Article

DIFFERENT BEE-FLOWER SURVEY METHODS IMPACT CONSERVATION RECOMMENDATIONS: COMPARING CITIZEN SCIENCE AND ACADEMIC SURVEYS

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Abstract—Promoting diverse and abundant flowering plants in cities is essential to counteract the decline in wild bee diversity due to urbanisation. To support effective conservation, it is crucial to identify which flowers best enhance wild bee abundance and species richness. This requires large datasets and robust analytical tools. Here, we use a plant selection tool developed by M'Gonigle et al. (2016), which recommends flower mixes that maximise pollinator species richness based on visitation data. We analysed bee-flower interaction data from the Brussels Capital Region (Belgium), comparing two contrasting sources: (1) citizen science records and (2) standardised academic surveys. We evaluated the bipartite networks of these datasets and their combination and generated optimised flower mixes from each using the plant selection tool. Our results show that dataset composition and inherent biases strongly influence outcomes. The bipartite networks differed substantially (compositional difference = 0.86), mainly due to rewiring of bee-flower interactions (0.69). Consequently, the flower mixes derived from each dataset overlapped by only 7% when optimising for species richness. The combined dataset network more closely resembled the citizen science data (WN = 0.106) than the academic survey data (WN = 0.590).

These findings highlight the substantial impact of data collection methods on ecological recommendations. Awareness of such biases is essential for making sound, evidence-based conservation decisions. To support wider application, we developed a free app that allows users to create flower mixes optimized for pollinator abundance, species richness, or both, using our dataset or their own.

Keywords—Conservation, urbanisation, wild bees, bipartite network, urban green spaces, citizen science

INTRODUCTION

Among the many taxonomic groups that are affected by habitat loss, wild bees (Hymenoptera: Apoidea: Anthophila) are well known to be widely declining in abundance and diversity (Potts et al. 2010; IPBES 2016). However, perhaps contrary to expectation, the magnitude of the negative impact of habitat loss due to urbanisation on wild bees is still a debated topic (Nieto et al. 2014; Prendergast et al. 2022). Several studies indicate that urban green spaces, with their high spatial heterogeneity, can represent an important safe haven for wild bees, hosting large numbers of species, including rare and/or declining taxa (Normandin et al. 2017; Vereecken et al. 2021), and partly mitigate wild bee declines. Furthermore, urban wild bees, particularly pollen generalist species, are expected to thrive in environments that host high floral abundance, which is encouraged by irrigation and appropriate ornamental flower landscaping (MacIvor & Moore 2013; Normandin et al. 2017).

BIPARTITE BEE-FLOWER NETWORKS

A key step towards evidence-based conservation of wild bees is the identification of flowering plants that are known to effectively support local urban bee populations (Nichols et al. 2022). An extensively mobilised and popular approach fit for this purpose is the study of bipartite bee-flower networks (Kuppler et al. 2023). Such networks consist of a graphical and mathematical representation of interaction patterns between two disjoint and independent categories of organisms, each composed of nodes or vertices (one for each species) connected in pairs by lines or edges depicting the diversity and frequency of their interactions. Bee-flower networks can be described structurally using a variety of metrics (Geslin et al. 2017) and have been used to assess a wide range of ecological phenomena (Philips et al. 2020; Ramos-Jiliberto et al. 2020; Olsson et al. 2021). When assessing the importance of flowering plants for wild bees via bipartite networks, it is important to include all bees and both sexes to take the full dietary needs for bees into account. When it comes the transfer of pollen (i.e. pollination), it is erroneously commonly thought that it is only the female wild bees that are important because they are seen as the sole pollinators. However, it is clear that male bees, as well as parasitic species, which do not collect pollen actively, can play an important role in pollination due to accidental pollen transport on their hairy bodies, which they do not actively transfer back to a nest (Cane et al. 2011; Ogilvie & Thomson 2015). Additionally, the nectar availability and structure of the flower can alter and shape local wild bee communities due to differences in nectar preference and tongue morphology (Stang et al. 2006; Goulson et al. 2008; Cariveau et al. 2016). As such, the visualisation and quantification of bee visits to certain plants can be effectively studied with bipartite bee-flower networks. However, the extent to which bee-flower networks are a reliable representation of ecological networks, and how they can be used as a basis for the identification of key flowering plants for bees depends heavily on the quality of the underlying dataset, specifically the *modus operandi* of the recording of bee-flower interactions, including the associated field survey efforts (Doré et al. 2020).

CITIZEN SCIENCE

An increasingly popular method to generate large databases of biological records is the use of so-called citizen scientists, mostly volunteers, to collect data associated with occurrence or biotic interaction records (Malek et al. 2018; Fontaine et al. 2021). The implementation of data collection through citizen science, when associated with a validation procedure by experts, can generate 'research-grade' records of great value for the study of biodiversity in general, and of bee-flower interactions in particular. It is assumed that citizen science can generate a bigger amount of data than classical (academic) surveys, but the data are less standardised and are more likely to be biased. However, it is not known how this specific source of data compares to more standardised academic surveys of bee-flower interactions using timed netting surveys on flowers, particularly in urban areas. Yet, exploring this issue is becoming a pressing priority for a variety of reasons, such as (i) the increasing popularity of citizen science and the annual flow of 'research-grade' biological records generated by volunteers and validation experts, (ii) the decreasing (or at best, *limited*) funding dedicated to biodiversity surveys by researchers deploying standardised field surveys, and (iii) the increasing use of modern technologies such as artificial intelligence (AI) online tools that allow identification of a significantly high proportion of native and exotic plants, but a comparatively lower proportion of wild bee species. Indeed, although some progress has been made in the field, the reliable identification of a considerable proportion of wild bee species still relies on the microscopic examination of diagnostic traits unavailable through even the best field macrophotography approaches (Flaminio et al. 2021).

AIMS

In this study, we investigated the difference between, and complementarity of contrasting sources of biotic interaction records, namely citizen science (CS) *versus* academic surveys (AS), across urban green spaces in the Brussels Capital Region (Belgium). We do this by using a recent bioinformatics tool by M'Gonigle et al. (2016) which is designed for the compositional optimisation of flowering plant mixes based on flower visitation data (hereafter: "flower tool").

We complemented this by investigating the difference between the two datasets with the use of bipartite bee-flower ecological networks, both when using the two datasets separately and combined in order to assess their relative contribution. The aim of the study is to provide an evidence-based method for assessing ideal flower mixes for wild bees and to show how inherent dataset biases influence the outcome of these analyses. The results are discussed in the perspective of a growing need to monitor pollinator diversity, and to develop appropriate and evidence-based tools to ensure their effective conservation in human-altered landscapes.

MATERIALS AND METHODS

DATASETS

Two complementary datasets were investigated which encompass the same area within the Brussels urban region and have enough data to make a comparison possible. Both datasets consist of observations of wild bee species accompanied by the plant on which they were seen and the date of the observation. The observations were pooled for the entire region, without specific site information, since this is the nature of opportunistic citizen science data.

The first dataset was compiled from standardised sampling by the Agroecology Lab of the Université libre de Bruxelles (ULB) in Brussels, Belgium in 2017 and 2018 (hereafter the AS-dataset) as part of study on urban bee diversity. A total of 21 sites spanning across a spectrum of urban green spaces were surveyed in 2017 between mid-March and late June (every two weeks) and in 2018 between early April and late June (every three weeks). Collection was performed by handnetting with the standardised methodology based on Lebuhn et al. (2003) and Westphal et al. (2008) which includes a targeted search for wild bees on flowering plants on each location for 1.5 hours in the morning and again for 1.5 hours in the afternoon in a period where all locations can be sampled during similar weather conditions. After collection, the specimens were pinned and identified using literature resources described in Vereecken et al. (2021) by using the adapted key by Falk (2020). Collectively, this dataset represents 109 collecting days in spring and early summer and consists of 2,771 observations. In order to focus the analyses on wild bees, all records of honeybees (*Apis mellifera*) were removed. This resulted in the removal of 507 records and the final dataset having 2,264 observations. All specimens are stored in the collection of the Agroecology lab at the ULB. Most of the plants were also identified to species level, except for 90 records where the plant was identified only to genus level.

The second dataset, created to compare to the former dataset, encompassed the same area of the Brussels Capital Region, but in this case, it was compiled *via* citizen science surveys (hereafter the CS-dataset) which were also performed between the months of March and June but from 2009 to 2018, representing a total of 148 days on which observations were made. These expert validated observations were extracted from the Natuurpunt/Natagora database where volunteers originally submitted them along with a photograph and a reference to the flower on which the bee was observed through the waarnemingen.be/observations.be online portal. The validation of the observations is done by a range of volunteer bee experts who work with wild bees in their professional career for organisations such as Natuurpunt/Natagora. More information on the validation process can be found at https://observation.org/pages/validation/ (in Dutch). The 10-year time period for these observations is much longer than the time period for the AS-dataset but was needed to create a large enough dataset which encompassed the same area as the other dataset. The majority of the observations on the online portal have either low-quality photos which make identification not possible, or do not include a host plant associated with the bee species and could therefore not be used. All species were identified to species level, except the *Bombus terrestris* complex and again all 13 records of *Apis mellifera* were removed. The final size of this datasets has 715 observations. For 105 of those observations, the plant was only identified to genus level. The CS-dataset is considered by default as non-standardised and as a source of opportunistic biological records.

STATISTICAL ANALYSIS

All statistical analyses were performed in RStudio (2022) for R (R Core Team, 2022).

All datasets consisted of a matrix of bee species and the flower on which they were observed, alongside the date of the observation. We used this matrix to first construct rank-abundance plots by using the *rankabundance* and *rankabunplot* functions in the 'BiodiversityR' package (version 2.14-1) (Kindt 2022), and Venn diagrams by using the 'VennDiagram' package (version 1.7.1) (Chen 2021) to determine the abundance, distribution, and shared and unique species for the datasets. Difference between the datasets in bee and plant composition was quantified with the *beta.multi* function from the `vegan` package (version 2.6-10) (Oksanen et al., 2025), which allows comparison of datasets without replicates and specific location or site information. The results were then visualised using the *mosaicplot* function. The *beta.multi* function the calculates Sørensen dissimilarity (beta.SOR), which ranges from 0 (communities have exactly the same species composition) to 1 (communities do not share any species). Additionally, the function shows to what degree the difference in species composition is caused by species turnover (beta.SIM) or species nestedness (beta.SNE). Bee-flower networks were created with the `Bipartite` package (version 2.19) (Dormann 2023) and visualised via the *plotweb* function. Differences between the networks was investigated via the *network_betadiversity* function in the `Betalink` package (version 2.2.1) (Poisot 2016). In this function, the total network dissimilarity is defined as the dissimilarity of interactions between the networks (WN). Partitioning of this total dissimilarity results in differences in species composition (species turnover, ST) and dissimilarity of interactions between species that are shared among the networks (OS), so that WN = ST + OS. These indices of comparing networks are robust even with incomplete sampling and networks of different sizes (Poisot et al. 2012). We then ran the flower selection tool created by M'Gonigle et al. (2016) on both individual datasets and the combined dataset. The tool can be used to investigate a plant mix optimised for maximising species abundance, species richness, or a combination of both. However, since the academic surveys were not combined with pan-trapping and the citizen science data is opportunistic and non-standardised, neither dataset can be used to assess abundances accurately. Additionally, in both the AS and CS-datasets, certain plants were only identified to the genus level, which could lead to bias when certain plants are grouped together, while others are split into multiple species and thus underestimating their contribution. Due to this, and the fact that in our datasets no monolectic bee species (defined as species that are specialised to a single plant species) were present, we chose to run the flower tool at the plant genus level and only for species richness. Specifically, we used the flower tool to generate a mix of 15 flowering plant genera (therefore only using plants with a visitation rate above 1%), in order to assess the appropriate floral diversity for maximising wild bee species richness. When generating this mix, the tool selects those plants that are visited by the highest number of wild bee species, whilst giving a higher valuation to plant genera that function as the only (or close to only) host for a certain wild bee species.

RESULTS

DATASET COMPARISON

After cleaning and dismissing *Apis mellifera* records, the AS-dataset consisted of 2,264 visitations out of a possible 6,720 and contained 42 bee species and 160 plant genera. The CS-dataset yielded 715 visitations from a possible 4,144, consisting of 56 bee species and 74 plant genera. Sørensen dissimilarity between the two datasets for the bees was 0.39, which was mostly caused by species turnover (beta.SIM = 0.29). The difference in plant genus composition was higher with an overall dissimilarity of 0.62, with 0.39 caused by species turnover and 0.23 by species nestedness. (see Fig. S3 for a mosaicplot showing the difference between the datasets). The combined dataset, consisting of 68 bee species and 189 plant genera, and had a total of 2,979 visitations out of a possible 12,920. Out of the total of 68 wild bee species, 30 were shared between the datasets, while 12 species were unique to the AS-dataset and 26 were unique to the CS-dataset (Fig. 1, left Venn diagram). Rank-abundance analysis shows a clear dominance of *Bombus* spp. in the AS-dataset and a dominance of the specialist *Andrena florea* in the CS-dataset (see figures S1 and S2 in the supplementary material for the top 20 most observed species in both datasets). Of the 189 plant genera, 45 were shared among the datasets, while 115 were unique to the AS-dataset and 29 were unique to the CS-dataset (Fig. 1, right Venn diagram).

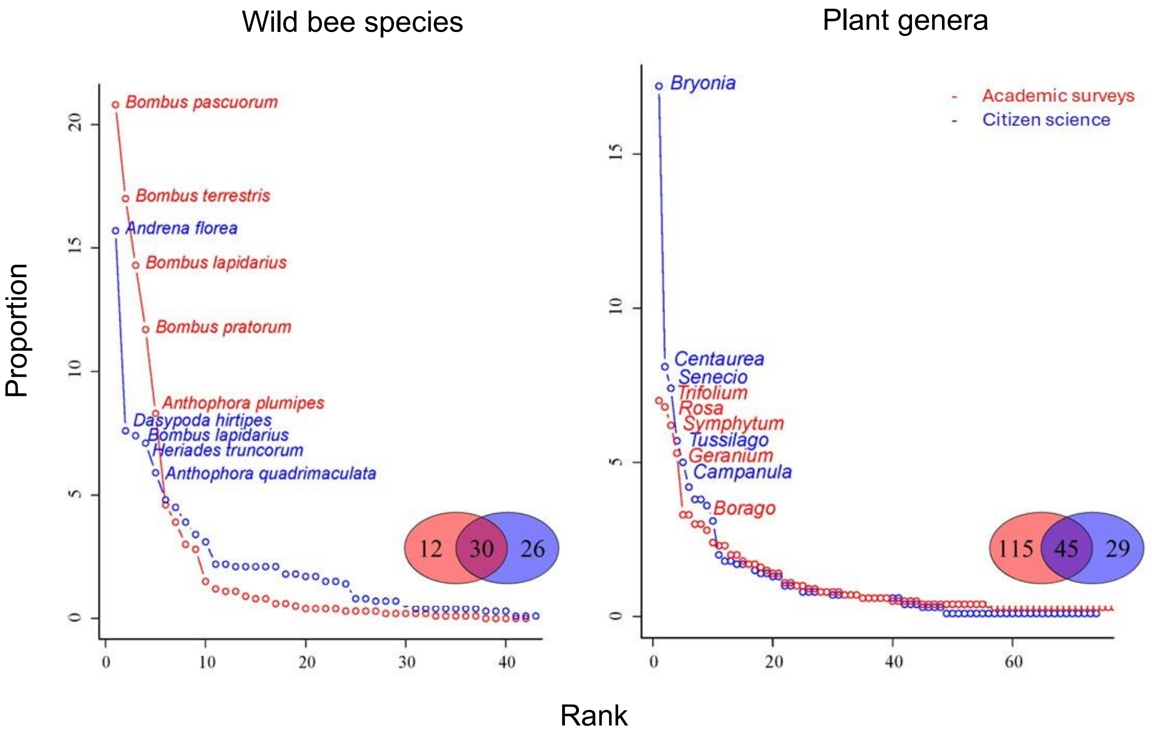

Figure 1: wild bee rank-abundance plots for both datasets, showing the five most commonly observed wild bee species (left) and the five plant genera on which they were most often observed (right). The Venn diagram for the bees shows that out of the 68 wild bees in the datasets, 30 are shared, 12 are unique to the AS-dataset and 26 are unique to the CS-dataset. The Venn diagram for the plants shows that out of the 189 plant genera, 45 are shared, 115 are unique to the AS-dataset and 29 are unique to the CS- dataset.

NETWORK DISSIMILARITY

The bipartite networks (Fig. 2) of the AS- and CS-datasets had a large total dissimilarity (WN) of 0.867. The difference explained by the species turnover (ST) was 0.194, meaning that the majority of the dissimilarity (0.673) could be attributed to differences of interactions between shared species (OS). Comparing the network for the combined dataset to the networks for the AS- and CS-datasets revealed that the combined network more closely resembles the CS-dataset (WN = 0.106) than the AS-dataset (WN = 0.590).

FLOWER MIX CREATION

The order of the plant genera in the suggested mix for maximising species richness is both connected to the number of the bee species that visited the flower and the importance it plays for certain bees. After running the flower tool on all datasets for species richness, a clear difference could be observed between them (Fig. 3). The only plant genus in the mix that is shared by the AS-dataset and CS-dataset is *Taraxacum*, which is in the top four for both datasets. For the combined dataset it is the most important genus for maximising species richness because it is visited by 22 species of wild bee, the highest number of all plant genera, and is the only host plant for two bee species (*Nomada bifasciata* and *Nomada fucata*) and one of only three or four hosts for another five bee species (*Andrena cineraria, Andrena tibialis, Halictus rubicundus, Lasioglossum calceatum,* and *Lasioglossum villosulum*). In the flower mix for the combined dataset, four plants from the AS-dataset are included and eleven from the CS-dataset (Fig. 3, blue lines). The main reason for this is that the plants from the CS-dataset include more genera that are the only host plant for certain wild bees. Examples of this are *Brassica*, which is the only host plant in the combined dataset for both *Hylaeus pictipes* and *Lasioglossum minutissimum*, and *Reseda*, which is the only host for *Hylaeus hyalinatus* and *Hylaeus signatus,* with the latter being oligolectic on *Reseda*.

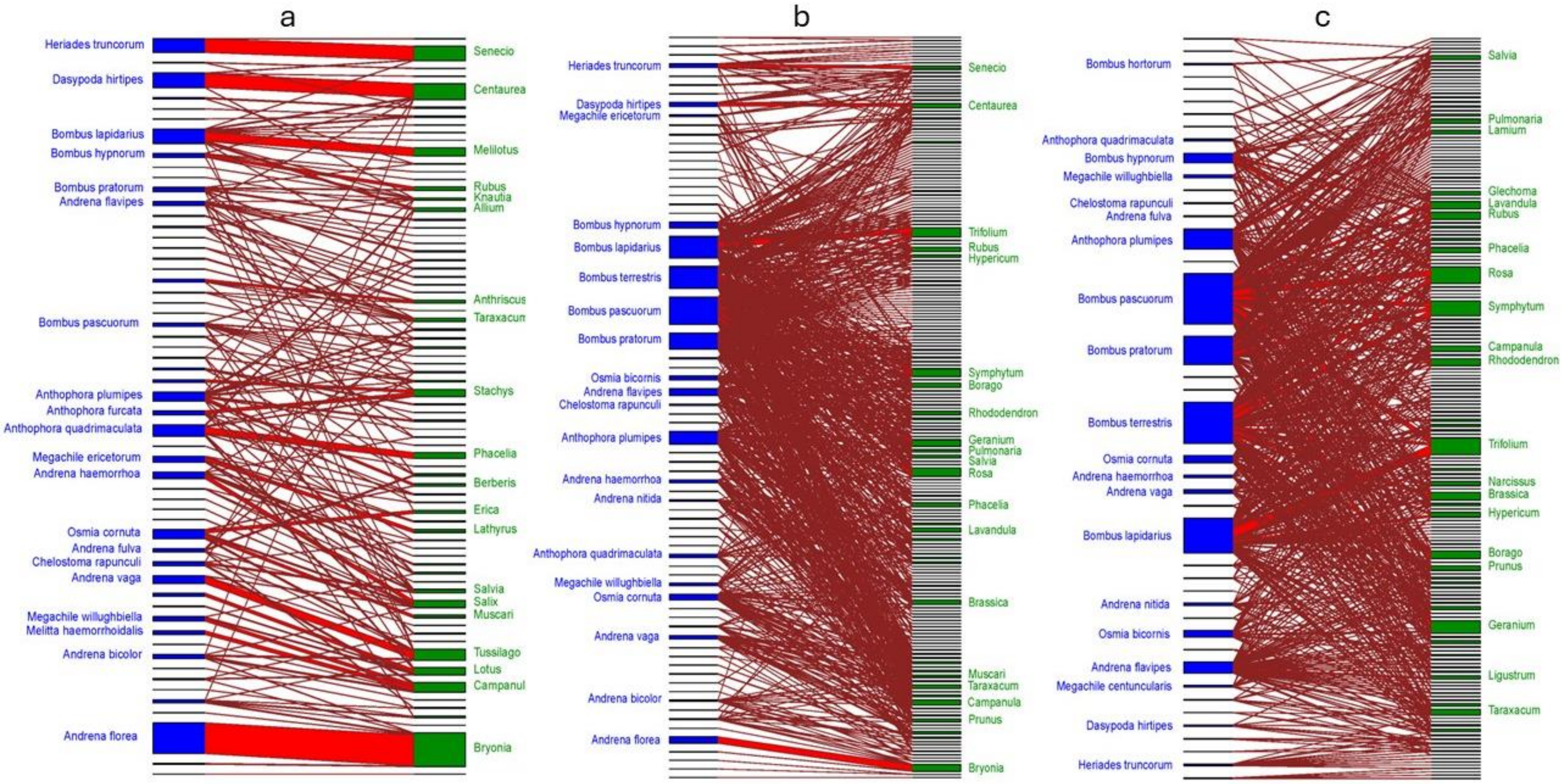

Figure 2: bee-flower networks for the (a) CS-dataset, (b) AS-dataset, and (c) combined dataset. The 20 wild bee species with the highest abundance are shown in blue and the 20 plant genera with the highest abundance in green. The thickness of the box indicates the relative abundance of the species or genus, and the thickness of the line indicates the relative number of interactions between the two.

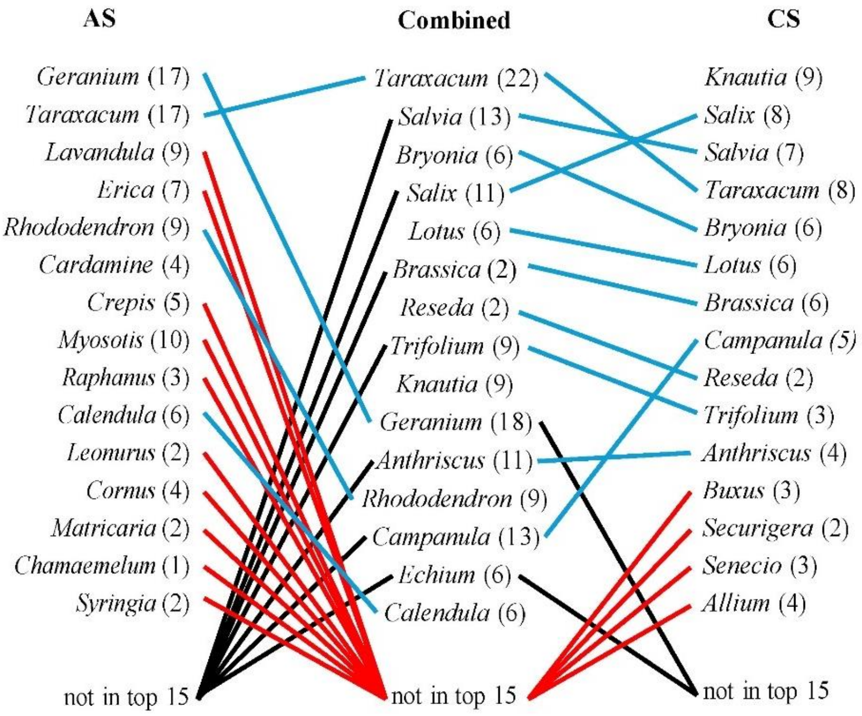

Figure 3: top 15 plant genera for increasing wild bee species richness for the AS-dataset, CS-dataset, and the combined datasets. Indicated in blue are the genera that are shared between the individual datasets and the combined dataset. In red are genera from the individual datasets that are not in the combined dataset and in black are the genera in the combined dataset that are also in the individual dataset but are not in their respective top 15 lists.

DISCUSSION

Our study shows that academic and citizen science data sources with their characteristic underlying methodology result in differences in the outcome of network analyses and subsequent recommendations for pollinator protection. Both datasets were compiled from sampling in the same wider area and focused on the same taxonomic group, but because they used different methodologies the resulting bee-flower networks and subsequent flower mix recommendations have little in common. Importantly, using one dataset over the other will therefore result in different practical conservation recommendations targeted at wild bees. The combined dataset however shows the potential for combining academic and citizen science data in order to create a more complete mix of flowers that is aimed at increasing species richness.

TAXONOMIC RESOLUTION

When assessing the interaction of wild bees with their floral resources, it is important to take host plant preference of the bees into account. This preference, as mentioned above, can either be for pollen or nectar. The pollen preference is a key factor since pollen is the food source for the offspring and as such directly connected to the next generation. Three types of pollen preference are distinguished (*sensu* Rasmussen et al. 2020): polylecty (generalists), oligolecty (specialist of a single plant genus), and monolecty (specialist of a single plant species). The nectar preference of bees is dependent on the colour and structure of the flower (Raguso 2004) and the sugar content of the nectar (Brown & Brown 2020). Especially the location of the nectar in the flower has considerable influence, with short-tongued bees being more limited in the range of flowers they are able to use. Flower preference of the bee community will directly affect the ideal flower composition, which is an important consideration when applying the flower tool, since a list of flowers can be created with plant species, genera or even families.

DATA LIMITATIONS

An important limitation in this type of study is the size and availability of comparable datasets. In our case, it was the lack of availability of citizen science observations that included both a photo of sufficient quality to be validated and a mention of the host plant on which the bee was observed. Overcoming this limitation can be accomplished by expanding the surveyed area but also by education of citizen scientists on how to photograph wild bees optimally (e.g. D'Haeseleer & Verheyen 2024) and by the emphasis on recording host plant information alongside the wild bee species identification when uploading observations to online portals. For the use of the flower tool, both of our datasets were smaller than the one used in the original paper of M'Gonigle et al. (2016). There, they used a dataset of 8,000 wild bee observations, consisting of 181 wild bee species, whilst the AS-dataset has 2,264 observations of 42 species and the CS-dataset only has 715 observation of 54 bee species (a similar number however to other studies such as Hadrava et al., 2022). These numbers do need to be put in the perspective of the location of the study. California, the location for the study of M'Gonigle et al. (2016), has a recorded 1,600 wild bee species (Frankie et al. 2009), while Belgium has 403 species, and the Brussels capital region has 246 (Drossart et al. 2019). This means that the dataset from M'Gonigle et al. (2016) included 11% of regional species, the AS-dataset includes 10.4% of Belgian species and 17.1% of Brussels' species, and the CS-dataset includes 13.4% of Belgian species and 22% of Brussels' species. Additionally, species accumulation curves indicate adequate sampling effort in both the AS- and CS-datasets (Supplementary material Fig. S4).

DATASET COMPARISON AND BIASES

The main difference in the bee-flower networks for the two datasets was due to differences in interactions of shared species, indicating that volunteers and researchers view the same bee species on different flowers or, conversely, they observe different bee species on the same flower. The two main reasons for this pattern are the difference in time scale between the datasets and the difference in vegetation composition between the individual locations. Flower phenology can vary from year to year, and it is likely that the CS-dataset captures this more accurately. Additionally, the difference in vegetation between the locations visited by volunteers (e.g. private gardens) and researchers (e.g. restricted protected areas) indicates that the suggested plants in the flower mixes could be associated with specific urban habitats. Based on this, one can argue that combining the two datasets would provide a comprehensive list of flowers for the entire urban environment. The difference in bee species composition between the datasets is likely due to the difficulty in the detection of rare bee species and the identification of smaller species (Griffiths-Lee et al. 2023). For the CS-dataset, even if the smaller bee species were located and photographed by the volunteers, a positive identification and therefore validation of the observation is highly unlikely. However, with the advancement of smartphone photography and identification via AI, this may become less of an issue towards the future. On the other hand, it is clear that the CS-dataset has more unique species that were missed by the academic sampling due to the difference in temporal scale or specific locations within the region, which consist for a large part of rarer and harder to locate species (e.g. *Melitta leporina* or *Andrena lathyri*). Again, combining the datasets has the potential to alleviate part of both of these sampling biases. It is crucial however, to understand how the composition of each individual dataset influences the statistical analyses of the combined dataset, and this is often not clear (Kosmala et al. 2016). CS-datasets are composed by volunteers but often include, as was the case with our CS-dataset, expert amateurs with a deep knowledge of the species group, and who are able to locate many, often rare species on a larger temporal and geographic scale. However, surveys by volunteers mainly focus on observing the widest range of species, forgoing observations of common species and thus creating skewed abundances. Conversely, academic surveys are often limited in range and time but give a better representation of relative abundance of species by following standardised observation protocols. As long as these biases are identified and corrected for (Ascher et al. 2020; Petersen et al. 2021), combining CS- and AS-datasets can lead to large, comprehensive datasets that encapsulate the entire floral spectrum of importance for wild bees of a target area. Moreover, when citizen science datasets represent an unbiased and standardised representation of the sampled areas and species (e.g. Vereecken et al. 2021), the academic sampling can shift its focus towards the underrepresented habitats and species, reducing workload and allowing the construction of much larger databases.

CONSERVATION IMPLICATIONS

The protection of pollinators encompasses a variety of measures, from conservation and restoration of habitats, reduction of pesticide use, reducing competition between native and exotic species, and providing sufficient (natural) resources (Decourtye et al. 2019). In order to accomplish the latter, we need a strong understanding of the floral needs of the wild bees and for this we need sufficient monitoring and analyses of bee-flower interactions. For monitoring, the benefits of the use of citizen science are clear, and the use of citizen science is encouraged or even recommended as long as the data has been gathered systematically and by standardised protocols (IPBES 2016; Potts et al. 2021), This data can then be used in conjunction with data collected and analysed by experts (Nichols et al. 2022). The applied use of plant-pollinator networks (Elle et al. 2012) together with modern tools and algorithms (e.g. M'Gonigle et al. 2016; Deguines et al. 2018) can aid not only in optimising wild bee abundance or species richness but also help in improving other important metrics for conservation, such as functional or phylogenetic diversity. For the flower tool, adding information on the different uses of the plants for the bees can give more insight into the importance of individual plants or certain plant groups. Some plants might be preferred for their pollen, while others for their nectar content, or even for their chemical composition (Klatt et al. 2013; Vanderplanck et al. 2023). An important caveat however is to consider that without creating sufficient and appropriate nesting opportunities for all different nesting strategies (e.g. open soil, cavities, stems), it is not possible to increase species richness by just adding pollen and nectar sources, independent on the amount of these resources added (Hadrava et al. 2022). Therefore, the plant mixes that the flower tool suggests, supplemented with expert input on plant placement and phenology (Klečka et al. 2018), and habitat restoration for nesting opportunities can be a powerful, accessible, and easy to use way of improving wild bee populations.

CONCLUSION

Our study shows that inherent biases that are present within different types of datasets greatly affect the outcome of the subsequent statistical analysis. Bot academic surveys and citizen science data have their uses for monitoring wild bees, especially in urban areas and can lead to evidence-based decisions for future conservation efforts aimed at our most important pollinators. The utilisation of modern statistical analyses such as the flower tool on large and harmonised datasets can lead to statistically robust assumptions about threats and drivers of population declines of wild bees. As such, we show that combining the two types of datasets has the potential to, at least partly, overcome gaps in sampling and identification methodologies. Finally, we believe it is of vital importance that organisations and the public are able to use results of studies such as this one. For this purpose, we have created an easy to use, open access app based on the tool from M'Gonigle et al. (2016). With this app, anyone may enter any plant-pollinator dataset, and the app will produce a plant mix of required size in order to maximise abundance, species richness, or both. For maximising species richness, the app will prioritise (datasets that contain) plants that serve as (close to) the only host for bee species, especially rare bee species. For abundance, the app will focus more on plants that support the largest number of specimens, indeterminate of the identity of the bee species. The datasets used in this study are also accessible here. Additionally, a visualisation option is added where the most important plant for each bee species can be viewed alongside a graphical representation of the number of visits per plant. The same options are available for the plants, in order to see which wild bee species is the most important visitor/pollinator.

The app is freely available at: https://lmar116.shinyapps.io/PlantSelect/.

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AUTHOR CONTRIBUTION

Concept and design JV & NV, data collection AD, JM & PV, data analysis JH, JV & NV, writing JV & NV, edits

JV, JH, LM & NV, and approval for publication all authors.

DISCLOSURE STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The two datasets are available in the shiny app. The plant tool code is available in the original paper by M'Gonigle et al. (2016) or upon request from the authors of this paper.

APPENDICES

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

Figure S1: top 20 bees for the AS-dataset

Figure S2: top 20 bees for the CS-dataset

Figure S3: Mosaic plots for the difference between the datasets in bee species and plant genera.

Figure S4: Rarefaction curve of the number of species in function of the number of individuals for the AS-dataset and the CS-dataset.

Table S1: Full list of all bee species and plant genera for the CS-dataset with the bee abundance per plant genus.

Table S2: Full list of all bee species and plant genera for the AS-dataset with the bee abundance per plant genus.

REFERENCES

Ascher JS, Marshall L, Meiners J, Yanega D, Vereecken NJ (2020) Heterogeneity in large-scale databases and the role of climate change as a driver of bumble bee decline. Science 8:685. https://science.sciencemag.org/content/367/6478/685/tab-e-letters

Baselga A (2009) Partitioning the turnover and nestedness components of beta diversity. Global Ecology and Biogeography 19:134-143. https://doi.org/10.1111/j.1466-8238.2009.00490.x

Baselga A, Orme D, Villeger S, De Bortoli J, Leprieur F, Logez M, Henriques-Silva R (2021) R package version 1.5.4.

Brown M, Brown MJF (2020) Nectar preferences in male bumblebees. Insectes Sociaux 67:221-228. https://doi.org/10.1007/s00040-020-00751-y

Cane JH, Sampson BJ, Miller SA (2011) Pollination value of male bees: the Specialist bee *Peponapis pruinosa* (Apidae) at summer squash (*Cucurbita pepo*). Environmental Entomology 40:614-620. https://doi.org/10.1603/EN10084

Cariveau DP, Nayak GK, Bartomeus I, Zientek J, Ascher JS, Gibbs J, Winfree R (2016). The allometry of bee proboscis length and its uses in ecology. PLOS ONE 11:e0151482. https://doi.org/10.1371/journal.pone.0151482

Chen H (2021) Generate High-Resolution Venn and Euler Plots. R package version 1.7.1.

D'Haeseleer J, Verheyen S (2024) Hanteren en fotograferen van bijen Natuurpunt: Aculea-wilde bijen en wespen. [online] URL: https://www.youtube.com/watch?v=RUrNDo9y6f8 and [online] URL: https://drive.google.com/file/d/1-dFVP10PwckNMZfK0kmutDDJk4gdv_cm/view

Decourtye A, Alaux C, Le Conte Y, Henry M (2019) Toward the protection of bees and pollination under global change: present and future perspectives in a challenging applied science. Current Opinion in Insect Science 35:123-131. https://doi.org/10.1016/j.cois.2019.07.008

Deguines N, Julliard R, Lois G (2018) Fostering close encounters of the entomological kind. Frontiers in Ecology and the Environment 16:202-203. https://doi.org/10.1002/fee.1795

Doré M, Fontaine C, Thébault E (2020) Relative effects of anthropogenic pressures, climate, and sampling design on structure of pollination networks at the global scale. Global Change Biology 27:1266-1280. https://doi.org/10.1111/gcb.15474

Dormann FC (2023) Visualising Bipartite Networks and Calculating Some (Ecological) Indices. R package version 2.19.

Drossart M, Rasmont R, Vanormelingen P, Dufrêne M, Folschweiller M, Pauly A, Vereecken NJ, Vray S, Zambra E, D'Haeseleer J, Michez D (2019) Belgian Red List of bees. Belgian Science Policy 2018, (BRAIN-be - (Belgian Research Action through Interdisciplinary Networks) Presse Universitaire de l'Université de Mons, Mons.

Elle E, Elwell SL, Gielens GA (2012) The use of pollination networks in conservation. Botany 90:525-534. https://doi.org/10.1139/b11-111

Falk S (2020) Veldgids Bijen voor Nederland en Vlaanderen. Kosmos Uitgeverij, Utrecht.

Flaminio S, Ranalli R, Zavatta L, Galloni M, Bortolotti L (2021) Beewatching: a project for monitoring bees through photos. Insects 12:841. https://doi.org/10.3390/insects12090841

Fontaine C, Fontaine B, Prévot A (2021) Do amateurs and citizen science fill the gaps left by scientists? Current Opinion in Insect Science 46:83-87. https://doi.org/10.1016/j.cois.2021.03.001

Frankie GW, Throp RW, Hernandez J, Rizzardi M, Ertter B, Pawelek JC, Witt SL, Schindler M, Coville R, Wojcik VA (2009) Native bees are a rich natural resource in urban California gardens. California Agriculture 63:113-120. https://doi.org/10.3733/ca.v063n03p113

Geslin B, Gauzens B, Baude M, Dajoz I, Fontaine C, Henry M, Ropars L, Rollin O, Thébault E, Vereecken NJ (2017) Massively introduced managed species and their consequences for plant-pollinator interactions. Advances in Ecological Research 57:147-199. https://doi.org/10.1016/bs.aecr.2016.10.007

Goulson D, Lye GC, Darvill B (2008) Diet breadth, coexistence and rarity in bumblebees. Biodiversity and Conservation 17:3269-3288. https://doi.org/10.1007/s10531-008-9428-y

Griffiths-Lee J, Nicholls EK, Goulson D (2023) Sow wild! Effective methods and identification bias in pollinator-focused experimental citizen science. Citizen Science Theory and Practice. https://doi.org/10.5334/cstp.550

Hadrava J, Talašová A, Straka J, Benda D, Kazka J, Klečka J (2022) A comparison of wild bee communities in sown flower strips and semi-natural habitats: a pollination network approach. Insect Conservation and Diversity 15:312-324. https://doi.org/10.1111/icad.12565

IPBES (2016) The assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food production. Potts SG, Imperatriz-Fonseca VL, Ngo HT (eds). Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn.

Kindt R (2022) Tree diversity analysis: a manual and software for common statistical methods for ecological and biodiversity studies. R package version 2.1.4-1.

Kosmala M, Wiggins A, Swanson A, Simmons B (2016) Assessing data quality in citizen science. Frontiers in Ecology and the Environment 14:551-560. https://doi.org/10.1002/fee.1436

Klatt BK, Burmeister C, Westphal C, Tscharntke T, Von Fragstein M (2013) Flower volatiles, cope varieties and bee responses. PLOS ONE 8:e72724. https://doi.org/10.1371/journal.pone.0072724

Klečka J, Hadrava J, Koloušková P (2018) Vertical stratification of plant-pollinator interactions in a temperate grassland. PeerJ 6:e4998. https://doi.org/10.7717/peerj.4998

Kuppler J, Neumüller U, Mayr A, Hopfenmüller S, Weiss K, Prosi R, Schanowski A, Schwenninger H, Ayasse M, Burger H (2023) Favourite plants of wild bees. Agriculture Ecosystems & Environment 342:108266. https://doi.org/10.1016/j.agee.2022.108266

LeBuhn G, Griswold T, Minckley R, Droege S, Roulston T, Cane J, Parker F, Buchmann S, Tepedino V, Williams N, Kremen C, Messenger O (2003) A standardized method for monitoring Bee Populations - The Bee Inventory (BI) Plot. [online] URL: https://fliphtml5.com/qaug/ytoo/basic

MacIvor JS, Moore AE (2013) Bees collect polyurethane and polyethylene plastics as novel nest materials. Ecosphere 4:1-6. https://doi.org/10.1890/ES13-00308.1

Malek R, Tattoni C, Ciolli M, Corradini S, Andreis D, Ibrahim A, Mazzoni V, Eriksson A, Anfora G (2018) Coupling traditional monitoring and citizen science to disentangle the invasion of *Halyomorpha halys*. International Journal of Geo-Information 7:151. https://doi.org/10.3390/ijgi7050171

M'Gonigle LK, Williams NM, Lonsdorf E, Kremen C (2016) A tool for selecting plants when restoring habitat for pollinators. Conservation Letters 10:105-111. https://doi.org/10.1111/conl.12261

Nichols RN, Holland JM, Goulson D (2022) A novel farmland wildflower seed mix attracts a greater abundance and richness of pollinating insects than standard mixes. Insect Conservation and Diversity 16:190-204. https://doi.org/10.1111/icad.12624

Nieto A, Roberts SPM, Kemp J, Rasmont P, Kuhlmann M, García Criado M, Biesmeijer JC, Bogusch P, Dathe HH, De la Rúa P, De Meulemeester T, Dehon M, Dewulf A, Ortiz-Sánchez FJ, Lhomme P, Pauly A, Potts SG, Praz C, Quaranta M, Radchenko VG, Scheuchl E, Smit J, Straka J, Terzo M, Tomozii B, Window J, Michez D (2014) European Red List of bees Publication Office of the European Union, Luxembourg.

Normandin E, Vereecken NJ, Buddle CM, Fournier V (2017) Taxonomic and functional trait diversity of wild bees in different urban settings. PeerJ 5:e3051. https://doi.org/10.7717/peerj.3051

Ogilvie JE, Thomson JD (2015) Male bumble bees are important pollinators of late-blooming plant. Arthropod-Plant Interactions 9:205-213. https://doi.org/10.1007/s11829-015-9368-x

Oksanen J, Simpson GL, Blanchet FG, Kindt R, Legendre P, Minchin PR, O'Hara RB, Solymos P, Stevens MHH, Szoecs E, Wagner H, Barbour M, Bedward M, Bolker B, Borcard D, Borman T, Carvalho G, Chirico M, De Caceres M, Durand S, Evangelista HBA, FitzJohn R, Friendly M, Furneaux B, Hannigan G, Hill MO, Lahti L, Martino C, McGlinn D, Ouellette MH, Cunha ER, Smith T, Stier A, Ter Braak CJF, Weedon J (2025) Package vegan: community ecology package. R package version 2.6-10.

Olsson RL, Brousil MR, Clark RE, Baine QB, Crowder DW (2021) Interactions between plants and pollinators across urban and rural farming landscapes. Food Webs 27:e00194. https://doi.org/10.1016/j.fooweb.2021.e00194

Philips RD, Peakall R, van der Niet T, Johnson SD (2020) Niche perspectives on plant-pollinator interactions. Trends in Plant Science 25:779-793. https://doi.org/10.1016/j.tplants.2020.03.009

Petersen TK, Speed JDM, Grøtan V, Austrheim G (2021) Species data for understanding biodiversity dynamics: The what, where and when of species occurrence data collection. Ecological Solutions and Evidence 2:e12048. https://doi.org/10.1002/2688-8319.12048

Poisot T, Canard E, Mouillot D, Mouquet N, Gravel D (2012) The dissimilarity of species interaction networks. Ecology Letters 15:1353-1361. https://doi.org/10.1111/ele.12002

Poisot T (2016) Beta-Diversity of Species Interactions. R package version 2.2.1.

Potts SG, Biesmeijer JC, Kremen C, Neumann P, Schweiger O, Kunin WE (2010) Global pollinator declines: trends, impacts and drivers. Trends in Ecology & Evolution 25:345-353. https://doi.org/10.1016/j.tree.2010.01.007

Potts SG, Dauber J, Hochkirch A, Oteman B, Roy DB, Ahrné K, Biesmeijer K, Breeze TD, Carvell C, Ferreira C, FitzPatrick Ú, Isaac NJB, Kuussaari M, Ljubomirov T, Maes J, Ngo H, Pardo A, Polce C, Quaranta M, Settele J, Sorg M, Stefanescu C, Vujić A (2021) Proposal for an EU Pollinator Monitoring Scheme. Publications Office of the European Union, Luxembourg

Prendergast KS, Dixon KW, Bateman PH (2022) A global review of determinants of native bee assemblages in urbanised landscapes. Insect Conservation and Diversity 15:385-405. https://doi.org/10.1111/icad.12569

R Development Core Team (2022) R: The R Project for Statistical Computing. [online] URL: https://www.r-project.org.

Raguso RA (2004) Flowers as sensory billboards: progress towards an integrated understanding of floral advertisement. Current Opinion in Plant Biology 7:434-440. https://doi.org/10.1016/j.pbi.2004.05.010

Ramos-Jiliberto R, Moisset de Espanés P, Vázquez DP (2020) Pollinator declines and the stability of plant-pollinator networks. Ecosphere 11:e03069. https://doi.org/10.1002/ecs2.3069

Rasmussen C, Engel MS, Vereecken NJ (2020) A primer of host-plant specialization in bees. Emerging Topics in Life Sciences 4:7-17. https://doi.org/10.1042/ETLS20190118

Stang M, Klinkhamer PGL, Van Der Meijden E (2006) Size constraints and flower abundance determine the number of interactions in a plant-flower visitor web. OIKOS 112:111-112. https://doi.org/10.1111/j.0030-1299.2006.14199.x

Vanderplanck M, Marin L, Michez D, Gekière A (2023) Pollen as bee medicine: is prevention better than cure? Biology 12:497. https://doi.org/10.3390/biology12040497

Vereecken NJ, Weekers T, Marshall L, D'Haeseleer J, Cuypers M, Pauly A, Pasau B, Leclercq N, Tshibungu A, Molenberg JM, De Greef S (2021) Five years of citizen science and standardised field surveys in an informal urban green space reveal a threatened Eden for wild bees in Brussels, Belgium. Insect Conservation and Diversity 14:868-876. https://doi.org/10.1111/icad.12514