TYPE Perspective
PUBLISHED 09 January 2024
DOI 10.3389/fevo.2023.1347447

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OPEN ACCESS

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RECEIVED 30 November 2023
ACCEPTED 19 December 2023
PUBLISHED 09 January 2024

CITATION
Kueneman JG, Dobler CN and Danforth BN (2024) Harnessing community science to conserve and study ground-nesting bee aggregations.
Front. Ecol. Evol. 11:1347447.
doi: 10.3389/fevo.2023.1347447

Harnessing community science to conserve and study ground-nesting bee aggregations

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Protecting diverse solitary ground-nesting bees remains a pivotal conservation concern. Ground-nesting bees are negatively impacted by anthropogenic land use change that often removes suitable nesting habitat from the landscape. Despite their enormous ecological and agricultural contributions to pollination, solitary, ground-nesting bees are often neglected, partly due to the significant obstacle of discovering exactly where these bees establish their nests. To address this limitation, we have developed a 'community science' project to map aggregations of ground-nesting bees globally. In certain locations, their abundances reach astounding levels, sometimes in the millions, but are scarcely known. Utilizing the iNaturalist platform, which permits geo-referencing of site observations and bee identification, we are providing public education and seeking public engagement to document bee aggregations in order to understand the nesting requirements of diverse species and open new opportunities for their conservation. Conservation priorities may then unequivocally be directed to areas of high species richness, nest densities, and nesting sites of rare bees. Such community-led efforts are vital for successful long-term management of native bees and the biotic and abiotic landscape data from nest-site localities can allow modeling to predict nest-site suitability and to readily test such predictions on the ground. Here, we summarize the progress, current limitations, and opportunities of using a global mapping project (GNBee) to direct conservation efforts and research toward solitary ground-nesting bees.

KEYWORDS

ground-nesting bees, solitary bees, nesting aggregation, community science, citizen science (CS), iNaturalist, species occurrence data, conservation

Introduction

Pollination services provided by bees are essential for sustaining the genetic variability in 85% of flowering plants and vital for securing yields of pollinator-dependent crops (Ollerton, 2017; Zattara and Aizen, 2021; Katumo et al., 2022). For 125 million years, bees have coevolved with and facilitated the vast radiation of flowering plants (300,000 angiosperm species), thus establishing terrestrial food webs (Vannette, 2020). To meet the extraordinary demand of pollinating diverse angiosperms, there are approximately 20,000 bee species, which differ greatly in morphology, life history, nesting habits, and the flower species with which they interact (Danforth et al., 2019). Despite the diversity of bee species, significant conservation concerns exist, and loss of bee diversity can negatively impact terrestrial ecosystems by reducing the genetic diversity of plants, which can lead to reduced ecosystem resilience (Potts et al., 2010).

Bees, like many organisms, face threats from human activities, primarily landscape changes, habitat loss, pesticide use, and invasive parasites (Willis Chan et al., 2019; Willis Chan and Raine, 2021; Zattara and Aizen, 2021). Studies, including those related to climate change, have consistently reported declines in bee populations, with shorter-term assessments at local, regional, or country levels (Biesmeijer et al., 2006; Goulson et al., 2008; Bartomeus et al., 2013; Ollerton, 2017; Powney et al., 2019; Simanonok et al., 2021; Janousek et al., 2023). Longer and broader assessments, biased toward the Northern Hemisphere, also confirm the decline in bee abundance and diversity (Sánchez-Bayo and Wyckhuys, 2019; Thomas et al., 2019). Zattara and Aizen (2021) conducted a global-scale study revealing a steady decline in the number of bee species observed since the 1990s, with 25% fewer species reported between 2006 and 2015 compared to before the 1990s. This collective evidence underscores the urgent need for swift actions to prevent further declines in bee populations.

Bees and their environmental struggles are currently experiencing increased attention in the media, and this is resonating with the public. However, this attention is largely centered around honey bees. The honey bee has been lauded as a conservation concern to the public, perhaps at the behest of commercial interests, and as a result, we are seeing an increase in backyard or rooftop honey bee husbandry. Unfortunately, honey bees, while great for inspiring public interest in insects, have overshadowed critical messaging about bee diversity and biologically sound conservation efforts. Managed honey bees, while beneficial in many agriculture settings, have been shown to outcompete native species (Iwasaki and Hogendoorn, 2022; Page and Williams, 2023) and can spread parasites and pathogens (Stout and Morales, 2009; Prendergast et al., 2022). Indeed, the honey bee is to bee diversity as the chicken is to bird diversity, and as a result, society is fixating on the wrong bees.

Subsection 1: Changing our societal perspective to value diverse ground-nesting bees

When people think of bees in the temperate zone, rather than only imagining a honey bee or bumble bee they should also envision solitary bees. Approximately 75% of described bee species are solitary, meaning each female constructs her own nest, provisions her own brood cells and lays her own eggs (i.e., there is no reproductive division of labor or cooperative brood care). If we combine brood parasitic bees, the solitary bees and their brood parasites account for ~90% of all bee species (Danforth et al., 2019).

Most of your average bee's life occurs during development, from egg to larva to pupa, and these stages are often punctuated by diapause (a period of suspended development, either as adults or last instar larvae). Solitary bee flight activity, which may last only a few weeks in many species, begins with their emergence as newly formed adults. Males typically emerge first and mate with females that store sperm in their spermathecae (Danforth et al., 2019). Males then perish, and females are left to choose a nesting site and begin the process of provisioning for the next generation. While each individual species has a relatively short period of adult flight activity, the diversity of species in one area allows for continual emergence and activity that corresponds with the pollination needs of native flowering species in the region. Solitary female bees generally construct and provision brood cells one at a time. They are 'single mothers hard at work', and their work is typically out of sight and underground.

The solitary, below-ground-nesting strategy is believed to be ancestral in bees and is shared with their crabronid wasp ancestors (Debevec et al., 2012; Sann et al., 2018). Ground-nesting is observed in every bee family and all places where bees occur (Danforth et al., 2019). It is estimated that approximately 75% of all bee species are ground-nesting (Antoine and Forrest, 2020; Harmon-Threatt, 2020). A typical bee takes one (or sometimes more) year(s) to develop and receives no additional parental care after the egg is laid. Successful development can only be achieved when bees nest in soils suitable to their biology with preferred environmental conditions (Harmon-Threatt, 2020), and the nesting substrates chosen by females appear to be specific to each species (Cane, 1991; Antoine and Forrest, 2020).

Antoine and Forrest (2020) provide a comprehensive review of ground-nesting bee site preferences in their published paper. They summarize research on abiotic factors, including soil compaction, moisture, temperature, surface features, and slope, that influence suitable nesting habitats. Their review also covers biotic factors that may influence nesting, such as the abundance of natural enemies, the density of conspecifics, and the availability and quality of floral resources. It is therefore not necessary to re-synthesize these attributes here, however it is paramount to convey that there are still substantial gaps in our understanding of ground-nesting bee biology. In a survey of the literature on the approximately 3,000 bee species in America north of Mexico, Harmon-Threatt (2020) examined the literature on 527 randomly selected species and found that only 20% of those species had any information on nesting biology. Indeed, most of our knowledge regarding nesting biology (nest architecture, immature stages of bees, parasites etc.), come from field observations typically done at a single locality, making it difficult to confidently identify general characteristics of each species (Antoine and Forrest, 2020). Several studies of multiple nesting sites and bee species have begun to uncover and compare the nesting depths (Cane and Neff, 2011) and soil parameters of that characterize each species (Tsiolis et al., 2022; Ulyshen et al., 2023). However, these efforts are only scratching the surface of what is possible and what needs to be done. Therefore, we recognize substantial opportunities to improve our understanding of nesting behavior which can be used to improve bee conservation.

Subsection 2: Conservation and efforts to manage and enhance ground-nesting bees

Bee conservation efforts for diverse wild bees principally focus on enhancing floral resources. As a result, ways to promote food resource availability are relatively well developed and include organized efforts, such as planting pollinator gardens, planting wildflower strips in public spaces, planting in unused agricultural lands or edge habitat, and community campaigns like No Mow May (Potts et al., 2003; Sheffield et al., 2008; Mader et al., 2011; Kirk and Howes, 2012; Rosa García and Miñarro, 2014; M'Gonigle et al., 2017). More recently, conservation efforts have expanded to include methods for enhancing nesting resources of above-ground cavity nesters, such as leaf-cutter bees and mason bees (MacIvor and Packer, 2015; Fortel et al., 2016). While the aforementioned strategies have had some positive and some mixed outcomes, they do not address the core limitations for most bee species (Gathmann and Tscharntke, 2002; Potts et al., 2005; Michener, 2007; Williams et al., 2011; Dicks, 2013). Rather, the vast majority of bee species are ground-nesting and limited by available nesting habitat, and with several notable exceptions discussed below and outlined in Table 1, few studies have tried to enhance nesting resources for ground-nesting bee species.

Particularly relevant to conservation of solitary ground-nesting bees, for most species, there is pronounced natal philopatry (i.e., females tend to nest in the same site as their mother), a condition unique, yet preset across diverse groups of animals (Byer and Reid, 2022). Nesting sites for many ground-nesting bee species can remain active for decades (Danforth et al., 2019) and we do not yet know the upper bounds of fidelity to a nesting location for ground-nesting bee species. This is a major component of ground-nesting bee biology that can build community engagement and facilitate research and conservation efforts. Clearly, nesting sites and nesting resources are not ubiquitous across the landscape and are not uniform in their ability to support bee communities (Potts et al., 2003; Grundel et al., 2010). Therefore, increased focus on the soil requirements and resources for ground-nesting species can improve conservation efforts.

To date, only a handful of studies have actively tried to promote the richness and abundance of ground-nesting bee species by constructing man-made or environmentally altered nesting habitat (Table 1). The most successful example of this work pertains to the sole species of managed ground-nesting bees, *Nomia melanderi* (Cane, 2008). Despite *N. melanderi's* peculiar affinity to bare, smooth, damp, salty alkaline soils, this gregarious, generalist bee has become the best studied species of ground-nesting bee in the world (Cane, 2023). Its success as a managed pollinator in the US is largely driven by its ability to propagate within man-made bee beds constructed in the vicinity of alfalfa fields. Since it can tolerate colder temperatures, it emerges when many other bees remain inactive to pollinate alfalfa alongside another managed stem nesting bee, *Megachile rotundata* (Pitts-Singer and Cane, 2011). Together they produce seed valued at $22 billion annually. The pairing of ground-nesting bee biology with agricultural objectives can offer substantial opportunities and benefits in agricultural systems and similar outcomes may be possible for other agricultural crops and non-crop plant species. Thus, there is a natural alliance between farmers and native ground-nesting bees that should be nurtured.

Subsection 3: Citizen science applied to the discovery of ground-nesting bees

Large-scale environmental science often requires a 'community science' approach (also called 'citizen science' or 'participatory science'). In this research methodology, non-professionals contribute their time, energy or expertise to a research aim. Community science makes the activity of discovery and observation available to all, not just a privileged few, and is an effective method of upscaling research projects and adoption of innovations both temporally and spatially (Pocock and Evans, 2014). As a result, research that involves community science is becoming increasingly common and includes projects on climate change, invasive species, conservation biology, ecological restoration, and monitoring of all sorts (Silvertown, 2009; Dance, 2022). For example, the Christmas Bird Count, run by the National Audubon Society, has taken place every year since 1900, generating one of the most impressive biological datasets that we have (63 million observations). Indeed, in many countries, community scientists are the bedrock of biological recording and monitoring.

Community science has previously been applied to projects on bees; for example, identifying the diversity of bees found on flowers across an urban gradient in France (Deguines et al., 2016), and assessing the numbers of squash bees found on farmland in Michigan, USA (Appenfeller et al., 2020). In an encouraging study, Maher et al. (2019) used a community science approach to locate and investigate the nesting requirements of four species of gregarious ground-nesters (394 nesting sites across the UK and Ireland): *Andrena cineraria* and *A. fulva* (Andrenidae), *Halictus rubicundus* (Halictidae) and *Colletes hederae* (Colletidae). Even with the limited foraging ranges of most bees, locating nesting sites is a substantial challenge in studying and/or conserving ground-nesting bees (O'Connor et al., 2012; Antoine and Forrest, 2020). It is therefore significant that a community science project successfully overcame this obstacle, and Maher et al.'s (2019) study also suggests this approach could be used to discover nesting site locations at larger scales. However, to do so, a more robust and sustained effort must be employed.

Project GNBee (GNBee.org) champions a community science approach to research, conservation of ground-nesting bees. This project aims to connect amateur observers (nest site discoverers) to experts in real time, working together to identify and validate new ground-nesting bee records. To date, Project GNBee contains over 2,500 observations of over 240 bee species. Contributions have been made by over 1300 people worldwide, and real-time records can be

TABLE 1 Studies that actively manage ground-nesting bees (excluding *Nomia melanderi*).

Location	Approch	Outcome	Reference
Baden-Württemberg, Germany	Removed vegetation, creating patches of bare ground. Soil nesting bee diversity and richness was recorded.	Increased biodiversity of ground-nesting bees.	Wesserling and Tscharntke (1995)
Surrey, England	Removed vegetation, creating patches of bare ground. Soil nesting bee diversity and richness was recorded.	Increased biodiversity of ground-nesting bees.	Edwards (1996)
West Sussex, England	Removed vegetation, creating patches of bare ground. Soil nesting bee diversity and richness was recorded.	Increased biodiversity of ground-nesting bees.	Edwards (1998)
Oregon, USA	Created experimental plots for endangered legume (Kincaid's lupine).	Documented nesting of *Lasioglossum anhypops.*	Severns (2004)
Oxford, Englend	Constructed 3 x 5 m slightly slopping bays, with a rear vertical face of 30 cm, to attract ground-nesting bees.	All bays were colonized in the first year and 80 solitary bees and wasps were recorded after 3 years.	Gregory and Wright (2005)
Logan, Utah, USA	Made soil plots with and without a pebble layer on top.	Found that flat stream pebbles promoted aggregations of the bee *Halictus rubicundus*.	Cane (2015)
Grand Lyon, France	Constructed 1 m soil squares with varying sand content in an urban setting. Removed plant growth within soil squares.	Documented 16 species of bees nesting in their plots. Soil texture had little influence on bee richness.	Fortel et al. (2006)
Göttingen, Germany	Removed vegetation in grasslands and examined nesting activity rates. Examined effect of adjacent floral resources.	Recoreded that the number of bee nests in areas with removed cover was 14 times higher. Documented a positive corralation between nesting activity and proximity to floral resrouces.	Gardein et al. (2022)
20 regions in Germany	Constructed nesting hills to attract ground-nesting bees.	Increased biodiversity of groud nesting bees. Bees preferred south facing sites with high soil temperatures. Substrate composition played a minor role in community assembly.	Neumüller et al. (2022)
Kent, England	Prepared plots of bare soil within an orchard with the aim of attracting ground-nesting bees.	Found that soil stoniness and increased soil temperature facilitated ground-nesting bees, and that increased vegetation cover and hydraulic conductivity inhibited ground-nesting bees in their study plots. While not significant across the study, soil compaction had a large influence on the length of time for nesting recruitment in the plots.	Tsioli et al. (2022)
Kent, England	Treated areas within apple orchards with herbicide to increase bare ground.	Fourteen species of ground-nesting solitary/eusocial bees were identified over three years and most nests occurred in areas free of vegetation, including areas treated with herbicide.	Fountain et al. (2023)

found at iNaturalist (https://www.inaturalist.org/projects/ground-nesting-bees-3e6882c0-a112-4ddb-b043-1da25638ce96). All observations are geolocated and thus provide the basis for studies of nesting biology, behavior, and ecology of ground-nesting bee species at local, regional and national scales (Figure 1). Furthermore, sampling and gathering observational data at nesting sites can help develop species distribution models to predict where additional nest sites are located and also prioritize conservation efforts at local and regional scales.

Discussion

The development of a robust global database that identifies ground-nesting bee sites has significant implications for understanding native bee ecology and offers new opportunities for native bee conservation. However, we must acknowledge several limitations. First, there is significant observation bias toward common bee species that make large and conspicuous aggregations. While such large aggregations are an intended focal target of Project GNBee, due to their sizable ecological contribution, many species nest at low densities with a few nests scattered over a large geographic area. Still others species nest under leaf litter or in dense vegetation. In these less visible cases, our community-driven approach to uncovering their nesting locations is far more difficult. Therefore, the detectability, which drives the species composition of our observations, will be biased. Second, the quality of our data is limited by the collective knowledge of our community. Thus, we seek experts and experienced amateurs to visit these sites and provide additional observations. Repeated observations from known sites, as well as observations in the literature, not currently available in Project GNBee, will help generate a consensus and

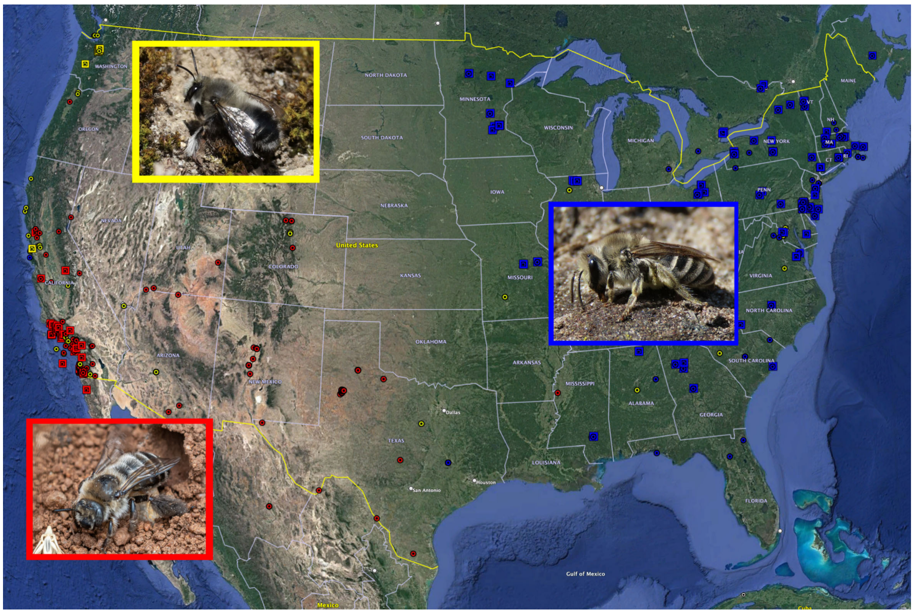

FIGURE 1
Potential to study bees at distinct scales and taxonomic levels: yellow = local and *Anthophora*, red = regional and *Diadasia*, and blue = national and *Colletes*. Yellow squares are records of *Anthophora pacifica*, red squares are records of *Diadasia bituberculata*, and blue squares are records of *Colletes inaequalis*.

improve the quality of the data by adding new sites and tracking bee seasonality and population dynamics through time.

Despite certain limitations and biases, Project GNBee can help fill current gaps in knowledge. The GNBee database has already incorporated rare bee nesting sites with high conservation priority, nest aggregations over 80 years in age, and numerous previously unknown high-density sites, several containing hundreds of thousands to well over a million individual solitary bees (Guilian et al., in prep; Hoge et al., in prep). Thus, we now can meaningfully prioritize discrete locations for research and conservation of ground-nesting bees.

Uniquely, aggregations can connect with people. A nesting aggregation is a place where bees live, much like a place in which humans live. One can return to nesting aggregations day after day to observe bees during their flight activity – a feature not possible in most animal community science projects. As such, these locations are part of a basic, local heritage. This can enhance efforts of property owners and land management agencies to prioritize the conservation of their resident bees. Signage (e.g., 'Wild bee crossing') that delivers educational information to the public should also be made available at these sites. Such on-site education and outreach could have profound impact on public sentiment and support. When possible, conservation agencies may seek to extend more robust protection to the most biologically significant nest sites, either through land acquisitions or through partnerships that establish guardians of these sites. We hope to make such recommendations in the future.

Beyond the conservation envelope, we are already able to study and compare the requirements of ground-nesting bees from locations in our own backyards to sites around the world. As such, we can move beyond single site descriptions of nesting biology and begin to understand the broader range of biotic and abiotic conditions that are required for a ground-nesting bee aggregation to persist. Furthermore, we can then attribute the degree of success (based on population size) of these local populations to their nesting conditions. This approach may help uncover meaningful predictors of nesting success within a species, across multiple species, and though space and time. While several attributes may be 'reliably' sourced using GIS, many attributes can be validated by the 'community of scientists' engaged with the project, who can send samples for further analysis. By using both remote sensing and community participation at scale, we plan to refine our models for predicting where individual bee species will be most likely to nest and how successful they are likely to become. Exploiting this framework, we may offer the building blocks needed to promote a more inclusive and robust community of pollinators that include the ground-nesting bees and lead to their successful management.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Ethics statement

The manuscript presents research on animals that do not require ethical approval for their study.

Author contributions

JK: Conceptualization, Funding acquisition, Writing – original draft, Writing – review & editing. CD: Writing – review & editing. BD: Funding acquisition, Supervision, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This project was funded by the Cornell Atkinson Center for Sustainability – Academic Venture Fund and NSF grant 1398331.

Acknowledgments

We acknowledge and thank the entire iNaturalist community who collected, identified and publicly shared the ground-nesting bee observation data. We would like to thank John Asher, Zackary Portman, and several other unidentified individuals for their significant contributions to the platform.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2023.1347447/full#supplementary-material

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