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Published Version

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To link to this article DOI: http://dx.doi.org/10.1111/icad.12557

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ORIGINAL ARTICLE

Inventorying and monitoring crop pollinating bees: Evaluating the effectiveness of common sampling methods

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Abstract

1. Wild bees provide a critical ecosystem service by pollinating globally important crops. Documented bee declines, notably in agricultural landscapes, therefore threaten future food security. Yet, evaluations of methods to inventory bees are rarely carried out in different crops or focus specifically upon crop pollinating species.

2. We utilise standardised field datasets to elucidate differences in the capacity of transect walks, observation plots and pan traps to sample wild bee pollinator communities in four contrasting crops. Our results indicate that individual survey methods detect different components of crop pollinator communities, with guild and body size potentially important causal factors behind these differences.

3. Transects detected half or less of the total potential pollinator community in three of our four study crops. Whilst transects were the most efficient method for sampling bumblebees, they often missed smaller solitary species, which were most efficiently sampled by yellow pan traps.

4. Crop type is likely an important determinant of the most suitable survey methods to sample bee pollinator communities. Whilst transects alone are sufficient in crops pollinated predominantly by bumblebees, pan traps, and potentially observation plots, may be an important addition in some crops where smaller solitary bee species are potentially important pollinators.

5. Our results indicate that the most efficient methods to sample bee species in agricultural landscapes are dependent upon crop type and pollinator community composition. We use our findings to make a set of recommendations on the inventorying and monitoring of bee pollinator crop communities that can inform regional and national monitoring programmes.

KEYWORDS
crops, observation plots, pan traps, pollinator monitoring, transect walks, wild bees

INTRODUCTION

Wild bees provide a critical ecosystem service by pollinating the majority of global food crops that are essential for human health (Potts et al., 2016). Furthermore, agriculture is becoming increasingly pollinator dependent due to a growing, global population driving increased demand for entomophilous crops (Aizen et al., 2008; Science for Environment Policy, 2020). Diverse assemblages of wild bee species

have been shown to increase yield quantity, quality and stability of insect-pollinated crops (Bartomeus et al., 2014; Garibaldi et al., 2011). Furthermore, it is now well established that, in many parts of the world, this pollination service cannot be reliably replaced by honeybees (Breeze et al., 2014; Garibaldi et al., 2013). As such documented declines in wild bees, notably in agricultural landscapes (Potts et al., 2010), and evidence of insufficient pollination limiting crop production (Garratt et al., 2014; Reilly et al., 2020), raise serious concerns about future food security. There are now growing calls for the urgent implementation of long-term schemes to systematically inventory and monitor crop pollinator populations (Potts et al., 2021; Woodard et al., 2021).

Despite the protection of pollinators rising as a policy priority (Breeze et al., 2021; Gonzalez et al., 2020), response actions have failed to keep pace with the threats facing the services they provide (Potts et al., 2016). Currently, our understanding of trends in wild pollinator populations is limited, being primarily based upon ad-hoc records (Powney et al., 2019). These records are rarely collected in intensively cultivated agricultural landscapes (Garratt et al., 2019), meaning the status of pollinating insects in crop areas is a particular evidence gap (Scherber et al., 2019). Additionally, emerging monitoring schemes in agricultural landscapes are currently focused upon the entire species community (Carvell et al., 2017; O'Connor et al., 2019), rather than specifically upon crop pollinators. Growing evidence suggests that individual crops have different pollinator communities (Hutchinson et al., 2021; Kleijn et al., 2015). The identification and monitoring of crop flower visitors in agricultural settings is essential to inform management that can improve and sustain crop production (Garratt et al., 2016; Hutchinson et al., 2021).

Whilst progress has been made in identifying the specific bee pollinators of individual crops (Hutchinson et al., 2021), the focus has been primarily upon common and dominant flower visitors (Kleijn et al., 2015), which also tend to be the main beneficiaries of agri-environment measures (Senapathi et al., 2015). Yet diverse communities, which can include rare species, are important for sustainable crop pollination service, due to species turnover (Winfree et al., 2018). Furthermore, supporting biodiverse crop pollinator communities is imperative to maintain ecosystem service resilience in the face of substantial predicted environmental changes (Oliver et al., 2015). A significant obstacle for establishing schemes to survey and monitor pollinating insects has been concern over the cost of such an endeavour (Science for Environment Policy, 2020; Senapathi et al., 2015). Recent evidence, however, demonstrates that even the most expensive professional-run monitoring schemes are cost-effective when compared to the economic consequences of further pollinator losses (Breeze et al., 2021) and that farmers, agronomists and citizen scientists are able and willing to implement pollinator surveys (Garratt et al., 2019).

Two broad categories of methods exist to sample pollinators; active (observation plots, transect walks) and passive (e.g. pan traps, trap nests) (Westphal et al., 2008). Active methods can assess flower visitors and visitation rates (Garibaldi et al., 2019), but results are contingent upon recorder skill (Krahner et al., 2021). Passive methods do not provide information on floral associations (Westphal et al., 2008), but are independent of surveyor experience. Whilst many studies have evaluated different sampling techniques, results can be conflicting, and may be

contingent upon the study system being tested. For example, pollinator size and trap colour may influence the efficacy of different sampling methods (Krahner et al., 2021). Furthermore, assessments of sampling techniques are predominantly carried out in non-crop areas (McCravy, 2018), or do not focus specifically on crop habitats, nor account for the impacts of crop type on results. Identifying the most appropriate survey methods for wild bees in agricultural settings is essential to ensure a representative sample of crop pollinator communities (Templ et al., 2019), support long-term monitoring of crop pollinators (Breeze et al., 2021) and to allow for localised assessments of pollination service to inform farm management (Garratt et al., 2019).

We evaluate the most commonly employed sampling methods (transects, observation plots, pan traps) to assess wild bees in European crops, focusing on four insect-pollinated crops that exhibit differences in morphology, growing conditions and pollinator community: apple – *Malus domestica*, field bean – *Vicia faba*, oilseed rape – *Brassica napus* and strawberry – *Fragaria × ananassa*. We had three aims: (i) investigate the frequency with which passive and active methods are used to survey crop pollinators in the wider literature; (ii) using an established list of bee pollinators for each crop (Hutchinson et al., 2021), compare the abundance, richness and proportion of bee species detected by these sampling methods; and (iii) compare the similarity of crop pollinator species communities sampled by active and passive methods, and evaluate to what degree body size and trap colour influences detection rates. We consider how this information could be used to inform protocols to effectively sample and monitor the bee communities of crops.

MATERIALS AND METHODS

Analysis

All analyses were performed using RStudio version 3.4.2 (RStudio Team, 2020). For generalised linear mixed models (glmer) and generalised linear models (glm) the relevant datasets were tested for overdispersion by generating qqplots, and either by running a DHARMa non-parametric dispersion test (Hartig, 2020) or a generalised function overdispersion test from the AER package (Kleiber & Zeileis, 2008). Subsequently, all generalised linear mixed models and generalised linear models were run with a negative binomial error distribution using the glmer.nb function from the 'lme4', v1.1–25 package (Bates et al., 2020) or the glm.nb function from the 'MASS' package (Venables & Ripley, 2002), respectively.

Crop bee community studies

We conducted a literature search to compile all available peer-reviewed European studies, which were published between 2010 and 2019, and in which the wild bee community of one or more of our four focal crops was sampled. We confined our search to European countries only, as previous studies suggest all four crops are visited by a similar suite of species (Hutchinson et al., 2021), whereas elsewhere these crops are visited by different species (Kleijn et al., 2015).

Additionally, wild bees make an important contribution relative to honey bees in this region (Breeze et al., 2014; Garibaldi et al., 2013; Hutchinson et al., 2021). We limited our search to the last 10 full years of publications, to focus on the methods used to make recent assessments of bee crop communities. We performed four separate searches on Google Scholar and Web of Science using the key words 'wild', 'bee', 'bees', 'pollination', 'pollinator' and 'pollinators', without the use of operators, and preceded in turn by both the common and scientific names of our target crops; 'apple', 'Malus domestica', 'bean', 'Vicia faba', 'oilseed', 'Brassica napus', 'strawberry', 'Fragaria x ananassa'. Studies using small numbers of 'bait' or phytometer plants were excluded from analysis. Sampling methods were categorised according to the main types identified by Westphal et al. (2008) – observation plots (a fixed plot of flowers observed for a set time, and bees either visually identified and/or caught for laboratory identification), pan traps (coloured bowls filled with water, and placed at ground-level, or mounted at surrounding crop flower height, in order to trap bees for subsequent laboratory identifications), or transect walks (a fixed or variable corridor of flowering plants walked for a set distance and/or time, and bees either identified through visual observations, caught for laboratory identification, or a mixture of both approaches). Trap nests were excluded from analyses as they are restricted to sampling a small number of cavity nesting species and generally have low species coverage (Prendergast et al., 2020; Westphal et al., 2008).

Field data and crop pollinators

To evaluate and compare the most commonly used methods to sample bee communities of our focal crops we focused upon Great Britain, where wild bees have been demonstrated to make a significant contribution to crop pollination (Breeze et al., 2011; Hutchinson et al., 2021). We used datasets held by the University of Reading, UK. The first collection of datasets was from sites of all four focal crops and collated as part of the UK Insect Pollinators Initiative (IPI) (University of Reading, 2018). Surveys were carried out by teams of researchers from the University of Reading and University of Leeds. All team members received training in catching insects and identifying broad taxonomic groups of pollinators to ensure all surveyors were well matched in terms of expertise and experience.

The second collection of datasets was from sites of bean and oilseed and collated as part of the European Union's Sixth Framework Integrated Project ALARM (Settele et al., 2005). Surveys were carried out by a hymenopterist and two field assistants from the University of Reading.

All bees were caught, where possible, during transect walks, for subsequent identification to species level, alongside pan trap specimens. In the IPI observation plots, only bumblebees and easily identifiable *Andrenids* were identified to species level. For the Alarm observation plots, species that could not be identified in the field were caught for identification. For full details of protocols see Supporting Information S1 (datasets 1.1a–1.2d).

We chose our focal crops and datasets as a case study for investigating the relationships between methods, and their potential biases, as they allowed us to control for other influential factors such as floral diversity and recorder expertise, and their methodology reflected how these approaches are typically executed in the field.

As we were specifically interested in the capacity of these sampling methods to detect the bee pollinators of these crops, we used an existing list of bee species known to definitely, or likely visit (recorded in British pan traps and recorded visiting these crops elsewhere in Europe), each of the four crops in the United Kingdom. This is referred to hereon as our 'reference list' of crop pollinators (Hutchinson et al., 2021; Supporting Information S2). Only species which met these criteria were included in analyses (Table S3). All other species which were recorded in our datasets were considered non-pollinators, and excluded from analyses. For subsequent analyses, bees were split into two guilds – bumblebees and solitary bees. We use the term 'solitary' to refer to all non-Bombus species of bee, however, it should be noted that many species commonly included in such categorisation are in fact primitively eusocial (Holzschuh et al., 2016).

Abundance of bumblebees and solitary bees detected by different sampling methods

To establish if the three main sampling methods detected similar numbers of the two main guilds of wild bee pollinators – bumblebees and solitary bees – in crop areas, we used datasets for three crops where observation plots, transect walks and pan traps were carried out simultaneously (datasets 1.1a–1.1c). Bean was excluded, from this analysis, however, due to it being almost exclusively pollinated by *Bombus* spp. (Hutchinson et al., 2021). To prepare the data for analysis, we calculated the abundance of each guild sampled per site ($n = 8$) and per round of sampling (apple: $n = 2$; oilseed and strawberry: $n = 3$) for each of the three sampling methods.

We fitted generalised linear mixed models with a negative binomial error distribution (glmer.nb function) and analysed the effect of both sampling method and guild, and their interaction, on the abundance of bees detected in each crop. Site and sampling round were included as random effects. The 'multcomp' package (v1.4–17, Hothorn et al., 2012) was then used to conduct multiple comparisons with Tukey tests.

Abundance and species richness of bee genera detected by different sampling methods

To establish if the three main sampling methods detected similar numbers of individual bee genera, we first used the data described above (datasets 1.1a–1.1c), but this time included the data for bean. We calculated the mean abundance and richness of crop pollinating bee species per site ($n = 8$) for the five most common crop pollinator genera as identified by Hutchinson et al. (2021); *Andrena*, *Bombus*, *Halictus*, *Lasioglossum* and *Osmia*, and abundance of unidentified solitary bees

for transect walks. For observation plots, we only calculated mean abundance as a limited selection of bees were identified to species.

Furthermore, we also estimated the mean abundance and species richness of bees that would be sampled by pan traps (dataset 1.1b) if they were carried out for an equivalent time period to that of transect walks (see Table S6a for full details). To do this, we repeated the analyses described above, but this time divided all of the pan trap raw data by 8 to approximate the number of bees caught in a 2- to 3-h time period per site (the total number of hours of transect walk carried out per site in each crop). This was done to account for the fact that pan traps are commonly left out at sites for a full day, whilst total transect walk time per site in most crop studies is generally much less than this. Therefore, pan traps may sample more individuals of different bee genera simply due to their much greater sampling time, and not necessarily because they are a more comprehensive sampling method.

Additionally, to further consider how crop type and pollinator community may influence sampling detectability during active and passive methods we used two additional datasets (datasets 1.2a–1.2d) carried out by a hymenopterist on the two crops with the most contrasting pollinator communities – bean, which is almost exclusively bumblebee pollinated, and oilseed which is pollinated by a wide variety of bumblebee and solitary bee species (Hutchinson et al., 2021). Again, we calculated the mean abundance and richness of crop pollinating bee species per site (bean: $n = 10$; oilseed: $n = 4$) for the most common crop pollinator genera as identified by Hutchinson et al. (2021). We then compared the mean abundance and species richness of bee genera sampled by active methods (bean – transect walks; oilseed – observation plots) with that sampled by pan traps in the same crop sites.

For all datasets (1.1a–1.1c and 1.2a–1.2d), we calculated the number of every bee species sampled by each survey method to provide an overview of whether or not detectability differed amongst individual species within each genus.

Proportion of the pollinator species pool sampled by pan traps and transect walks

To assess the proportion of the total crop pollinator community sampled by different methods we first used the IPI datasets (datasets 1.1a–1.1c), but excluded the observation plot data due to the lack of species-level identifications. We calculated the total number of bee species identified as pollinators that were sampled across eight sites per crop across both methods (transect walks and pan traps). We then calculated the total number of those species sampled by each method individually.

Additionally, we calculated the percentage of the two main guilds of pollinators – bumblebees and solitary bees – that were identified to species levels on transect walks (pan traps were not considered as they provided species level identification for all but eight specimens of solitary bee in apple surveys). For apple and oilseed, there were an additional year of sampling for comparison (dataset 1.1d) in which a further 15 (apple) and 8 (oilseed) sites were sampled.

Finally, we carried out all analyses described above for datasets 1.2a–1.2d for the additional bean sites ($n = 10$) and oilseed sites ($n = 4$). In this case, we compared the proportion of the pollinator community sampled by transects walks (bean) and observation plots (oilseed) to that of pan traps, and calculated the percentage of both bee guilds identified to species level.

Pollinator community comparisons between pan traps and transect walks

We assessed the degree of dissimilarity between the bee pollinator communities sampled by passive (pan trap) and active methods (transect walks) in datasets 1.1b–1.1c using permutational multivariate analysis of variance (R: vegan: adonis v2.5-6, Oksanen et al., 2015) against random permutations ($=999$ for each crop dataset) of the original dataset as per the methodology described in O'Connor et al. (2019). We did not use datasets 1.1a and 1.1d for this analysis due to the lack of species level data in the observation plots, and because no simultaneous pan trapping was carried out for the second year of transect walks. We also excluded datasets 1.2a–1.2d due to the relatively few oilseed sites ($n = 4$) and because the bean dataset largely comprised of bumblebee pollinators only. Results were visualised using multidimensional scaling (NMDS) based on Bray–Curtis dissimilarity (R: vegan: MetaMDS; Oksanen et al., 2015). The similarity of the pollinator communities sampled by pan traps and transect walks was then compared using a visual assessment of the NMDS plots. Additionally, SIMPER analyses were used to determine which species contributed most to the observed differences in the pollinator communities sampled by pan traps and transect walks in each crop.

Body size and abundance of bee species sampled by active and passive methods

To explore whether the dissimilarity in the pollinator communities sampled by pan traps and transect walks was related to bee body size we again use datasets 1.1b and 1.1c. A generalised linear model with a negative binomial distribution was used to explore the relationship between the abundance of bees sampled (response variable) and crop type (all crops), survey type (transect walks and pan traps) and bee body size, based upon intertegular distance (ITD; mm) measurements (obtained as per the methodology described in Greenleaf et al., 2007) in a traits database (compiled by Stuart Roberts for the EU-FP6 ALARM-project). All three explanatory variables and their two- and three-way interactions were included in the model. We use overall AIC as our criterion for model selection.

For *Bombus*, we used the measurements for workers, rather than queens. It should be noted, however, that some *Bombus* records in our datasets will likely represent queens and thus our results for the relationship between body size and abundance of bees sampled will be a conservative estimate.

Effects of trap colour on bee guilds and species sampled by pan traps

To compare the catch rates of different colour pan traps when sampling bee crop pollinators, we first used dataset 1.1b. To establish if the three pan colours caught similar numbers of the two main guilds of wild bee pollinators – bumblebees and solitary bees – across crop sites, we fitted generalised linear mixed models with a negative binomial error distribution and conducted multiple comparisons with Tukey tests as per the methodology described above in the section on the number of bee pollinator guilds detected by different sampling methods, but only calculating the mean abundance of bees, not species richness this time.

Finally, to compare the attractiveness of different pan colours to individual bee species, we calculated the total number of each bee species caught in each pan colour per crop study. We also compared the additional ALARM pan traps samples (datasets 1.2b and 1.2d) in the same manner.

FIGURE 1 Number of studies that used observation plots, pan traps, transect walks, or a combination of methods to sample bee communities in crops. Total number of studies = 42

RESULTS

Crop bee community studies

A total of 42 studies were found which sampled bee communities in our focal crops (Supporting Information S4). Of those, 27 used transect walks, 13 used observation plots and 12 used pan traps (Figure 1). All but one study employing pan traps identified all bees to species level, and all studies mounted pan traps at the approximate height of the surrounding crop flowers. Six studies used blue, white and yellow bowls, three studies only used yellow bowls, two studies used only white bowls and one study used both white and yellow bowls. All but two studies employing transect walks used a fixed transect protocol, in which a set corridor was walked to observe bees. Most studies (17) employing transect walks recorded all bees to species level, but five only recorded *Bombus* to species, with solitary bees recorded to genera or guild. Studies employing observation plots typically sampled an area between 0.9 and 4 m^2 in size for 5–15 min and conducted between 3 and 24 observation plots per site. Studies employing transect walks generally used a corridor of between 50 and 150 m long and between 1 and 4 m wide, and carried out around 1–15 transects per site. Most studies employing pan traps used between 2 and 15 pan traps per site and left them out for between 1 and 4 days.

Eight studies employing transect walks identified bees through visual observation only, 10 by netting all bees for later laboratory identification, and 9 using a mixture of both approaches. Just three studies employing observation plots identified all bees to species, using a combination of visual identifications and netting for subsequent identification. A further three studies only identified *Bombus* to species, all through visual observations in the field. The remaining seven studies were primarily focused on recording the visitation rates of individual guilds and only recorded bees as bumblebees or solitary bee. Four of those studies, however, did record species level data also, three using transect walks and one using pan traps.
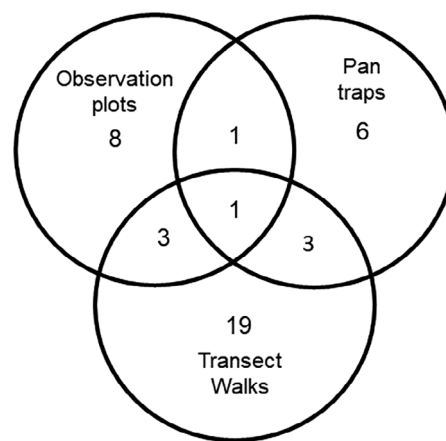
Field data and crop pollinators

Eight datasets were used to evaluate the most commonly used methods to sample bee crop communities (datasets 1.1a–1.2d) and 36 bee species from seven genera were identified as pollinators of one or more of our four focal crops in Great Britain (Table S3). Based upon Hutchinson et al. (2021), the following number of species were identified as pollinators per crop: apple – 32, bean – 8, oilseed – 31, strawberry – 15.

Abundance of bumblebees and solitary bees detected by different sampling methods

Guild and sampling method both had a significant effect on the abundance of bees detected in all three crops [apple ($F_{2,84} = 13.062$, $p \leq 0.001$); oilseed ($F_{2,144} = 8.3404$, $p \leq 0.001$); strawberry ($F_{2,144} = 51.288$, $p \leq 0.001$). In particular, there were significantly more ($p \leq 0.001$) solitary bees detected by pan traps than observation plots or transect walks in all crops (Figure 2; Supporting Information S5).

Abundance and species richness of bee genera detected by different sampling methods

The method which sampled the greatest mean abundance and species richness of bees differed according to genera (Figure 3; Tables S6a and S6b). A greater mean abundance of *Bombus* was sampled by transect walks in all four crops, including the additional bean surveys by a hymenopterist, as was species richness in all crops, except oilseed. Conversely, a greater mean abundance and species richness of *Andrena*, *Halictus* and *Lasioglossum* were sampled by pan traps in apple, oilseed and strawberry in all datasets, including the additional
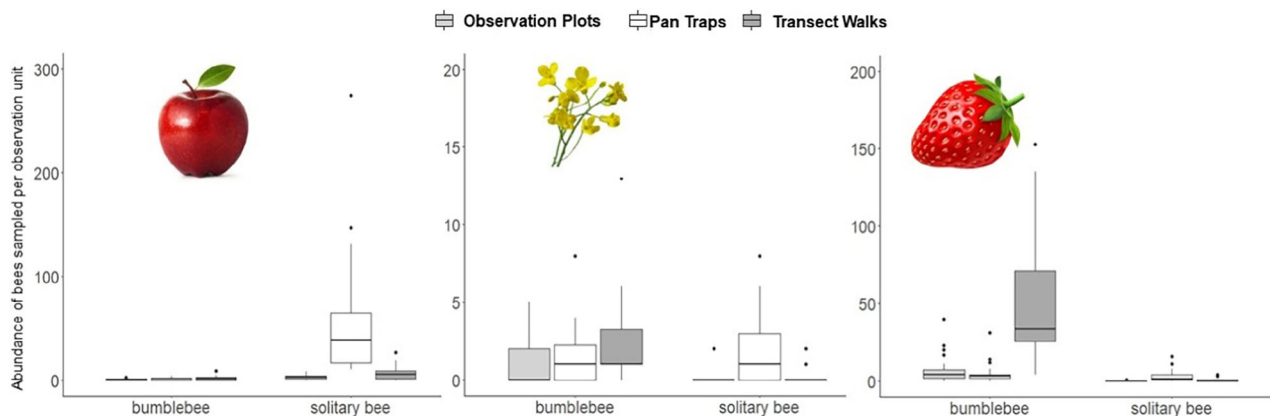
FIGURE 2 Abundance of bumblebees and solitary bees sampled per sampling method (observation plots [light grey/left], pan traps [white/middle] and transect walks [dark grey/right]) across eight sites of apple, oilseed rape and strawberry crops
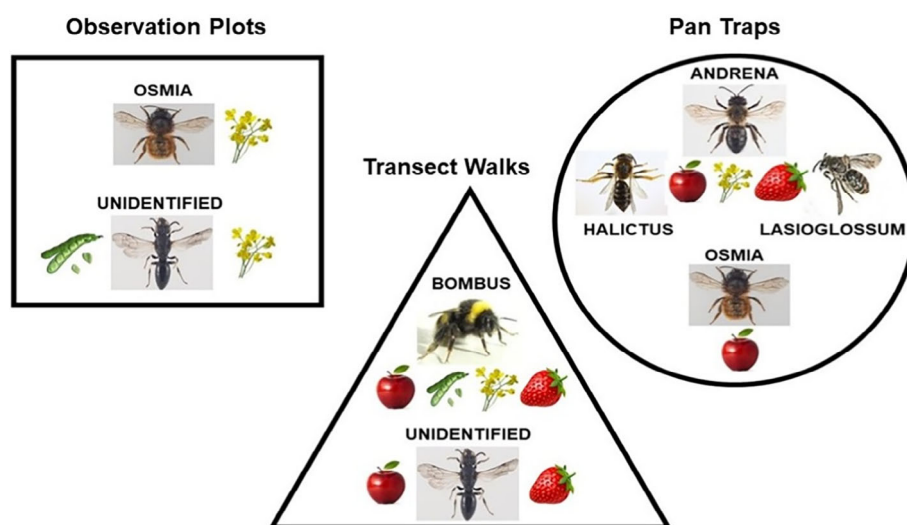

FIGURE 3 Genera of bee species sampled in apple, field bean, oilseed rape and strawberry crops sites and which sampling method – observation plots (squares), pan traps (circles), transect walks (arrows) – generally detected the greater abundance and/or species richness of that bee genus/group

oilseed surveys by a hymenopterist. *Osmia* were only present in apple and oilseed, where they were sampled most abundantly by pan traps and observation plots respectively.

For the dataset in which the pan trap sample data were standardised to estimate, and compare, the mean abundance and species richness of each bee genera sampled if pan traps and transect walks were carried out for equal amounts of time, the patterns followed those above, except for a couple of notable exceptions. When the pan trap data sample time was standardised for a direct comparison with transect walks, it was estimated that a lower mean abundance of *Andrena* species would be sampled by pan traps, compared to transect walks, in apple and strawberry sites, and that a lower mean species richness of *Andrena* would be sampled compared to transect walks in oilseed sites.

The remaining unidentified solitary bees that were recorded in crop sites (datasets 1.1a–1.1.c) were sampled in a greater abundance by transects in apple and strawberry, and by observation plots in bean and oilseed.

For the crop surveys where both observation plots and transect walks were carried out simultaneously (datasets 1.1a and 1.1c), whilst a similar average proportion of bumblebee and solitary bee visits were recorded in apple by both methods, on average 10 and 86 times more bumblebee visits were recorded in oilseed and strawberry sites respectively by transect walks compared to just 4 and 5 times more visits recorded during observation plots.

All but one *Bombus* species were consistently sampled by both active methods and passive methods in each crop dataset (Table S6c), whereas only two-thirds of *Andrena* species were detected by both active and passive methods, mostly comprising of relatively larger and easily recognisable species. The remaining Andrena species were sampled by pan traps only. Only 2 of the 11 *Halictid* species sampled

TABLE 1 Total number of bee species identified as pollinators by Hutchinson et al. (2021) that were sampled in apple, field bean, oilseed rape and strawberry sites ($n = 8$) for datasets 1.1b and 1.1c (top row) and field bean and oilseed sites (bean: $n = 10$; oilseed: $n = 4$) for datasets 1.2a–1.2d (bottom row), and number of those detected by pan traps and transect walks (including in brackets the number of species that were sampled by that method only)

Crop	Total number of bee species sampled	Number of species detected by pan traps (number sampled by this method only)	Number of species detected by transect walks/ observation plots (number sampled by this method only)
Apple	31	31 (19)	12 (0)
Bean	8	6 (0)	8 (3)
	7	6 (0)	7 (1)
Oilseed	14	13 (8)	7 (2)
	20	20 (12)	8 (0)
Strawberry	14	13 (6)	8 (1)

TABLE 2 Number of bumblebees and solitary bees observed during transect walks that were identified to species level, and number that were unidentified, in sites of apple, oilseed and strawberry crops

Guild and identification	Apple	Oilseed	Strawberry
Bombus identified	27 (36)	89 (45)	1022
Bombus unidentified	8 (0)	26 (13)	156
Solitary identified	26 (26)	2	3
Solitary unidentified	87 (11)	6	11

Note: The results for datasets 1.1a–1.1c are provided on the top row. The results for the additional year of data of apple and oilseed sites, dataset 1.1d, are provided in brackets on the bottom row.

across all crop datasets were detected by active methods, with the remainder sampled by pan traps only.

Proportion of the total pollinator species pool sampled by pan traps and transect walks

A total of 36 bee species identified as pollinators by Hutchinson et al. (2021) were sampled by pan traps and/or active methods (transect walks) across the four crops (Table 1). Pan traps sampled a greater proportion of the total bee pollinators in all crop sites, except bean, where more species were sampled by transect walks. Most species were also sampled by pan traps only in all crop sites, except bean.

During transect walks for datasets 1.1c–1.1d, the majority of bumblebees observed were identified to species level in apple (89%), oilseed (78%) and strawberry (87%) crops. Conversely, in most cases, the majority of solitary bees observed visiting apple (66%), oilseed (75%) and strawberry (79%) were not identified to species (Table 2; Supporting Information S7).

For datasets 1.2a–1.2b, where transect walks were carried out in bean sites, and observation plots in oilseed by a hymenopterist, 100%

of all bees visiting bean were identified to species, as were 100% of bumblebees during observation plots in oilseed. During the oilseed observation plots, 90% of observed solitary bees were identified to species level.

Pollinator community comparisons between pan traps and transects walks

There was significant dissimilarity between the pollinator communities sampled by pan traps and transect walks (Figure 4) in all crop types (apples ($R^2 = 0.310$, $F_{1,14} = 6.281$, $p = 0.001$); field beans ($R^2 = 0.279$, $F_{1,14} = 5.411$, $p = 0.004$); oilseed rape ($R^2 = 0.143$, $F_{1,14} = 2.341$, $p = 0.014$); strawberries ($R^2 = 0.391$, $F_{1,14} = 8.972$, $p = 0.001$).

The SIMPER analysis indicated that across the 4 crops, 10 species collectively contributed to more than 50% of the dissimilarity between the pollinator communities sampled by pan traps and transect walks in one or more crops (Table S3): *Bombus lapidarius* and *Bombus terrestris*, which were sampled more abundantly by transect walks in all crops and *Andrena flavipes, Andrena haemorrhoa, Andrena minutula, Andrena nigroanea, Lasioglossum calceatum, Lasioglossum malachurum, Lasioglossum morio* and *Lasioglossum pauxillum* which were sampled more abundantly by pan traps in all crop sites in which they were present.

Body size and abundance of bee species sampled by active and passive methods

The GLM indicated that there is significant two-way interactions between body size and crop type, and body size and survey type ($p = \leq 0.05$) on abundance of bees sample, suggesting that whilst there is a relationship between body size and the abundance of bees (Supporting Information S8a), that this relationship is dependent upon sampling method and crop type. Notably, there was a clear negative and positive relationship respectively between body size and abundance of bees sampled by pan traps and transect walks in
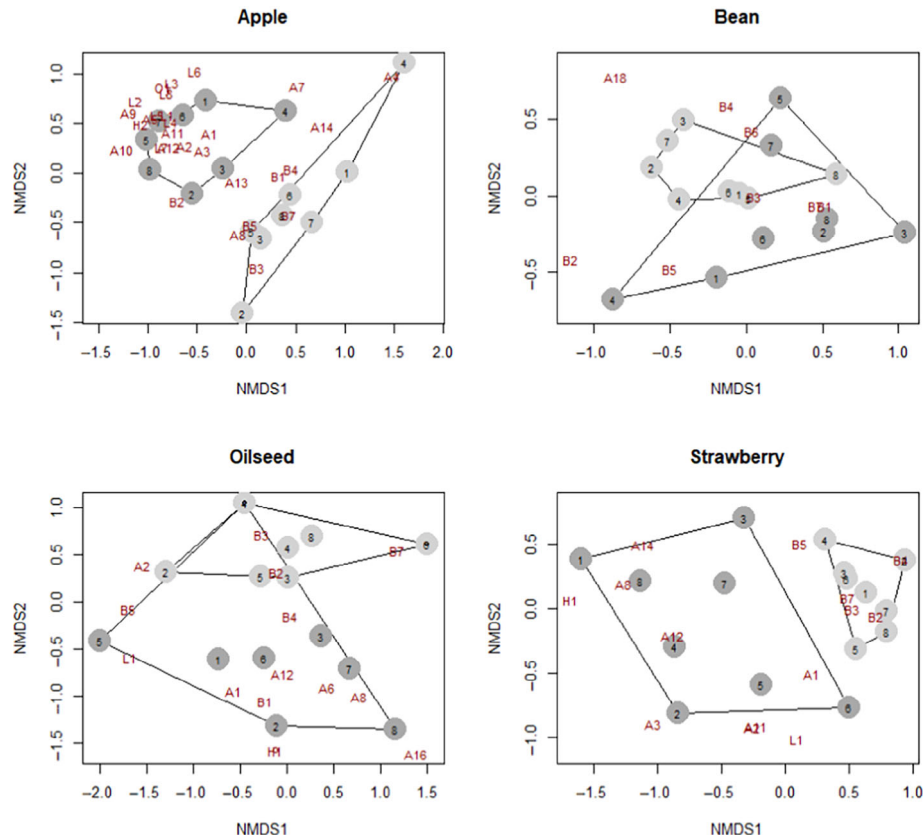
FIGURE 4 Non-metric multi-dimensional scaling (NDMS) plots of pan traps (dark grey circles) and transects (light grey circles) for all plausible pollinating bee species detected in apple (stress = 0.1141659), field bean (stress = 0.1069335), oilseed rape (stress = 0.1167524) and strawberry (stress = 0.1068908) crop sites. Number in circles represents the site number and the polygons connecting sites indicate the overlap between samples

FIGURE 5 Number of bumblebees and solitary bees caught in blue, white and yellow pan traps in sites of apple, oilseed and strawberry crops

apple sites, whereas this was not the case for bean, oilseed or strawberry crops (Supporting Information S8b).

Effect of trap colour on bee guilds and species sampled by pan traps

A greater overall mean abundance of bees was caught in yellow pan traps in all crops, except bean, where a greater mean abundance was caught in blue traps (Table S9a). Guild and colour had a significant effect on the number of bees caught by pan traps in apple

($F = 10.986$). In particular, there was a highly significant difference ($p \leq 0.001$) in the number of solitary bees caught by different pan colours, with significantly more solitary bees caught in yellow pan traps than in blue or white ones, and significantly more solitary bees caught in white pan traps than blue ones (Figure 5). Whilst neither guild nor colour had a significant effect on the number of bees caught by pan traps in oilseed or strawberry, the same pattern was observed in both crops as in apple, with more solitary bees caught in yellow pan traps than blue or white ones. Conversely, more bumblebees were caught in blue and white pan traps than yellow ones in apple and oilseed (Table S9a).

Across all crop and datasets combined 27 of the 30 solitary bee species included in analyses were caught in yellow pan traps, the remaining 3 were all sampled solely in white pan traps (Tables S9c and S9d). Ten solitary bee species were not caught at all in blue pan traps. Conversely, all 7 Bombus species were sampled by blue pan traps in all four crops.

DISCUSSION

Declines in wild bee populations pose a significant threat to future food security (Reilly et al., 2020). There is an urgent need to inventory and monitor pollinator populations in order to develop effective conservation and management strategies (Breeze et al., 2021; LeBuhn et al., 2013). Yet, the status of pollinator trends in agricultural settings is currently especially meagre. Whilst monitoring schemes for pollinator communities are emerging (Carvell et al., 2017; Potts et al., 2021), a specific emphasis on crop pollinators in agricultural settings is vital to safeguard crop production (Garibaldi et al., 2020). Whilst several studies have compared wild bee sampling methods, they are rarely carried out in crop areas, or consider multiple different crops (Krahner et al., 2021 and references therein). Furthermore, where studies have been carried out in crop habitats (O'Connor et al., 2019; Westphal et al., 2008) they have included the entire bee species community, and thus likely many non-crop pollinating bee species. Here, we used a comprehensive list of crop pollinating bee species in Great Britain (Hutchinson et al., 2021) to evaluate the effectiveness of the most commonly employed survey techniques to sample bee pollinator communities in different crop types.

As reflected in recent global assessments (Dainese et al., 2019; Kleijn et al., 2015), we found that observational methods are the principal methods by which to identify crop pollinating bee species. We confirm the results of previous work showing that individual survey methods are biased towards different components of pollinator communities (O'Connor et al., 2019; Westphal et al., 2008), with the relative effectiveness of survey methods differing according to taxon (Prendergast et al., 2020). Our results concur with the results of a recent assessment of the performance of different methods to sample wild bees in a single and different crop (vineyards) habitat (Krahner et al., 2021). As in our study, there was evidence of an effect of body size and guild on the capacity of survey methods to sample bee pollinators. Netting along transects was found to disproportionately sample bumblebees, compared to pan trapping, which again, sampled both the highest number of individuals and species. Pan trap colour was also found to differ in its attractiveness to different guilds, with, as in our study, yellow traps being more attractive to solitary bees and blue pan traps generally being more attractive to bumblebees.

Our findings substantiate evidence that observational methods are less effective at distinguishing finer taxonomic levels (Prendergast et al., 2020), with pan traps being a more effective means to inventory species richness of some crop pollinator communities. Additionally, as well as reinforcing evidence that pan trap bowl colours vary in their attractiveness to different bee guilds, we demonstrate that the optimal colour to sample pollinators is based upon bee guild. Notably, we provide some of the first evidence that differences in the capacity of survey methods to sample pollinating bee species in crop habitats are likely driven by a combination of bee guild and body size, and that the most efficient method to sample pollinator communities is contingent upon crop type.

Whilst observational methods are currently the principal means by which to identify insect species that are delivering crop pollination services (Kleijn et al., 2015; O'Connor et al., 2019), many field studies only identify larger bees such as Bombus to genus or species, with other bees grouped together into one guild (e.g. see Supporting Information S4). Pan traps have been associated with low captures of pollinating species compared to netting techniques (e.g. Cane et al., 2000). But, in our study, transect walks generally detected a relatively small proportion of the overall crop pollinator bee community, while pan traps sampled almost the entire suite of pollinating species present in three of the four crops, with the exception, of bean, which is almost exclusively visited by bumblebees, that are often sampled more comprehensively during active methods (Krahner et al., 2021). Our results build upon an established body of research indicating that solitary bees are more comprehensively sampled by pan traps (McCravy, 2018; Roulston et al., 2007; Westphal et al., 2008). This was especially prevalent in our results for apple, which had the greatest proportion of solitary bees in its pollinator community, and was the one crop showing a negative association between bee body size and abundance sampled by pan traps. Furthermore, we excluded species from pan trap samples that, whilst known to forage on the target crop plant family (Hutchinson et al., 2021), lacked visitation data to substantiate their status as potential pollinators. Most of the species we excluded as such were particularly small solitary bees. Given this, and the fact that we used ITD measurement for Bombus workers, rather than queens, which are significantly larger, it is therefore likely our results are a conservative estimate of the impacts of body size on detection rates.

Pan traps do not provide information on floral associations, and their effectiveness may vary depending on the density of floral resources in some crops (O'Connor et al., 2019). As such observational methods play an integral role in inventorying those species visiting crop flowers. Whilst trained citizen scientists could record most bumblebees on the wing (excluding cryptic species, e.g., the Bombus lucorum complex [see Bossert, 2014]), taxonomic experts, who can produce species data commensurate with pan traps, are indispensable for identifying solitary species visiting flowers (O'Connor et al., 2019). We found that whilst our surveys were conducted by trained researchers, high proportions of solitary bees present in fields were not identified during transect walks. This was especially pronounced in oilseed rape fields, potentially due to it being grown in dense masses in fields, whereas the other crops are primarily grown in spaced out rows, making it easier to capture insects for identification purposes. Furthermore, oilseed was the only crop in which similar numbers of solitary bees were observed during observation plots and transect walks. It is possible in such densely grown crops that the

movement of surveyors during transect walks may disturb small solitary bees, which are subsequently not detected. Despite solitary bees known to often be frequent visitors of oilseed flowers (Hutchinson et al., 2021), solitary bees were also caught in very low numbers in pan traps, which could also reflect the high density of flowers in oilseed fields. There is evidence that there may be a negative relationship between flower abundance and pan trap sample size (O'Connor et al., 2019). Despite pan traps being promoted as a means to measure bee abundance, our results support evidence that there may be no clear relationship between catches and actual abundance (Cane et al., 2000; Portman et al., 2020). As such, inferences should not be made about the abundance of individual crop pollinators based upon pan trap captures.

Efforts to inventory crop pollinators would also benefit from cross-national collaborative efforts. Observational data from other countries with a similar bee fauna can supplement national surveys and inform protocols using pan trap samples, by allowing the differentiation of pollinators from non-pollinators (Hutchinson et al., 2021). Additionally, it can also be used to identify 'insurance' species which could deliver this service in the future, should current pollinators undergo declines. Some species may currently be absent in agricultural areas in certain countries due to climatic or ecological constraints, but could undergo climate-induced range shifts or be promoted via agri-environment measures. It is important to note, however, that our results solely reflect the capacity of these sampling methods to identify those species potentially contributing to pollination service. There is a clear distinction between establishing the presence and abundance of insects in crop fields, and measuring their actual contribution to pollination service. In that respect, observation plots have been evidenced elsewhere as the most reliable means by which to measure visitation rates (Garibaldi et al., 2020).

Once the suite of pollinating species for individual crops has been established, the critical task of monitoring them using taxonomically robust, standardised protocols (O'Connor et al., 2019) can be implemented. Given that a lack of skilled taxonomists remains a major bottleneck in monitoring pollinators (Science for Environment Policy, 2020), the verified capacity of trained volunteers to implement pollinator surveys (Garratt et al., 2019) will prove integral to monitoring programmes. To facilitate this, however, protocols may benefit from being as simple as possible, particularly where resources are a limiting factor, focusing on the quality, rather than quantity of data. Bumblebee species are relatively easy to catch, due to a combination of their large size and slow flight speed (Prendergast et al., 2020). As such transect walks alone are likely sufficient to sample them in crops, such as field beans, which is almost exclusively pollinated by them (Hutchinson et al., 2021).

In crops where small solitary bees are a key provider of pollination service delivery, such as apple and oilseed (Hutchinson et al., 2021), pan traps may be an important source of complementary data. One approach is to use bowl colours that match the colour of the target crop flower (Ahrenfeldt et al., 2019; Marini et al., 2012), but more detailed pilot studies to determine the efficacy of such an approach are required. Our results support existing evidence that the driving influence behind pan trap colour efficiency is the guild (eusocial,

e.g., Bombus or non-eusocial [solitary] bees) being targeted (Campbell & Hanula, 2007; McCravy, 2018; McCravy et al., 2019). As also indicated in our study, eusocial bees may be more attracted to blue pan traps, whereas non-eusocial bees may be more attracted to yellow (Sircom et al., 2018). Using colour to target specific groups may help reduce pan trap by-catch of non-pollinators, if the time to process specimens and a lack of taxonomic experts remains a major bottleneck in pollinator sampling (Science for Environment Policy, 2020).

Given increasing evidence, here and elsewhere (O'Connor et al., 2019; Templ et al., 2019), of the propensity of observational methods, notably transect walks, to under-sample small solitary bees, monitoring programmes can benefit from employing separate searches for bumblebees (and potentially larger, conspicuous Andrena species, which our results indicate may also be efficiently sampled by transect walks), and small solitary bees. This may be particularly beneficial in densely grown field crops, such as oilseed, where reduced visibility may present a constraint on the accurate recording of small species (Garratt et al., 2019). In our study, a far higher proportion of bumblebee visits were recorded relative to solitary bee visits in oilseed and strawberry during transect walks compared to observation plots. Transect walks may overestimate the relative abundance of bumblebees on crop flowers relative to solitary bees, possibly due to solitary bees being more visible, and less likely to fly away, if the surveyor is relatively stationary, as in observation plots. As such observation plots, by trained surveyors where solitary bees are recorded to at least genus, may provide more accurate information on the relative abundance of solitary bees compared to bumblebees. Equally, employing designated transect walks for solitary bees alone, could help increase recordings of small inconspicuous species, which findings here, and elsewhere (Prendergast et al., 2020), indicate are otherwise underrepresented. Whilst some especially small species may still be overlooked, it is likely such an approach will still cover larger species, which often make the greatest contribution to pollination service delivery (Földesi et al., 2021). A final point of note is the similar under-representation of non-bee pollinators during observational surveys (Földesi et al., 2021), which may also be mirrored in pan trap samples (Hall & Reboud, 2019). Given the important contribution to crop pollination of such insects (Rader et al., 2016), more work evaluating the best means to inventory, and monitor, non-bee crop pollinators should be considered an urgent next step. Additionally, the anthropocentric view of protecting ecosystem service providers should not be the sole basis for biodiversity conservation (Prendergast, 2020) and monitoring programmes should consider the whole spectrum of species in agricultural landscapes, and not just those bee species that contribute to crop pollination.

CONCLUSIONS

Threats to food security are no longer a theoretical future concern (Aizen et al., 2008). Empirical evidence now demonstrates the capacity of wild pollinator limitations to translate into reduced crops yield and productivity (Reilly et al., 2020). Whilst national-level monitoring

schemes of all species is critical for conserving wider biodiversity, a specific focus upon crop pollinators in agricultural landscapes is essential for resilient crop pollination service delivery (Carvell et al., 2017). Given the established benefits of diverse assemblages for resilient crop productivity (Potts et al., 2016), inventories of crop pollinators should aim to sample the whole suite of species delivering the service (Winfree et al., 2018). The elucidation of the roles of different pollinator taxa is a critical first step as optimal management strategies will differ amongst species (Woodcock et al., 2013). Applying the most effective method(s) to ensure a representative sampling of crop pollinator community species richness by trained volunteers will help optimise the sampling of target bee species or groups (Garratt et al., 2019; Templ et al., 2019). Future work should also focus on how to apply survey methods that more accurately reflect relative abundance of individual species. Inventorying bee species that visit crop flowers will allow for targeted management to conserve and promote their persistence at both the national and farm level. Monitoring thereafter is essential to verify whether policies are having the desired effect (Science for Environment Policy, 2020). Our findings can inform the design of optimal and comprehensive sampling protocols for crop pollinating species. Key to their success will be collaboration and standardisation to ensure national and international policies can protect crop pollinators and the integral ecosystem service they provide for human well-being.

ACKNOWLEDGEMENTS

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

Data S1 Supporting Information