference in contrast between a bowl and its background, which will vary among localities as well as over time at the same site. Sheffield et al. (2013) controlled for this by placing traps within a grey plastic base that was substantially wider than the bowl itself. This kind of design also decreases the impact of vegetation growth, though it does increase cost, weight, and awkwardness when setting out traps and takes additional time to deploy and retrieve. Its impact on capture rates remains untested.

Bowl traps are usually deployed as part of a multicolour transect with all captures from a transect pooled to create a single sample. Tracking captures by individual bowl or colour is time-consuming and, given the variability and low numbers of bees/bowl, perhaps not greatly informative. Bowls placed too close together will compete with one another for captures; one study in Maryland, USA, using only white bowls, documented that bowls should be placed 3–5 m apart to prevent competition effects (Droege et al. 2010). Trap distances much farther than 10 m can lead to difficulties in re-finding the traps unless they are individually flagged. Shapiro et al. (2014) performed statistical analyses that suggested that a single deployment of 30 bowl traps is likely sufficient to sample the richness of bees along an individual transect. Information in LeBuhn et al. (2012) presents estimates of capture variability for bowl traps and other bee-monitoring techniques, permitting calculations of the required sample sizes under different statistical tests.

3.3.4 Vane Traps

Vane traps have an orthogonal pair of coloured vertical vanes placed over a funnel leading to a collection bucket (Fig. 3.1f). They were first recognized as being useful for sampling bees by Stephen and Rao (2005) in an agricultural setting and subsequently widely deployed in more natural habitats (e.g. Kimoto et al. 2012). The container may remain empty for short-term non-lethal capture or used with dry insecticide (such as dichlorvos strips) or partially filled with soapy water (with or without salt, formalin, and sodium benzoate) or other preservatives such as propylene glycol. The bees are likely attracted to the brightly coloured vanes and funnel, perhaps also to the container beneath, which in some designs is bright yellow. Blue and yellow vanes have been used, with blue substantially outperforming yellow. For example, Hall (2018) found that blue vanes caught six times as many bees as yellow ones (Hall's figure 1b suggests his yellow may have been closer to orange). However, the blue vanes available are generally somewhat translucent, whereas the yellow is commonly entirely opaque (although Hall's were translucent), and so colour per se in most studies of vane traps is likely confounded with differences in hue, value, and saturation. Joshi et al. (2015) found that blue vane traps captured more bees than yellow as well as all three standard colours of bowls in apple orchards on a per trap basis. Although the vanes were placed approximately 0.5 m higher than the bowls (which were also placed above the ground surface), there is likely confounding of trap type with proximity to the apple blossom. These authors also presented data on the reflectance patterns of their traps and showed that there were differences in the spectra between traps at the end of a field season and traps at the beginning: after use, the blue vane traps reflected somewhat less in the blue range of the spectrum and the yellow reflected somewhat more (see their Figs. 8a, b). In a study of fruit tree crop pollination, Gibbs et al. (2017) found that blue vane traps placed in the canopy primarily collected species that were not observed visiting the fruit tree flowers. As noted previously, numbers of captures can be changed by simply changing the number and placement of traps.

Unfortunately, with the more commonly used design, the blue funnel which screws into the trap base deteriorates after a few months in bright sunshine (L. Packer, unpublished observations) limiting the duration that the traps can be used. There is a need for testing a variety of paints, colours, and opacities in vane traps as well as improving their structural integrity for long-term deployment.

When partially filled with propylene glycol, these traps can be left outside for months at a time especially in arid areas. Partial embedding into the ground is needed (half of the bucket depth seems sufficient) to prevent displacement of the trap by wind. This permits extensive sampling in areas where bees are so rare that netting and traps that require more frequent visits are an inefficient use of a melittologist's time. For example, Packer and Graham (2020) found two specimens of a new species of cuckoo bee in a vane trap that had been left in an extremely arid part of Chile for over 3 months. At sites where rainfall might dilute the preservative and/or result in overflow, a clear transparent lid can be concocted to reduce the impact

of precipitation. The senior author has had trouble with long-term deployment of vane traps, partially dug into the ground, as a result of rodents gaining access to the inside of the container through the space between the vanes and the funnel and meeting their demise. Bees are still extractable from this situation, although one would likely give the task of processing them to someone else. This problem was eliminated by pushing two heated nails at right angles through the funnel effectively halving the space through which the rodents could gain access (Postlethwaite, pers. comm.).

3.3.5 Trap Nesting

Trap nests are constructions that replicate the kinds of narrow tunnels that cavity-nesting bees most commonly use (MacIvor 2017). They have been employed with a wide range of substrates, dimensions, housing, and height. The most common tube types are either naturally occurring hollow- or soft-centred plant materials, such as *Phragmites*, *Sambucus*, or *Rubus* stems, or cardboard tubes or paper drinking straws. Care has to be taken to ensure that the design does not permit natural enemies to gain access to the entire broods of bees: the senior author's first attempt at trap-nesting bees (with drinking straws in a tin can) resulted in all tubes being occupied by *Osmia bicornis* (L.) but no surviving brood due to 100% parasitism, likely by *Monodontomerus obscurus* Westwood (see also Krunić et al. 2005). Trap nest designs have become extremely popular as a way of making people's homes more "bee-friendly", but such "bee hotels" (MacIvor and Packer 2015) are often of remarkably poor design (some likely acting as sinks rather than sources for populations), and even well-designed ones (Fig. 3.1g, h) will catch many wasps (not in itself a bad thing) and large numbers of non-native species (which probably is) (MacIvor and Packer 2015). Given the popularity of "bee hotels" among the general public, obtaining concrete data on the efficacy of different designs in augmenting native bee populations in different habitats should be considered a high research priority.

While the proportion of bees that use hollow cylinders as a nesting site is taxonomically and numerically restricted, a comparison of multiple methods of sampling bees found that the ecological patterns obtained with such smaller datasets generally paralleled those of more extensive ones and that trap nests can find bees that were undetected with other methods—in this case netting along transects, observation plots, and bowls (Westphal et al. 2008). A distinct advantage of trap nesting is that it permits far more detailed ecological and behavioural analyses than any of the other methods: rates of mortality, fecundity, and parasitism are all obtainable (e.g. Jayasingh and Freeman 1980). It is also relatively easy to place recording equipment at the entrance(s) to determine activity patterns of nesting females; within-nest behaviours can be monitored with designs that incorporate a transparent side to the nest; pollen is more readily identified from trap nests than from ground nests (MacIvor et al. 2014); natural enemy associations and behaviours can be documented (MacIvor and Packer 2015); and sound recordings can be made (Peebles 2011).

Trap nests can be more readily placed at different heights in a forested area than bowls and other fluid-containing trapping methods. Stangler et al. (2016) found that traps 10 m from the ground caught significantly fewer bees than those at 2 m or those at 20 m. Additionally, the two more elevated sets, while capturing fewer species, had higher diversity indices than those close to the ground. Unsurprisingly, different species were sampled with different frequencies at different heights.

There are a few bees that nest under stones and these can be "trap-nested" by placing suitable objects in the environment for them to nest under. Sheffield et al. (2015) placed terracotta saucers into the environment where *Osmia inermis* (Zetterstedt) was common and found that 10% of the artificial nest sites were occupied. Similar approaches could be taken to sample bees that nest in empty snail shells (e.g. *Osmia conjuncta* (Cresson) (Richards et al. 2011).

Emergence traps placed over patches of ground are something of an analogue of trap nests for sampling of the difficult-to-detect ground-nesting bees (Sardiñas and Kremen 2014; Pane and Harmon-Threatt 2017). They do not have the behavioural/ecological data collection advantages of the trap nests noted above, but they do not influence the make-up of the local bee community by adding nest sites suitable for only a portion of the local fauna. Capture rates are relatively low, thus requiring higher trap numbers and/or greater sampling intensity and to get phenological data they need to be checked frequently; sampling strategies such as working in uneven terrain or heavy vegetation, moving traps within a year to maximize trap captures, and reducing trap costs while increasing sampling footprint per trap and trap placement within a study site would be useful avenues of research (Pane and Harmon-Threatt 2017). Such traps will be susceptible to similar sources of damage as are malaise traps.

3.4 Additional Considerations

Sampling continuously throughout the bee flying season evens out the vagaries of intra-annual phenology and punctuated sampling. Several of the trap designs (e.g. vane, larger bowl/cup traps, and malaise traps, all usually filled with propylene glycol) are amenable to continuous trapping. Colour fading, dust accumulation, and dilution or overaccumulation of specimens require periodic repainting, replacement, and specimen removal for the trap to remain effective (Joshi et al. 2015). Similarly, trap nests can be left up for the entire year. Here the decreased availability of unused holes may cause a bias against later emerging species; this can be avoided by replacing nest tubes as they are completed, though this is more time-consuming.

Punctuated sampling is the norm in most studies, and given the rather short activity periods of many solitary bees, extended activity of most eusocial bees, the between year shifts in emergence dates, and the vagaries of weather, this temporal sampling strategy introduces a variance and bias component to the resulting counts that are generally not acknowledged. Given that most bees are protandrous, reporting the sex of all individuals sampled could indicate whether 1 year's sampling was early (male biased) or late (more female biased) in the season for each species.

Given that the amount of mandibular and wing wear increases monotonically (though not necessarily linearly, Foster and Cartar 2011) as a bee ages, comparisons of such relative age measures among years may prove informative. An even better approach would be to survey bees at least twice a week and then subsample the data to investigate cut-offs in sampling frequency for given sampling accumulation goals. This would also permit sampling frequency impacts on the statistical power to detect changes in population and biodiversity statistical parameters.

Bee surveys are often sponsored or undertaken by those interested in the conservation of insects; thus the amount of non-target by-catch of lethal techniques will be of concern. Other flower-using insects (e.g. wasps, flies, beetles) are attracted to and expire in coloured bowl and vane traps, while malaise traps capture an even larger range of flying insects. Studies optimized for bees often have opportunities to look at parallel results for other taxonomic groups, though identification can be problematic. Furthermore, splitting the by-catch among other insect researchers and taxonomists often results in range expansions and/or the discovery of new taxa (Spears and Ramirez 2015).

A disadvantage of passive trapping methods is that they generally do not permit assessment of ecological relationships, especially floral ones, and although a full scopa of pollen may still provide identifiable host plant material, no passive method is likely to prevent cross contamination of pollen among specimens other than via dissection of the gut.

3.5 Why Sample Bees?

All research questions related to the world's most important pollinators require some form of sampling, and fundamental to all of biology is the taxonomic research that results in species descriptions and identification guides. Although this is not something that is normally considered in treatments of sampling methods, it is clearly an essential component of bee biodiversity research, and so we treat taxonomic reasons for sampling before the ecological ones.

3.5.1 Sampling for Taxonomy, Systematics and Biogeography

Each of these research areas requires catching as much of the diversity and richness of a regional bee fauna as possible and, especially for biogeography, from across as many locations as possible. A good general approach here is to combine spot netting with various passive sampling techniques. As most bees do not start flying until some hours after sunrise and cease activity well before sunset, passive traps can be put out before, and brought back in after, the best times for netting, with longer-term deployment possible if the researcher remains in the region for several days or can return to it later.

Passive trapping is a good way to obtain research material from difficult-to-access localities, and propylene glycol allows traps to be in operation for weeks to months especially when deployed in deeper traps, such as those from painted drinking cups or vane traps. This makes good use of fieldtrip time as traps can be placed out over large areas at the beginning of a trip and brought back in on the way back or even on a subsequent fieldtrip (Packer et al. 2017).

Molecular approaches to taxonomy require material preserved in a way that permits DNA amplification. Currently, a greater range of collection and preservation techniques are acceptable compared to those of early allozyme techniques (e.g. Packer et al. 2005) which generally required the use of liquid nitrogen in the field. More recently, strong ethanol (usually 96%) has been used for molecular grade specimen storage and works best if the pickled materials can be stored in a cold and dark place. However, genomic methods are increasingly efficient at the extraction of ultra-conserved elements and other suites of loci even from old pinned specimens and/or other materials containing degraded nucleic acids (Zhang et al. 2019). For those wishing to perform transcriptomic research, DNeasy can preserve fresh net-caught material appropriately. Nuclear and mitochondrial DNA have been successfully sequenced from specimens collected into propylene glycol in traps left out for weeks in bright sunshine and high daytime peak temperatures (Praz and Packer 2014).

3.5.2 Sampling for Conservation Biology

Lethal sampling for conservation is something of an oxymoron. However, in most cases, it is far more efficient than alternative non-lethal techniques and much more likely to result in appropriately high sample sizes necessary for surveying insect groups, increase detection of rare species, and permit the identification and DNA analysis of difficult to identify species. Citizen scientist initiatives using non-destructive sampling via photography are increasingly used to document the relative abundance and, more convincingly, the distributional range of bumble bees (e.g. MacPhail et al. 2019). These initiatives are extremely useful given that the personnel involved would otherwise not sample bees at all. However, given the difficulty associated with species-level identification of most bee species in most parts of the world, photographic approaches would not work well even in relatively depauperate faunas, except for a small proportion of the taxa.

3.5.3 Sampling for Biodiversity Statistics/ Ecological Assessment

The considerable growth in interest in the ecosystem services provided by wild bees (e.g. Grab et al. 2019) has resulted in exponential growth in the survey efforts aimed at assessing wild bee biodiversity. Unfortunately, as outlined above, the diversity of

approaches that have been used makes comparison among studies often difficult. Consistency in deployment of techniques across the temporal or spatial extent of a study or in comparison to other studies is critical for replicable ecological research. Small variations in the type, colour, or timing of placement of traps can have significant impacts on the numbers, size, species composition, etc. of the bees collected. Even minor deviations from consistency can create unwanted and usually uncorrectable biases. Researchers should be aware that if they want people to replicate their studies in the future, they need to clearly document all aspects of the types, dimensions, materials, colour signatures, and placement of their traps. A problem arises when specific trap types become unavailable due to changes in manufacturing procedures or cancellation of a product line. Exactly this happened for Packer when Solo stopped making the "bright blue" coloured 12 ounce dinner bowls which had been much more successful at collecting bees in the Atacama Desert than their nearest other blue shade, which is darker. This can be overcome by painting bowls using purchased pigments that are likely to be available more consistently over time (Anonymous 2015) or to not degrade during long-term storage. Similarly, traps that are used for long periods in bright sunshine will suffer some bleaching or loss of gloss, and, although this has been formally assessed only for vane traps (Joshi et al. 2015), it is abundantly obvious under extended field conditions with coloured bowls (whether painted or not). This can happen within a season after repeated or long-term use. Traps should be replaced or repainted regularly with varying frequencies depending on the amount of exposure to the sun or abrasion by wind. All replacements would need to be documented in detail.

Standardization is possible with all described methods. Because visual identification is a learned skill, it is perhaps the least amenable to formal standardization; although there can be little doubt that the development of instantaneous recognition skills is possible, we are aware of no studies where multiple observers have simultaneously assessed the same individual bees in the field to permit validation (for a more detailed and wider ranging assessment of taxonomic validation, see Packer et al. 2018) nor tracked how observer skill changes with time. Photographic methods can provide accurate identifications and have the added advantage of being verifiable through inspection by additional personnel (e.g. bumblebeewatch https://www.bumblebeewatch.org/ and MacPhail et al. 2019), though most bees spotted while in the field cannot be photographed, photos are often unidentifiable, and pictures are skewed towards large, distinctive species. Experts can disagree over an identification even with specimens in hand. For example, Stribling et al. (2008) found 21% identification disagreement among experts with microscopic identifications of freshwater arthropods and that only 1/3 of the disagreements were resolved through further discussion among identifications by the experts. Visual and photographic techniques are usually only appropriate for a small proportion of any local fauna.

Sweep netting can be standardized in terms of the type and size of the net, the extent of sampling in terms of area, and/or the duration of net deployment. However, it is not so easy to standardize the style with which the net is used with variables such as speed of movement, force with which the net hits the vegetation, and the

number of sweeps per unit area or unit of time. Gravel (2010) found that differences in sweep net catches among individuals could cause similarity indices to vary substantially such that one collector's sample clustered with the wrong year of data collection. Arm length, and perhaps even brightness or colour pattern of clothing, may have an impact on what an individual catches.

Passive sampling techniques are more readily standardized. Bowl, vane, and malaise traps as well as trap nests can each be made to the same design, deployed in the same number, and set in similar positions for similar durations. Care must be taken with malaise traps, even of identical mesh and colour, as the degree of tautness of the mesh impacts the number and composition of the captures. As mentioned in previous sections, vegetation density has an impact on captures, so in long-term sites, vegetation control or bowl platforms may be necessary (Sheffield et al. 2013). Subtle differences in the way different people put out identical traps may also influence the samples obtained, but this has not been investigated.

3.6 Comparisons among Methods

There is a burgeoning literature of comparisons of sampling techniques (Prado et al. 2017). Most suffer from two problems. 1. The true population size and composition of the bees in the study are almost always unknown. 2. Corrections cannot or are not made to account for sampling effort. Given that the actual number of individuals and bee species are almost always unknowable, it will always be unclear how well a bee-surveying technique acts as an index. Comparisons are useful, but raw totals can easily be changed by simply altering the amount of trapping effort for an individual technique (e.g. time used to net or observe, number of traps deployed, number of locations, number of days or hours within a day). Proportional comparisons are more useful, and such comparisons can and would be indicative of patterns of capture probability across species and genera. If sampling effort is documented, then such studies are also a good indication of the time and money required per individual capture of a target group. Comparative trials are an important part of starting bee surveys in previously unexplored biogeographic regions.

For example, S. Droege (pers. comm.) recently looked at capture proportions in netting and bowl trapping studies in the Mid-Atlantic states, USA. Using a pool of roughly 1/4 million records, he looked at all bee genera with 50 or more total captures across 2079 netting and 6840 bowl trapping events (Table 3.1). An event was defined as a collection of bees netted or captured in a bowl transect from a date and location. Captures of bees for a genus for either netting or bowls were roughly corrected for effort by dividing captures by the total number of collection events for netting or bowls. These results could have been different had the number of bowls put out in an individual collection event or the amount of time spent netting been different; as such, this only represents a comparison of capture rates of given

standard procedures. Major differences in capture rates, however, were clear, as illustrated in Table 3.1, with no clear bee taxonomic, size, or social structure associations apparent. With these results in hand, one might choose different survey techniques for *Agapostemon* vs. *Bombus*, yet it is unclear, despite extremely large sample sizes, that netting or bowl trapping is a better index to the actual proportions of bees in the Mid-Atlantic simply because we have no way of knowing what that true value might be. What is apparent, though, is that the best strategy is to use both techniques if the objective is to capture the greatest number of species.

3.7 Future Research Needs

Here we suggest what may be the most urgent areas for additional research effort:

1. Comparisons among methods in a standardized fashion in all the world's major biomes, to illuminate relative capture probabilities for different groups (both taxonomic and functional guild) of bees in different major habitats.
2. Assessment of impacts of variation of trap colours on capture rates, including shades of colours (e.g. shades of blue, shades of yellow), fluorescent vs. non-fluorescent colours, metallic, iridescent, and UV.
3. Direct comparisons among pairs or groups of observers/collectors in skill-based techniques such as spot netting, photography, and in-field observation-based identifications.
4. Assessments of lethal sampling frequency and intensity on subsequent year's populations of bees and the impact of such sampling on the calculation of population change.
5. Assessment of within and between season deterioration of trap colour and visibility—whether due to vegetation changes in the sampled habitat or the visual properties of the traps themselves.
6. Creation of a repository for pictures of traps and their colour spectra both before and after periods of deployment.
7. Impacts of supplied trap nests on bee density, species composition, assessment of bee health, and bee population change.

Acknowledgements We would like to acknowledge all our students, technical assistants, and colleagues who contributed and published information on monitoring, trap design, and sampling. Additionally, we also appreciate the tolerance and support of our families at home. We are particularly grateful to S. Droege for permission to cite many examples of his unpublished research findings and for discussions about the subject. We are grateful to Sam Droege, Madison Marshall, Caroline Tiegs, and Elsa Youngsteadt for permission to use their photographs in Fig. 3.1, to Scott MacIvor for arranging for us to receive some images, and to Liam Graham for amalgamating the photographs into one figure. The senior author's research has been made possible by funding from a wide range of sources, in particular from the Natural Sciences and Engineering Research Council of Canada and the National Geographic Society.

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