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Geospatial Tools for North American Native Bee Inventorying and Monitoring

Strategic Recommendations and Mapping Priority Areas

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List of Abbreviations and Acronyms

CEC	Commission for Environmental Cooperation
ECA	Environmental Cooperation Agreement
GBIF	Global Biodiversity Information Facility
GIS	Geographic Information System
HPZ	High Potential Zone
IUCN	International Union for the Conservation of Nature
SCAN	Symbiota Collections of Arthropods Network
SGCN	Species of Greatest Conservation Need

Abstract

Pollinators play a crucial role in sustaining natural ecosystems and ensuring food security. With their contribution to the reproduction of a significant portion of crop species and wild plants, their decline poses grave threats to the environment and to society. Proactive steps are needed to effectively address pollinator conservation on a continental scale. Native bee experts from Canada, Mexico and the United States are using various geospatial decision-making tools that aim to empower stakeholders with comprehensive data for informed conservation actions. These tools can facilitate targeted research efforts and foster public awareness and engagement, particularly in identified priority areas for native bee inventorying and monitoring. By joining their efforts and sharing knowledge, experts from North America aimed to align the goals of land managers, policymakers, scientists, and educators, and have identified existing geospatial tools, proposed enhancement, and created range maps for common bee species. By leveraging technology and collaboration, this work aims to bolster pollinator conservation efforts throughout North America, safeguarding these vital species for generations to come.

Executive Summary

Pollinators are vital for the sustainability of natural ecosystems, food security, and human well-being, supporting the reproduction of a significant portion of crop species and wild plants. However, worldwide declines in pollinator populations, due to various factors, pose significant threats to the environment and society.

Through workshops convened by the Commission for Environmental Cooperation, North American native bee experts refined and implemented geospatial decision-making tools to aid land managers, academics, researchers, and practitioners in prioritizing native bee inventories and monitoring efforts. They have identified conservation goals, explored available geospatial tools, suggested enhancements, created range maps, and determined priority areas for bee inventorying and monitoring.

To aid and foster collaboration on a continental scale, this report presents essential strategies for advancing pollinator conservation throughout North America. By describing existing tools and proposing the development of comprehensive, user-friendly geospatial resources, this report aims to support researchers, land managers, policy makers and stakeholders in understanding bee populations and identifying conservation priorities. In addition, it highlights the urgent need for action to promote the long-term health of pollinator communities.

Recognized challenges in bee data collection and utilization include the need to digitize historical data, the lack of standardization across contemporary records, the capacity for incorporating citizen science data, and integrating Traditional Ecological Knowledge. Proposed strategies to address these challenges include prioritizing digitization efforts, incentivizing taxonomic work, acknowledging citizen science contributions, and engaging with Indigenous communities.

Based on expert opinion, North American priority areas for bee inventory, monitoring and conservation were identified, emphasizing regions with high species' richness and under-sampled areas. To effectively address these priorities, an ideal geospatial tool should amalgamate data from various sources, visualize bee occurrences across different spatial scales, incorporate specimen-level data, and facilitate data sharing and community engagement.

Acknowledgments

In attendance at the CEC native bee workshops; October 2022 through April 2023:

*Disclaimer: The affiliations of workshop participants mentioned in this report are included for reference purposes only. Note that participants' contributions were made in their personal and professional capacity as experts. The views and opinions expressed in the report are solely those of the participants and do not necessarily represent the positions of their affiliated organizations.

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1 Background

Pollinators are fundamental to natural ecosystems, food security, and human well-being, as they support the reproduction of 75–85% of crop species and 80–90% of wild angiosperms. Worldwide pollinator declines, resulting from habitat degradation and loss, intensive agricultural management, superfluous agrochemical use, invasive species, pathogens, and climate change, have significant repercussions for the natural environment, and human well-being, and require immediate attention. It is increasingly vital to recognize the environmental, social, and economic benefits that pollinators provide to communities, food production, and natural ecosystem functioning (CEC 2020). Efforts to develop and maintain effective decision-making tools and communications materials that bolster stakeholder engagement and community involvement, especially on a continental scale, will be increasingly meaningful in the face of significant pollinator losses.

The Commission for Environmental Cooperation (CEC) is an international organization collectively established by Canada, Mexico, and the United States under the Free Trade Agreement and the Environmental Cooperation Agreement (ECA). The CEC promotes direct collaboration and public participation to cultivate conservation, protection, and enhancement of the North American environment in the context of increasing trade, economic, and social networks for the benefit of present and future generations.

Building on enduring work for monarch butterflies and other pollinators, the CEC met in 2019 and 2020 with the aim of strengthening regional pollinator conservation in order to secure local benefits. They sought to identify the gaps in knowledge about pollinators and pollinator health, as well as to discuss ways of engaging local communities to focus on pollinator-friendly initiatives and to provide those communities with information about the ecological and socioeconomic benefits of pollinators. Significant knowledge gaps, particularly about native bees, were identified as needing to be addressed in future work.

Continuing its work on pollinators, the CEC launched a new project, titled ‘Advancing Pollinator Conservation Throughout North America,’ as part of its 2022 Operational Plan (CEC 2022). This project’s collaborations focused on sharing lessons learned, best practices, and strategies to inform native bee inventorying and monitoring. The goal was to identify ways to equip land managers and decision makers with more robust data that would better inform conservation actions across North America: incorporating new and emerging tools that could address the paucity of relevant data. Furthermore, the project promoted effective decision-making tools and communication materials to better organize and prioritize native bee inventory and long-term monitoring efforts and increase awareness about the importance of native bees. Finally, it also aimed to facilitate citizen science and community engagement across the three countries.

In total, five meetings were held: two online meetings in early May 2022, an in-person meeting in Santa Fe, New Mexico, United States, in October 2022, an online meeting in January 2023, and a final in-person meeting in Mexico City, Mexico, in April 2023. These meetings brought together pollinator experts from Canada, Mexico, and the United States to discuss the refinement and implementation of geospatial decision-making tools, for the use of land managers, academics, researchers, educators, practitioners, policy makers and other key audiences across North America. These tools can help to identify priority areas for native bee inventorying and long-term monitoring for each country, motivating more focused research endeavors, and supplying more relevant data to inform conservation, outreach efforts, and promote public curiosity and community engagement.

The objectives of these meetings were to: 1) identify bee conservation and native bee management as goals for policy makers, scientists, and educators, 2) explore currently available geospatial tools that can help with these goals, 3) suggest improvements to geospatial tools in service of the stated goals, 4) create niche-modeled range maps for common bee species, in order to increase the usefulness of some geospatial tools, and 5) determine areas where inventorying and monitoring of bees would most aid our understanding of bee distributions.

2 Definitions

A common understanding of foundational concepts was needed to ensure that all participants had a shared frame of reference. These concepts included:

> **Geospatial tool:** A geographic information system (GIS)-based mapping tool that helps users better understand bees: their ranges of distribution, areas of occupancy, and abundance. It can show trends through time—in terms of population dynamics—and may rely on underlying data sources that provide specific information about bees (e.g., species name, floral preferences, nesting habitat, and phenology) and the geographies where they occur (e.g., ecoregion, climate, land use, ownership, habitat, soil type, coordinates of where specimens were collected, and more).
>
> **Hot spot:** An area of high bee richness. It may also refer to an area in which many species of interest occur, including species of conservation concern, and species with high levels of endemism. Participants recognized that hot spots are scale-dependent and may appear or disappear, depending on the scale of focus. It was also noted that hot spots are relative; they may not be recognized if sufficient historical collecting had not occurred, and they may falsely appear as richer than the surrounding area if the sampling effort was greater. Furthermore, hot spots are conceptually and functionally contingent on the inverse notion of cold spots.
>
> **Cold spot:** An area characterized by reduced species richness. Alternatively, a cold spot may be defined as an artifactual area where nominal or no collection efforts have occurred. Participants acknowledged that considerable discretion is essential if deprioritizing apparent cold spots, given the potential lack of data points in a geospatial tool. It is important to note that the term ‘cold spot’ does not imply that these areas are of little conservation concern or value.

Threatened, Species at risk, SGCN species: Each country shared a similar lexicon to describe organisms whose populations are decreasing or are otherwise imperiled. Specifically, the United States and Canada recognized NatureServe's Conservation Status Ranks, with the following rankings: 1) critically imperiled, 2) imperiled, 3) vulnerable, 4) apparently secure, or 5) secure, based on criteria including range extent, abundance, population trend, and potential threats. Canada further recognized Species at Risk with classifications including: 1) extinct, 2) extirpated, 3) endangered, 4) threatened, or 5) special concern, as well as species that are data deficient and not at risk. The United States recognized federally listed species under the Endangered Species Act, including: 1) endangered, 2), threatened, 3) proposed, or 4) candidate. Each US state has its own classification system, as do many provinces in Canada. Similarly, Mexico recognizes species that are: 1) extinct, 2) endangered, 3) threatened, and 4) under special protection. Everyone shared a common familiarity with the work of the International Union for the Conservation of Nature (IUCN) which relies on experts, an extensive review process, and all available data to create a red list of threatened species.

Stakeholders: Those individuals whose work includes bee conservation and management across numerous agencies, sectors, roles, and positions. Specifically, they included Indigenous communities, policy makers at the city, county, subnational (state/province/territory), and national levels, farmers, growers, and other agronomists, non-profits, journalists, scientists (such as taxonomists), and data intelligence officers, as well as land managers ranging from protected area directors and managers, watershed managers, and city planners, to government biologists and ecologists, and threatened and endangered species specialists. Examples of stakeholders include blueberry growers who are looking to know more about the distribution of *Habropoda laboriosa*, and suitability of nearby habitat in areas where blueberry farms occur; the US Bureau of Land Management, wildlife biologists tasked with identifying habitat that might harbor the declining *Bombus occidentalis*; US National Park Service natural resource managers, who want an inventory of bee species within their unit; taxonomists in Mexico looking for all areas where a particular taxon may occur; and zoologists in Canada whose work includes determining which bee species are imperiled, based on present distributions compared with historical distributions.

Standardized data are records of bee specimens that are being generated as part of an effort to standardize methodologies (i.e., documentation of sampling effort) so that scientists can compare bee populations across larger areas and over many years. Widely tested international standards—including Darwin Core, Plinian Core and the Global Biodiversity Information Facility (GBIF) standards—can be used for different types of records and mapping datasets.

3 State of the Science

3.1 Knowledge about bee distributions accumulates slowly

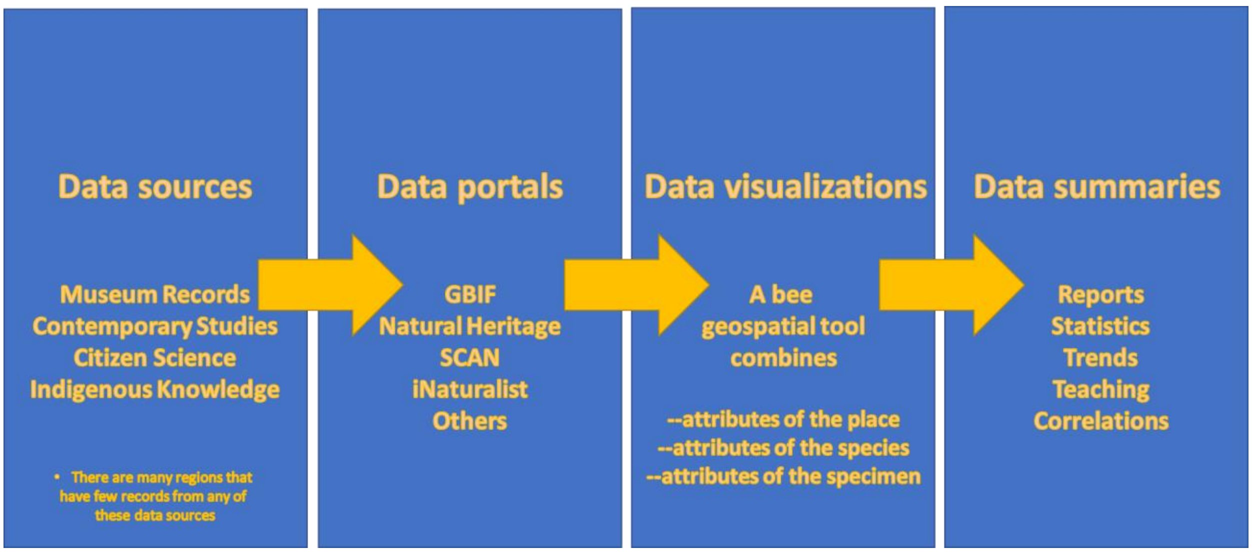
Historically, advances in the study of native bees have been gradual and sometimes tenuous. For many years, such occurrences were documented with locality lists and static maps. Much bee locality information, then and now, exists only on the label beneath a bee in a museum or private collection, and which may well have never been entered into a digital database. Recent estimates suggest that, of the eight million bee specimens that reside in insect collections across North America, just over two million (25%) have been digitized (Chesshire et al. 2023). This leaves to be digitally recorded some six million, in locations likely concentrated in the contiguous United States. Even recorded digital data struggles with issues of accuracy: many old records document a place name that is vague or encompasses an entire county or city, making it difficult to use the record when associating bees with habitat, plant populations, or range change.

The advent of geospatial tools, which analyze digitized insect records, are increasing our ability to understand bee populations and predict changes. For data that have been recorded digitally and are relatively accurate, GIS (Geographic Information Systems) tools have been created that allow for easy correlation between digitized occurrence records and underlying characteristics of the area where the bee occurs. Thus our ability to understand bee resource requirements, habitat needs, and how they intersect with human activities, have advanced dramatically (e.g., Saturni et al. 2016; El Qadi 2017; Westerfelt et al. 2018; Du Clos et al. 2020; Soroye et al. 2020; Woodard et al. 2020; Zattara 2021; Orr et al. 2022). Modern bee research commonly makes use of geospatial tools to inform important work pertaining to bees, their population dynamics, ecosystem services, and conservation. These geospatial tools can be updated instantly in response to system changes and other management decisions. They can capture various data from numerous sources to better inform users of the current status and trends. They can also be overlayed with other information layers to give a more complete picture of distribution, habitat type, degree of ecosystem functioning, and the impacts of key management decisions. And because they are based on relational databases, they can incorporate and store multiple types of metadata (e.g., plant associations, habitat, date) in one location.

3.2 An ideal geospatial tool for analyzing bee distributions

The process of creating data summaries involves multiple steps, beginning with the collection of data from all available sources (including, perhaps, surveying in areas where bees are poorly known) through a data portal that curates any associated metadata. That data set is then output to a data user interface

Figure 1. Process of analyzing bee distributions



that shows bee data overlaid on maps that contain the geographical, political, or ecological data that are specimen-level attributes (determiner, sex of the bee, date collected, etc.). Ideally the bee data also include species-level attributes (nesting, diet, sociality, etc.), and components can be used to interpret bee population dynamics, beta diversity, areas where surveying are focused, or areas where bee communities or species are most threatened (Figure 1).

An ideal geospatial tool would address a core group of needs identified by researchers and stakeholders. Below are laid out the key objectives of bee researchers and stakeholders associated with bee studies. While there are many priorities for those who study bees, a well-designed geospatial tool would aid most stakeholders and bee researchers.

1. *Identify at-risk species, prioritize bee species for national status assessments, and track listed species.* Identifying bee species of conservation concern at subnational and national levels are significant responsibilities for many policy makers. Understanding where bee species of interest are common or rare and where species are at the edges of their ranges, helps to focus monitoring, surveying, and reporting efforts to inform policy makers about which species are of highest conservation concern.
2. *Understand a species' range and focus in on one particular bee group.* In addition to focusing on at-risk species, land managers and bee scientists want a tool that can help them better

understand what is known for particular species. Currently, there is considerable focus on bumble bees and their distributions, given the importance of this information for understanding the impacts of pathogens, pesticides, climate change, and invasive species.

3. *Document hot and cold spots of bee biodiversity.* Recognizing areas where bee species' richness has been shown to be either high or low can be important for different reasons in different countries. For example, in the United States, a priority for land managers who oversee vast land areas is to determine regions where bee diversity is high, or areas that contain one or more particular species of interest, so that those areas can be prioritized for conservation or restoration efforts. Alternatively, using ranges of species to identify cold spots where bee diversity seems to be low, due either to a lack of sampling effort or a natural depression of bee diversity, can help those in Mexico determine which states and national protected areas to survey or prioritize for conservation. In Canada, documenting species ranges can help identify areas where at-risk bees may occur. Last, species range maps can supplement efforts to establish standardized long-term monitoring protocols for bees, resulting in statistically robust data.
4. *Create lists for protected areas, provinces, territories, states, or other land units.* Lists that include presence, and ideally abundance data, are important and useful to land managers, policymakers, educators, and others to determine which bee species warrant more attention in a given area. These lists also help to identify potential pollinators of rare plant species, nonnative bee species, and can aid the development of identification guides for common bees in a region. Moreover, such lists can help educators engage local communities in understanding the bees that live in their area.
5. *Associate bees with their floral, soil, and habitat associations for a particular area.* Understanding the intimate relationships between bees and the surrounding environment can support efforts to minimize habitat loss. Identifying important floral resources, particularly the plant species used by floral specialists, and determining soil and nesting preferences can help to direct efforts to maintain bee communities in areas of interest.
6. *Make associations with threats (current or emerging) on the landscape and using these data to help predict or model threats and species responses*. In the United States, and likely elsewhere, Environment Sites Assessments (ESA) rely heavily on recognizing threats to various organisms; being able to model pollinator health for these areas would be beneficial to many land managers. One aspect of this is assessing the potential threat of apiaries, solar arrays, transmission lines, the effects of thinning and burning, and other threats categories outlined according to the International Union of Conservation of Nature threats classification scheme.

Though not objective-oriented, a useful bee tool would also:

7. *Aid in the ability to assess spatial and temporal trends in bee populations*. Ideally, a geospatial tool could be used to visualize or assess changes in bee populations over time and space in relation to historic and predicted changes in environmental conditions.
8. *Be comprehensive in the data that it includes*, pulling from all available digitized data, and it should be associated with efforts to add new, currently undigitized data as well. It should

include as much meta data as possible, including dates of collection, location accuracy, and floral data. The tool should include the ability to predict occurrences based on associations with climate, and habitat and floral resource presence.

9. *Include the ability to download filtered records for additional 'offline' analyses.* Given the myriad ways in which geospatially references data may be used by various stakeholders, the ability to quickly and efficiently classify the data, according to specific objectives and/or geographical aspects, will ultimately increase the use of any geo-spatial tool, re its data accessibility.

3.3 Current geospatial tools

Presently, geospatial tools facilitate and enhance bee studies and conservation efforts. As indicated by the numerous creative applications and the diversity of geospatial tools now available (see below), the potential for aiding bee research by interfacing metadata with bee locality records is immense. The results of a survey of BLM employees (presented at these workshops) showed that geospatial tools are being used by wildlife biologists and conservation practitioners to identify locations where at-risk species have been documented, as, for instance, in the case of the endangered rusty-patched bumble bee (*Bombus affinis*). Likewise, they are being used to identify where permits and consultations may be required under Endangered Species Acts or similar laws for protected species; and to help prioritize areas for additional conservation activities, like surveys, habitat management, and research. Others use geospatial tools, to illustrate to the public and conservation stakeholders, how much work has (or has not) been done to understand bee populations in a particular region. For instance, hot spots and cold spots can be quickly captured and visualized for systematic assessment. Field biologists use them to identify exact (georeferenced) locations where particular species are known to occur, to determine what is currently known about these specific occurrences, and to plan for future surveys. Researchers working in the natural resources and agricultural sector use them to identify bee species likely to occur near crop fields. Taxonomists and systematists use them to clarify problems with species definitions. And finally, bee scientists are using geospatial tools to test models that correlate bees to climate, land cover, land use change or landscape structure, soil, and plant communities.

Multiple tools currently exist for thinking through bee distribution and population questions; however, many are localized or singular in their purpose. Geospatial tools have arguably become inherent to the contemporary study of bees of North America. Multiple tools exist; however, each caters to the needs of particular stakeholders and their objectives. Ideally, one central tool, or a small handful of them, could address the needs of the majority of those who study bees, regardless of their objectives. Below is a summary of currently available tools that have been created to meet the needs of particular researchers and land managers. Note that this is not a list of data portals, but instead a list of the tools that allow the visualization of bee records based on data pulled from a data portal.

1. North American Bee Distribution Tool. The Bee Tool, developed in Power BI and actively managed by the US Fish and Wildlife Service, includes updated data from the GBIF (including data from iNaturalist). To date, the Bee Tool assimilates and graphically displays data from 2.92 million records, and documents 4,225 bee taxa across Canada, Mexico and the United States.

With its solid foundation of extensive georeferenced data, the tool incorporates an intuitive graphical user interface to address user needs powerfully and efficiently. Chiefly, the tool allows the user to see all bee occurrences at both the subnational and national levels. More explicitly, the tool features an interactive map that may be rapidly updated using simple drop-down menus and sliding scales to refine the output for specific questions. Specifically, it features data from the US Environmental Protection Agency so users may discriminately select bees by Ecoregion designations (i.e., Levels I, II, and III). It includes interactive pie charts showing the percentages of species in each NatureServe ranking, allowing users to select and display SGCN species on the main map. Users may also select for certain bee species by land parcel within major US government land agencies (e.g., US Forest Service, US Fish and Wildlife Service, US National Park Service, and US Bureau of Land Management) and this functionality could easily be extended to Canada and Mexico as well. The tool also incorporates filters for date of collection/observation as well as phenological information. Furthermore, users can export refined digital records (i.e., datasets) detailing the bee species documented for specific land units or ecoregions.

2. **Bees of Mesoamerica.** In order to analyze the distributions and population trends of bee species across Mesoamerica, records were digitized from museums, private collections, and universities and entered into a mapping tool. Developed with the help of Ricardo Ayala and Rémy Vandame, this tool includes 335,000 records dating from 1842 to the present.
3. **Explorador de cambio climático y biodiversidad (Biodiversity and Climate Change Explorer).** This tool, developed by Adrián Ghilardi, shows climatic information for regions of Mexico, including actual and predicted temperature, and regional percentages of habitat fragmentation.
4. **Barómetro de la Conservación de la Biodiversidad (Barometer of Biodiversity Conservation).** This tool, also developed by Adrian Ghilardi and colleagues, comprehensively displays land unit information, including percent and type of ground cover, changes in tree and plant species cover through time, and levels of ecosystem conservation status.
5. **Bumble Bee Atlas.** These maps, developed by the Xerces Society, are based on community science data used to track and monitor bumble bees specifically, and to aid in their conservation. According to Sarina Jepsen, participants and volunteers adopt a square from an established grid overlaying a state or region, and systematically survey for bumble bees using photos and catch-release methods. The interactive maps include numerous observations from the Pacific coast and into southern Canada from coast to coast. The Great Plains are also well-surveyed, but regions east of the Mississippi River, the Great Basin, and North America's hot deserts are relatively underrepresented.
6. **BeeBDC.** Recently, a new R package has been created that contains a working dataset of 'cleaned' bee specimen records from all major public repositories (Dorey *et al*., 2023). Cleaned records refers to records where species names have been synced with current bee taxonomic names, country names, and collection dates, and specimens have been ranked according to the quality and accuracy of the record associated with the bee.
7. **Rusty Patched Bumble Bee Maps.** This high potential zone (HPZ) map was generated with an ArcGIS model with the involvement of Tamara Smith, Steven Choy, and other USFWS biologists. The publicly available interactive map displays different layers highlighting where *Bombus affinis*

is most likely to be found based on recent occurrence records and predicted movement through various land cover types. The data incorporates locality information as well as detailed observation records such as the last year the bee was observed. A second map (the 'grid map') was developed to prioritize surveys and other conservation work.

8. **Abeilles citoyennes.** This community science project, developed by the Fournier Lab at Université Laval, Québec City, in collaboration with the Montréal Insectarium, is designed to inventory bees and hoverflies throughout Quebec. Pan traps are deployed for 24 hours once a month from May to September, and the collected bees and hoverflies are sent to taxonomists who identify the specimens and enter the data into a georeferenced database. Map information includes the species name and the number of specimens for each property that was sampled (Rondeau et al. 2023).
9. **Pollinators of British Columbia.** This user-friendly tool, developed by Laura Melissa Guzmán and collaborators, and presented by Lora Morandin, enables backyard naturalists and enthusiasts to discover associations between regional plant and pollinator communities in British Columbia. The tool's simple drop-down menu interface allows users to select specific features of interest, including pollinator abundance, native versus non-native plants, and plant type.
10. **Bee Mapper.** This tool was developed by Brianne Du Clos specifically with blueberry farmers in mind. It maps the occurrence of bees around blueberry fields at two levels, indicating the flight distance for small bees (~250 yards) and large bees (1000 yards). Moreover, it incorporates layers for land cover and predicted native bee abundance, allowing growers to digitally view the most locally common pollinators and their associated habitat resources.
11. **Discover Life.** This website includes a number of tools for bee scientists. By pulling data from the Global Biodiversity Information Facility (GBIF), a widely recognized data repository that holds records for museums, projects, and universities across the Canada, Mexico, and the United States, and also by pulling from historic, published data sets, Discover Life generates drillable maps, that can show data at finer scales as one zooms in. Eventually, the specimen record can be accessed, including phenology and exact location data. For each species, known plant data is also included, as well as photos of the insect. Discover life has also included interactive keys for specimen identification, though with bees the emphasis is more on eastern species from the United States and Canada, as compared to western, Mexican, or northwest Canadian species.
12. **NatureServe.** NatureServe is a growing online website that pulls together all known information about organisms (including more than just bees) and their conservation status. Threats are recorded from a thorough literature review, as well as estimated occurrences, life history information, and population viability information.
13. **iNaturalist.** This online community/citizen science tool for photographic geo-referenced documentation of living organisms, includes over two million bee observations from all over the world. It documents location, phenology, and allows users to weigh in on the name of a species, growing the power of the tool exponentially by allowing more than just a handful of experts to help with identification; in a sense part of the taxonomic bottleneck that plagues scientific inventory and monitoring is lessened with this tool. The tool includes options for creating atlases for various geographic regions or times of year. The drawback is that because the observations are photo-based, fine scale species identifications are not possible for some individuals, and

reference material is lacking. In Mexico, iNaturalistMX (Naturalista) provides a similar service, allowing users to share their own observations, and learn from the observations and compiled natural history information provided by others.

There are other smaller-scale data capture tools available. For example, the Bees of Canada website is a portal for information on the distribution, natural history including floral hosts and nesting preferences, and other information. Bugguide.net is also a useful tool for summarizing natural history information for pollinator specimens, and for interacting with a community of insect enthusiasts; the site pulls together natural history information in an easy-to-use way, but the data visualization, in terms of mapping bee distributions, is rudimentary at best. Also, iDigBees is a collaborative effort aiming to make data from the SCAN database only (Data Portals, below) accessible in a geospatial platform.

Although many useful applications exist, overall, researchers, scientists, policy makers, and other stakeholders find presently available geospatial tools limiting**.** Most importantly, currently available tools lead researchers to need multiple tools to accomplish any one goal. A single comprehensive geospatial tool, designed with stakeholder needs in mind, could achieve many overarching goals. Either by modifying a currently available tool, or by pulling parts from multiple applications that already exist, the useability of this type of analysis could be greatly increased.

4 Creating a Bee Data Visualization Tool

A widely usable geospatial tool will rely on a solid data portal that draws from all available data and provides meaningful, scalable, and prudent data summaries (Figure 1). Each of these pieces (data sources, data portals, data visualizations, and data summaries) will have challenges to overcome. Below, each piece is discussed, highlighting present challenges and presenting suggested solutions.

4.1 Data Gaps

One of the issues with current bee geospatial tools is that they suffer from a lack of records that could feed the visualization**.** A robust database of bee occurrence records is at the heart of an optimally functioning geospatial tool. At a minimum, a record informing any bee data visualization must include a bee species (or genus) name, and geographic coordinates or other locality information. Ideally, the specimen record also includes a date, and (if there was one) the plant associated with the bee at the time of capture. There are two reasons for insufficient data. First, the data may have been recorded and exists in some form but has not been made available for use by digitally-based data visualization tools. Second, large swaths of North America do remain significantly understudied, and even if all data that currently exists were included, these areas could still lack information about bees. Each of these situations will be discussed below.

There are many untapped records that currently exist concerning bees but are unavailable to scientists; they can be thought of as falling into one of four categories. Though over two million unique records are currently available for bee analysis across North America, this likely represents less than one-quarter of all specimen-level data that exist (Cobb et al., 2019; Chesshire et al., 2023). Unpublished data can be broadly placed into one of four categories.

4.1.1: Undigitized museum records: An untapped resource and important investment

Historical data represents a vast treasure trove of bee data, but only a small portion of it has been digitized. Historical records include specimens that reside in collections maintained by federal agencies (e.g., national parks agencies, agricultural research services, US Fish and Wildlife Service, US Geological Survey, and others), universities, states, counties, regional parks, museums, and private collections. Insect specimens recorded from these collections may have been the result of an expedition, a funded survey, a student project, or opportunistic collecting by an entomologist. Historical data thus refer to the many millions of specimens that have been collected and stored, but never documented digitally. Cobb et al. (2019) list over 223 insect collections in North America. There are numerous challenges to digitizing these records, including difficulties associated with rather limited and shrinking funding, especially funding that is project-oriented, and thus provides no support for the long-term upkeep or maintenance of the database or that of the specimens. In the United States, historical data are only available for geospatial tools if they are directly associated with the developer of the geospatial tool, or if they have been uploaded to a publicly available server that stores data generated by different users. One of the difficulties of this, however, is that uploading to publicly available servers often requires credentials that are difficult to attain for those who do not represent a governmental or academic institution. In addition to undigitized records, many specimens have also been collected and curated, but not identified to the species level; thus, an extra step is needed in order to get these specimens to a point where they could be digitized, which is exacerbated by the paucity of taxonomists, already stretched thin across various projects.

Older records seldom represent a systematic collection of an area, and so may appear as disparate spots when plotted on a map or, because the locality information is vague, do not represent a detailed understanding of where the bee was found. Those that are the result of a systematic collection often employ different methodologies from region to region, and so are only comparable for quantitative analyses within the region of collection or where sampling methods were similar. Furthermore, even if all historical records were digitized, there remain large areas of North America where sampling of any kind has been done so infrequently as to be uninformative.

Strategies for incorporating more historic data.

1. **Prioritizing support for identification and digitization of large collections at underfunded institutions** to incorporate all existing records is one possible solution, although it would likely require a significant monetary contribution.
2. **Using new data portals, such as the emerging USDA Pollinator Knowledge Network,** may simplify data uploads, compared to more common portals, like GBIF.
3. **Using niche modeling to represent bee ranges more accurately,** with the data we have currently, may be a way to minimize the challenges of under-sampled areas, by using computational techniques to analyze environmental variables and species' occurrence data to

predict species distributions, and fill the gaps in our understanding of bee distributions, particularly in regions where data collection has been limited.

4. **Incentivizing the identification of museum specimens that are currently unnamed or unidentified in collections** would add to the number of records that could be input (see gathering metadata, below).
5. **Emphasize future collecting in areas where sampling would be most beneficial for informing our understanding of bee population dynamics or our understanding of bee distributions.**

4.1.2: Contemporary studies: Valuable locally, hard to use globally

Contemporary records are more standardized than older data sets but represent incredible variation in the method of standardization. A growing understanding of the value of national or even global standardization is leading to the development of collecting techniques that could be methodically applied across large regions. As data standardization continues, it will become more of an integral component in future bee research and in the databases storing those data. For example, standardized data should include records of absence, as well as presence, which will make it unique (and also data-heavy) compared to other data sources. Also, from a geospatial standpoint, standardized collection methods may delay or constrain access to valuable data about the ranges of bee species compared to more opportunistic collecting, which can afford greater flexibility to collect at adjacent sites with more resources. Another important consideration is the substantial taxonomic impediment, which refers to the challenges and limitations inherent in accurately classifying and identifying bee species. This obstacle subsequently hinders the timely sharing of data and a comprehensive understanding of bee populations.

Strategies for incorporating more contemporary data.

1. The United States National Native Bee Monitoring Research Coordination Network (RCN) is working to develop a standardized strategy for collecting and storing bee data that would ideally help to support data visualization efforts.
2. The US Bureau of Land Management, which is the largest federal land managing agency in the United States, is developing a standardized protocol, which aligns into the RCN's larger goals around bee conservation.
3. Additional funding for bee taxonomists and the development of new bee identification tools would significantly help to widen the taxonomic bottleneck. There is hope that eDNA technology will help resolve many taxonomic issues, but currently this technology is costly, and the DNA libraries are incomplete. The involvement of taxonomists remains crucial in confirming identifications and maintaining the accuracy of the reference DNA.

4.1.3: Community/Citizen Science Data: Extensive, but often not detailed

Community/Citizen science data are incredibly easy to generate by anyone with a camera or phone, and thus greatly increases the number of samples that can be recorded for an area. Citizen Science data usually refers to records generated by amateur naturalists, typically via photographs uploaded to websites such as iNaturalist, Naturalista, and BugGuide.net, that allow others to aid in identification as well as to curate the photos and their metadata. Moreover, these records are usually generated by volunteers, and thus funding needed for the field portion of bee ID work is minimal. However, some bee species require microscopic examination for accurate identification, and photographs alone may not suffice.

Because these records are captured photographically, it is unusual to have physical specimens associated with these data. So, while citizen science data works well for gathering sufficient data to map the distribution of easily identified species of interest, the data may be less specific and possibly less accurate for species whose identities can be difficult or impossible to ascertain from photographs. These sites also rely on the considerable expertise of a handful of taxonomists who can identify bees from photos, based on their knowledge of the bee's gross morphology and their most likely range and phenology.

Strategies for incorporating more community/citizen science data

1. Community/Citizen science records should be tagged as such in databases that draw from multiple locations, and the option to filter them out should be available. For users requiring a higher level of data accuracy, it is essential that the option exists to filter out these records.
2. Taxonomists who identify from photographs should be acknowledged in publications that draw from citizen science databases. The time and effort dedicated to online bee identification are extraordinary, and there should be incentives for continuing this tedious work.
3. Amateur naturalists can also be involved in specimen collecting in hybrid citizen science approaches like *Abeilles citoyenne*s, or the Oregon Bee Atlas by the Master Melittologist Program.

4.1.4: Traditional Ecological Knowledge (TEK): An underutilized and poorly understood resource

Tribal and Indigenous lands often harbor vast and poorly documented bee communities.

> "Traditional Ecological Knowledge is the ongoing accumulation of knowledge, practice, and belief about relationships between living beings in a specific ecosystem that is acquired by indigenous people over hundreds or thousands of years through direct contact with the environment, handed down through generations, and used for life-sustaining ways."
> (National Park Service, 2023)

Working with First Nations and Indigenous Peoples to incorporate not only their historical understanding of the bees they steward, but also data they may collect henceforth will be essential to gaining a full understanding of bee populations across North America. In the United States, tribal lands comprise 227,000 km^2 (87,800 mi^2), an area roughly the size of the state of Idaho. In Canada, 6.3% of the total landmass is stewarded by Indigenous Peoples. Though Mexico does not have tribal lands or reservations, nearly 10% of the Mexican population identifies as indigenous, with 6% of households including a person who speaks an indigenous language. Moreover, indigenous Mexicans are concentrated in many of the areas where bee species' richness is predicted to be at its highest in the country.

The paradigm of Indigenous tribes may not include the same assumptions made by Western-educated scientists. For example, the concept of a species is interpreted differently by university-educated scientists than by Indigenous Peoples in some regions of Mexico; and thus, the concept of biodiversity may be defined differently in these regions as well.

Strategies for incorporating more Traditional Ecological Knowledge.

1. Working with First Peoples will require conscientious conversations between parties willing to consider multiple perspectives on land use and pollinator conservation. The lexicon pertaining to bee specimens may need to be expanded in databases that include TEK.
2. Efforts should be made to ensure that the inclusion of Indigenous names in digital bee databases is done in consultation with Indigenous communities and respects their cultural practices and knowledge systems. This collaborative approach can enrich the databases with diverse perspectives and foster mutual understanding and respect.

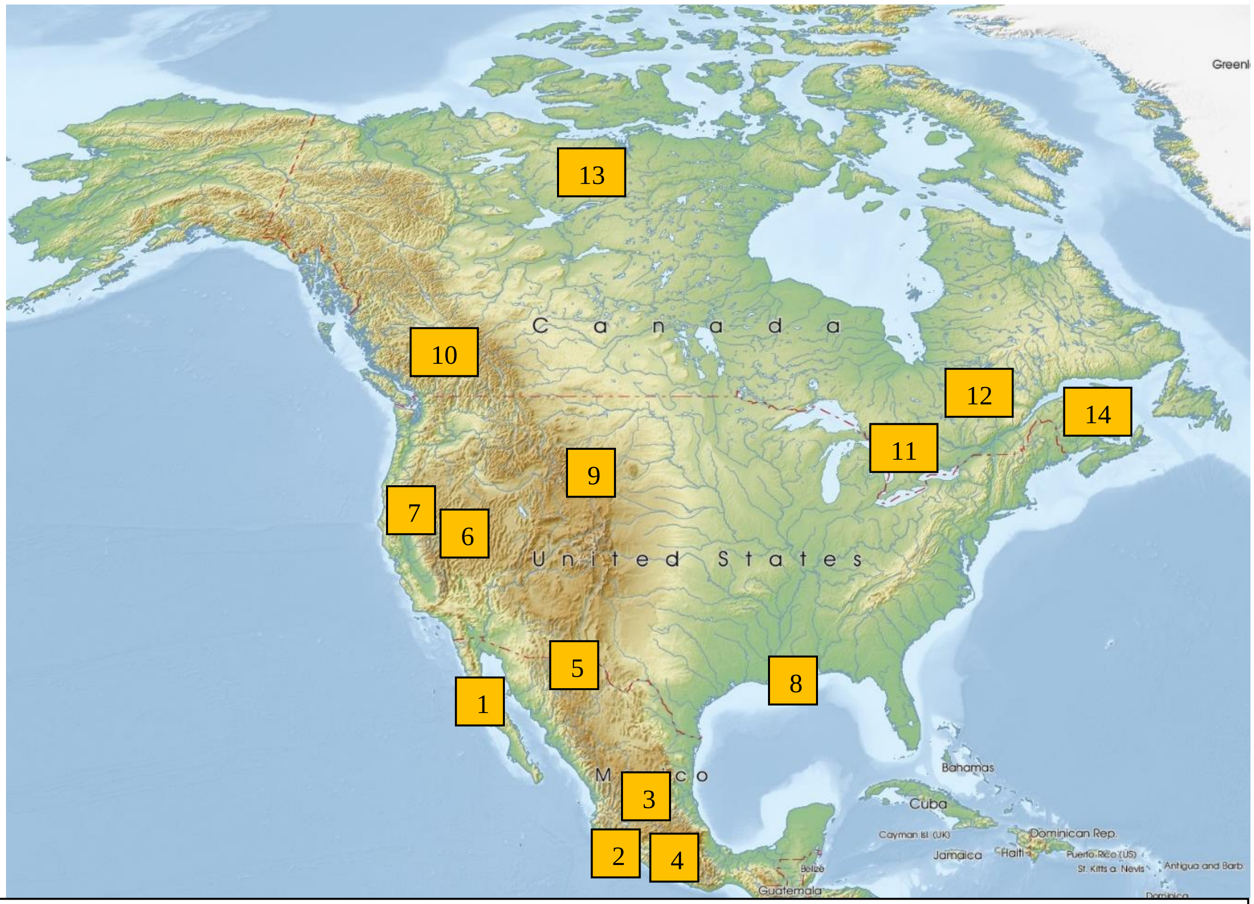
4.2 Sampling Holes: Places that have not been prioritized for bee surveying or monitoring

Even if all existing specimens were documented and this documentation were made publicly available, there would still be a need for future sampling across North American landscapes. In terms of species and habitat management, these areas fall into various categories: 1) areas that should be sampled because they represent significant knowledge gaps, or 2) areas that should be sampled so that changes in bee diversity can be documented right away, either because the areas are species-rich and have good historical data, or because the habitat is especially imperiled.

Large areas of North America remain critically under-sampled. At 24.3 million km^2 (9.4 million mi^2), the North American continent is vast and includes ecoregions ranging from the Arctic tundra and Taiga to temperate and tropical rainforests, grasslands, and hot and cold deserts. Elevations range from over 6000 m (20,000 ft) above, to nearly 100 m (282 ft) below sea level. Several thousand bee species are thought to occur in Mexico (~2,000 species), the United States of America (~4,000 species), and Canada (~900 species). Many of these have been identified only as morphospecies, or have unpublished names (e.g., Urban-Duarte *et al*., 2021); thus, estimating bee diversity for each region is difficult. It is no surprise then, that bee species are not well-documented across many large areas of the continent, and relatively few annotated lists exist for ecoregions, habitats, or political regions. While some of the less well-documented areas may harbor only a few species, there is ample evidence to suggest that a handful of areas across Mexico, the United States, and Canada, are likely home to a rich and varied suite of bee species. For conservation reasons, and to increase our understanding of bee biogeography, bee-plant relationships and bee evolution, it is important to prioritize these areas for surveying and monitoring. Moreover, in order to create bee geographic visualization tools that include accurate niche-models and other types of predictive power, filling in these gaps is essential

4.2.1: Under-sampled priority landscapes for bee research

Figure 2. Areas of North America that are a high priority for sampling native bees in order to fill knowledge gaps of species' distributions



1) Baja California, Mexico 2) Sierra Madre del Sur, Mexico 3) Altiplano, Mexico 4) Oaxacan Arid Lands, Mexico 5) Chihuahuan Desert, Mexico and the United States 6) Great Basin Desert, United States 7) Eastern Sierra Nevada, United States 8) Southeastern United States 9) Short and tall grass prairie remnants, United States and Canada 10) Western Interior Basins, Canada 11) Carolinian Zone, Canada 12) Mixedwood Plains, Canada 13) Arctic and Boreal Habitats, Canada and the United States 14) Maritime Provinces, Canada.

The following priority areas are based on expert opinion, gathered from the April 2023 CEC native bee workshop. They are meant to serve as valuable starting points for inventory and monitoring efforts in North America. Although identified through expert consensus at the workshop, the selection is not static and may evolve over time with further research, emerging data, and changing conservation needs.

1. **Baja California, Mexico.** This unique peninsula has never been thoroughly sampled for bees (Ayala et al. 1993; Falcon-Brindis and Leon-Cortes 2022). Although it represents a portion of the much more thoroughly investigated Sonoran Desert, its isolation over the last 5.5 million years gives it a significantly different evolutionary trajectory (Garcillán et al. 2020). At 800 miles, the Baja region is the second-longest peninsula in the world, and its climate and ecology are thus significantly influenced by the surrounding sea. From palm beaches to sky islands, the habitats in this area are many and unique. The region spans 30° latitude and thus includes elements of desert to the north, and more mesic ecoregions to the south. This diversity in habitats suggests opportunities for a unique and diverse bee fauna, with at least some endemic species. As an indication, nearly 20% of the vascular plant species are endemic, as are 57 of 84 reptile species (Grismer 2002). Within invertebrates, nearly 40% of the scorpions and 45% of the tenebrionid beetles are also endemic. A limited study of bees at just six sites in the region found 151 species in 48 genera (Falcon-Brindis and Leon-Cortes 2022). Between 30 and 70% of the bee fauna is likely distinct to the region, with rates of endemism increasing to the south (Ayala et al. 1993). Interestingly, it appears that most of the bees known from this region arrived from the areas to the north, in the United States, with few occurring in the linearly closer Mexican mainland. Finally, this region should be prioritized because the rapid expansion of urban centers, and growing agricultural use threaten this region's wild places and will impact the region before the bee species can be fully documented.
2. **Sierra Madre del Sur, with emphasis on the Guerrero and Atoyac Mountains, Mexico.** The Sierra Madre del Sur is a mountain range that runs parallel to the Pacific Coast for over 1,000 km, from western Guerrero to southern Oaxaca. The mountains are steep-sided and rugged, with volcanic parent material, and a climate that ranges from temperate to subhumid. This region is known for its exceptional biodiversity, housing a wide variety of flora and fauna. It includes pine-oak forests that continue south to Costa Rica and north to New Mexico and Arizona. In addition, there are numerous tropical dry forests. This unique combination of ecosystems, including tropical rainforests, cloud forests, and montane forests, supports numerous endemic and rare species, making it a hot spot for biological diversity (Gonzalez-Iturbe et al. 2018; Myers et al. 2000). Moreover, studies hint at high rates of speciation in bees of the region, due to varied topography and the isolation it produces (Duennes et al. 2017). This region is under threat from deforestation, land-use changes, habitat destruction, and climate change (Santos-Moreno et al. 2017).
3. **Mexican Plateau (Altiplano), Mexico.** The Mexican Altiplano is a vast region of elevated terrain in central Mexico. The highlands cover a substantial portion of the country, and the region encompasses a diverse range of habitats due to significant topographical variations and elevational differences. These habitats include montane forests, grasslands, desert scrub, wetlands, and agricultural lands. Evidence suggests that a number of bee species found here are endemic to the region, including entire genera and subgenera (Ayala et al. 1993). In addition, several North American genera reach peak diversity here, including *Centris, Exomalopsis* (Timberlake 1980), *Mexalictus*, and several other in the subfamily *Panurginae*.
4. **Oaxacan Arid Lands, Mexico.** Located in southern Mexico, primarily in the state of Oaxaca, this semi-arid region is home to a unique flora and fauna that includes not only endemic species but

also species at the northern and southern edges of their larger ranges. Spanning the region between the Sierra Madre del Sur and the Transverse Volcanic Axis, this region includes species associated with the Sonoran Desert to the north, including numerous columnar cacti and nearly 3,000 other species of vascular plants, as well as elements of the ecoregions that dominate further south (Ayala et al. 1993).

5. **Chihuahuan Desert, Mexico and the United States.** The Chihuahuan Desert extends across the southwestern United States and northern Mexico. At over 360,000 km^2 (140,000 mi^2), it is one of the largest deserts in North America. Within this vast region are numerous oases, endemic species, and a wide variety of plants and animals adapted to arid and semi-arid conditions. Arid regions of North America have long been known to harbor the highest bee species richness (Michener 2007; Orr 2022). Few bee studies have been carried out in the Chihuahuan Desert, but those few that exist hint at a large and diverse bee fauna (McAlister, 2012; Minckley and Ascher, 2012; Minckley et al. 1999; Kazenel et al. 2020; Munguia-Soto et al. 2022), rich in specialist bees (Minckley et al. 2000) that is at risk due to threats from overgrazing (Cane 2011; Minckley 2014), urban land use (Hostetler and McIntyre 2001), and climate change (Argueta-Guzmán et al. 2022; Munguia-Soto et al. 2022). Interestingly, there appear to be distinct bee faunas associated with the Chihuahuan and Sonoran Desert, which is directly to the west (Ayala et al. 1993).
6. **Great Basin Desert, including sky islands, United States.** While some surveys of bees have been conducted in the southern portion of Nevada (Griswold et al. 1999), which includes the Mojave Desert, the rest of the state remains largely under sampled. To the north, 647 bee species have been recorded in the Columbia Basin; to the south, nearly 700 bee species are documented for one county of Nevada (Clark County), but the vast area between, spanning nearly 750 km (490 mi), is relatively unknown (Orr 2021; Chesshire 2023). The region likely contains high diversity for several bee families, especially Megachilidae (Griswold et al. 2014), and mountainous sky islands may harbor undiscovered endemic bee species; they have most certainly served as refugia for North American bumble bee species (Koch et al. 2018). The southern portions of the state have already documented several rare and presumably imperiled bee species, with strict ties to host plants with small geographic distributions (Portman et al. 2019). In addition, several groups of bees appear to have originated in this region of the eastern Mojave Desert (Griswold and Mille 2010; Nelson and Griswold 2015). Northward, the vast Great Basin Desert harbors 92 species in the genus Anthidium alone (Gonzalez et al. 2014). Throughout the state, land conversion, especially for solar facilities, and ever-increasing urban sprawl are threats to bee species (McCoshum and Geber 2020).
7. **Eastern Sierra Nevada and Cascade Mountains, United States.** Adjacent to the Great Basin on the west side, the eastern portion of the Sierra Nevada Mountain range, which runs from southern California nearly to Oregon, and the Cascade Mountains in Oregon, remain an area where new discoveries could be made, and range maps could be elucidated. This area is incredibly threatened due to climate change, suppressed fuels reduction, and the resulting uncharacteristic wildfires, which are likely to result in significant changes in bee community members. It would be beneficial to prioritize collecting in this region to establish species baselines before it is no longer possible.

8. **Southeastern United States.** Surveying for bees in the southeastern United States is important because it represents a gap in our understanding of bee distributions. Past studies have found the region to include bees restricted to unique habitats including dune fields along barrier islands and coastal plains. Several bee species in the region appear to originate from desert and neotropical regions and represent significant disjuncts (Cane 1996). Though the area is not likely as bee rich as some western regions as evidenced by the many small and local surveys in the area (Jones and Jones 1980; Pascarella et al. 1999; Little 2013; Deyrup et al. 2002; Owens et al. 2018; Stephenson et al. 2018; Bartholomew 2004; Bartholomew et al. 2006; Hall and Ascher 2010; Schlueter and Steward 2015), it nonetheless represents an area with unique and poorly understood bee species. The presence of a vertical habitat component suggests unique habitats as well; one study found a notable component of the bee community foraged in trees when resources nearer the ground were scarce (Ulyshen et al. 2010). Forest habitats in the region, ranging from temperate deciduous to pine, harbor intact and stable bee populations that are threatened by poor forest health from a century of fire suppression (Hanula 2015; Odanaka 2019; Ulyshen 2021), invasive ant species (Ulyshen and Horn 2023), climate change, and by habitat loss as urban centers expand.
9. **Short and tall grass prairie remnants, United States and Canada.** Two hundred years ago, most of the middle of North America was dominated by grasslands; short and tall grass prairies featured the migration of enormous herds of buffalo and antelope and deer and moose (Samson et al. 2004). The disturbance created by these hooved herds provided an opportunity for an incredible diversity of forb species and their associated pollinators (Knapp et al. 1999; McMillan 2019). A number of bee species that are now seldom seen, including *Florilegus*, *Cemolobus*, and *Anthemurgus*, (Carril and Wilson 2022) may once have been more abundant across the vast central areas of the United States and Canada (Carper et al. 2019). Today, only remnants of this large ecoregion remain, but those areas have the potential to inform us about bee communities that are now rare and hard to find intact. As an indication of the diversity of bees that short and tall grass prairie remnants can support, just three 1-ha sites in mixed grass prairies of southern Canada yielded over 100 bee species across two years of sampling (Patenaude 2007), and similar results were found in tall grass prairie remnants in Illinois (Griffin et al., 2017; Tonietto et al. 2017) and Iowa (Hendrix et al. 2010). Even agriculturally dominated lands here still seem to harbor large bee faunas (Arathi et al. 2019), suggesting that a focus on the conservation of remnants could be important for conserving the native bee fauna in the region.
10. **Western Interior Basins, Canada.** Grasslands dominate landscapes between the interior mountain ranges of western Canada. It is suggested that these areas have the highest bee diversity per unit area of any region in Canada (Sheffield et al. 2014), despite this being the smallest of Canada's ecozones (~57,000 km^2). Several larger ecoregions converge here, including elements of the Great Basin sagebrush and grasslands, and dry forest ecotones (Shorthouse 2010). Both of these habitat types are at the northern extent of the region, and it is expected that bees associated with understory forbs may be at the northern extent as well. The modest amount of research done in the region suggests a unique fauna, with many species found nowhere else in Canada (Gibbs 2010; Sheffield et al. 2011; Heron and Sheffield 2015). However,

these are also the regions that have been most dramatically modified (Blackburn 2010) by conversion to cropland and pesticide use (Shorthouse 2010; Vankosky 2017), through cattle grazing (Samson et al. 2004), and because of urbanization (Javorek and Grant 2011).

11. **Carolinian Zone, Canada.** This region, located primarily across the southern portion of Ontario, and extending south into the northeastern United States, exhibits a milder climate compared to the surrounding areas, and thus supports a diverse range of plant and animal species, some of which are typically found further south. The area is poorly studied for bees, though a modest study of just three grasslands in the area recorded an astonishing 124 species, with predictions of considerably more (Richards et al. 2012), and other studies have reported similarly high numbers, relative to surrounding areas (MacKay and Knerer 1979; Grixti and Packer 2006; Taylor 2007). Comprised of karst landscapes, oak savannas, grasslands, deciduous forests, and wetlands, the many ecotones likely help to boost bee richness and abundance numbers.
12. **Mixedwood Plains, Canada.** Forests of Canada's mixed wood plains are characterized by a blend both coniferous and deciduous trees and are associated with a transition zone between the more boreal and northern forests, and the deciduous dominated forests of southern Canada. The region is primarily located in the southern parts of central Canada, primarily Ontario and Quebec. Because this area represents an ecological transition zone, the makeup of bee communities here are likely distinct; however, little survey or monitoring work has been carried out to flesh this out (but see: Grixti and Packer 2006; Proctor et al. 2012; Syer 2016; Liczner et al. 2023). This area is likely to manifest the effects of climate change more noticeably than other areas which do not show this mix of boreal and temperate ecosystems, especially for bumble bee species (Colla 2010). It is important to note that the areas described by the Carolinian Zone and the Canadian Mixed wood Plains overlap (and Canada's Carolinian forests occur within the Mixed wood Plains ecozone).
13. **Arctic and Boreal Habitats, Canada and the United States.** While extreme northern climates are not likely to be hot spots of bee biodiversity, in terms of the number and abundance of species, they do represent the limits of our understanding of bee species' ranges. Moreover, as the climate changes, these are the areas where new fluctuations in monthly temperature, shifts in seasonality, and the accompanying changes in bloom time of important pollinator-visited forbs are likely to be seen. Surveying for bees here and setting up areas for long-term monitoring through the Arctic Council-Conservation of Arctic Flora and Fauna's Arctic Pollinator Monitoring Framework (in development), are expected to yield important information about bee population dynamics in the near term. Rich in bumble bees (Sakagami and Toda 1986; Laverty and Harder, 1988; Hicks and Sheffield 2021), but limited in solitary bees (Burns et al. 2022), this vast region harbors bees with adaptations to the short season and the cold climate, and range extensions are frequently documented (e.g., Ratzlaff 2018).
14. **Maritime Provinces, Canada.** With ten national parks and nearly 50 islands, this region represents a unique opportunity to study a coastal bee fauna at northern latitudes. Habitats range from beaches and sand dunes, to inland mixed Acadian and boreal forests. In the spring, early-blooming wildflowers predominate, and associated bees include the eastern- and/or northern-most occurrences of some species (Michener 2000). To the north the same has been found to be true for species of sweat bees on Cape Breton Island (Packer 1989). The area also

includes areas used for agriculture, including low bush blueberries, cranberries, and apples. The intersection of wild habitat patches and agro-environments is common here (e.g., Martins et al. 2015; Moisan-DeSerres et al. 2015; Martins et al. 2018; Slupik et al. 2022; Vega et al. 2023), and the bees associated should be a priority when documenting bee ranges across North America. Threats to pollinators here include the establishment of nonnative, invasive plant species, which disrupt pollinator networks (Stubbs et al. 2007) and loss of habitat (Gervais et al., 2017).

4.2.2 Other priority landscapes

In addition to ecologically unique areas high in endemic species, or areas that are under-sampled, there are other landscapes that deserve consideration for intensive surveying for bees for other reasons, including adding to a growing understanding of trends in bee population dynamics, tracking bee biodiversity in areas that are known hotspots, and monitoring the pollinators associated with agricultural systems.

1. **Areas that have been sampled before**. Areas that have had rigorous, methodologically sound sampling in the past should be resampled at future dates, in order to document changes in bee populations. Though many efforts to establish baseline data are underway, they will require many years of study in order to shed light on the health and trends of bee populations. While historical surveys of bees that are standardized are few and far between, those that exist provide an opportunity to monitor changes in both bee communities as a whole and also specific bee species much sooner. For example, in Pinnacles National Monument in California, monitoring of bee communities has been carried out for nearly 30 years, providing a deep understanding of how bee communities fluctuate naturally (Meiners et al. 2019; Messinger and Griswold 2002). Similarly, meticulous documentation of plant-pollinator interactions, compiled over 130 years ago in Illinois, has provided a data set that allows scientists to revisit and reassess how pollinator interactions have shifted over a century of land-use change (Burkle et al. 2013). In the Sevilleta National Wildlife Refuge, New Mexico, bee populations have been assessed every year, using passive traps for over two decades, and providing important information about variation in seasonal bee-species turnover in relation to climatic fluctuations (Kazenel et al. 2020). There are a handful of locations in North America where studies were conducted methodically in past years, and these areas, despite the fact that the fauna is well-known, could provide important information on bee population dynamics if they were revisited. Numerous areas, often sampled for a master's or PhD project, could be resampled following the same, or a similar, methodology with great effectiveness. Several National Parks in the United States have also been sampled systematically, and repeated sampling in these regions, which represent a 'control' against some of the landscape-level disturbances that habitats experience outside protected areas, would be informative. National Parks, with standardized sampling, include: Yosemite National Park, Grand Staircase Escalante National Monument, Bandelier National Monument, Carlsbad National Park, and Zion National Park.
2. **Areas that are known hotspots**. Areas known for high species' richness should also be prioritized, as these are areas where documenting an important change in regional or local

richness of the community as a whole might be best assessed. Not surprisingly, some of the areas which have recorded the highest richness in bee species are also areas that have been well-studied, and usually in a methodical and standardized manner. As an example, the Rocky Mountain Biological Laboratory, in Colorado, USA, is a place where bees have been systematically surveyed for decades, in conjunction with plant work, and are providing an invaluable record of changes in plant and bee phenology across time (Stemkovski et al. 2020; Gezon et al. 2015; Forrest and Thomson 2011). Areas of exceptional bee diversity that could be candidates for monitoring so that documented changes can be assessed. As an example, Cane, Minckley, and colleagues (2000; 2006; 1999) have thoroughly sampled creosote shrub communities throughout the Phoenix and Tucson area. Resampling of these communities could provide important insights into changes in bee presence/absence, and richness/abundance because contemporary results could be compared to their findings, which were often standardized by time or space, from 20 to 30 years ago.

3. **Agricultural areas.** Areas often overlooked but of significant importance for standardized sampling are agricultural systems reliant on, or benefiting from, pollinators (Steffan-Dewenter et al. 2005; Klein et al. 2007). Agricultural regions often undergo more sampling than other land types due to numerous small to large agricultural projects with funding. However, standardization is lacking among these various projects, many remain undocumented, and coverage varies widely across different crops and geographical regions (Schindler et al. 2013). Given the crucial role of bees in crop pollination and the challenges facing honey bee health and supply, understanding bee populations, trends, and the factors driving their decline are essential. It is imperative that we prioritize standardized sampling in agricultural areas across North America.

4.3 Data Portals: Unifying all existing data in one place

Just as important as the georeferenced datapoint for analyses are the associated metadata. Each record contains metadata that include the date of collection, a floral association record, if relevant, taxonomic information (ideally, as to species), and location of collection. The metadata should also include the collection method (e.g., net, pan trap, photograph) as well as a measure of the location accuracy for each record. Through access permissions, sensitive records could be 'blurred,' while other records for which precise localities are unknown, could be flagged and potentially excluded, when necessary. It would also be informative to provide information on the collector and the person who carried out the identification, and potentially their professional affiliation and contact information, if they wish. This would allow users of the georeferenced dataset to question, as well as acknowledge, the collectors and taxonomists in any resulting publications. Ultimately, the databases informing geospatial tools need to be flexible and inclusive to be maximally effective for subsequent analyses and decision making.

Ideally, a geospatial tool would amalgamate data from one geospatial database, regardless of the type (photograph or specimen) or source (standardized survey or historical collection) of the data records. Currently, most geospatial tools pull from GBIF, which has compiled not only historic records from museums, but also records from iNaturalist and other online photographic-based databases. These data are Darwin Core Compliant, meaning that they are uploaded into a flexible but stable framework, where all recorded aspects are categorized using similar naming conventions, so that multiple disparate datasets can be integrated into one large dataset.

1. **GBIF**: While GBIF is by far the best source of geospatial data for bees, it has some limitations. As noted earlier, data uploads to GBIF require specific credentialing which precludes many sources of meaningful data. Not all entities with geospatial bee data are qualified to publish to GBIF, which requires endorsement from participant nodes, and requires that data be from an organization and not an individual. Thus, a graduate student who collected bee data but then leaves the institution with which they were associated, may never publish their bee records, especially if their institution is not a publisher. Furthermore, GBIF records do not always reflect the most up-to-date species naming conventions; therefore, data visualization tools must periodically scrub GBIF data for TSNs (Taxonomic Serial Numbers), which record the most recent information. Another limitation is the reticence of some data holders to upload and share their data due to a strong sense of ownership. This sense of ownership may be due to a culture of data guarding, or to the sensitivity of the information which would necessitate a process for blurring records—a function that is currently not available in GBIF. GBIF data are sometimes incomplete and may be missing important information such as plant records. Last, uploading data to GBIF may represent a significant investment of time if all the required metadata are to be included, and this may represent a barrier to some participants.
2. **NatureServe and Natural Heritage Programs.** State Natural Heritage Programs in the United States may share data through NatureServe, though, depending on the state, data sharing efforts may be inconsistent or unreliable.
3. **The Symbiota Collections of Arthropods Network (SCAN)** is another database from which records could be pulled for a geospatial bee tool.
4. **Biotics**, in Canada, is typically used only for species-at-risk; however, this platform hinders efficient transfers into data visualization tools.
5. **Conabio**, in Mexico, maintains extensive databases of geo-referenced records for all the biological groups in the country (SNIB, National Information System on Biodiversity).

Other databases have their own limitations. None are currently as comprehensive as GBIF, and many focus only on rare or imperiled species or specific taxa (e.g., *Bombus* species). Data sets can be sent directly to the person building the geospatial tool, but this cannot be a long-term sustainable solution.

The USDA is currently developing a pollinator knowledge network that may serve as a platform from which data can be pulled in the future, or into which data from multiple sources can be uploaded if GBIF is deemed insufficient. In terms of data sharing, incentivization seemed to be the most logical solution. One way to incentivize might be to create an impact factor based on the amount of data published, the value of the data, and the frequency of publication. An impact factor for taxonomists and for museums might help incentivize the identification of bees that have yet to be examined in large insect collections, too. Having more data is important, not just because it informs our understanding of bee distributions, but also because it can help us recognize when enough work has been done in an area, so that goals can be more focused, and overcollection is not an issue. In addition, creating a process to blur sensitive information—for example, allowing data contributors to specify the level of access provided to users—would enable certain researchers and scientists to upload and share more generalized but important data.

The Bee Library is collaborative effort between over a dozen universities, natural history collections, and research stations to compile and share data about bees, including images, and functional trait data (body size, host plant information, and diet) (Setlmann et al. 2021). The Bee Library is an offshoot of Symbiota, already an established data portal. It allows participants who might not be able to upload to GBIF to add data to a widely used online hub.

4.4 Data Visualization: What a geospatial tool should do

A geospatial tool must function in a way that allows users to answer questions about bees that relate to land type, habitat management, species inventory, and population dynamics (i.e., size, distribution/range) over time and space. The uses of a geospatial tool for bees can be categorized in a few ways, relating to the characteristics of the bee species, and the ability of a tool to cross-cut geographical, ecological, ecoregional or political boundaries. Communicating effectively with different stakeholders and being able to present data in a way that both answers questions important to users and maintains clarity for those who are not bee specialists should be the focus of a visualization tool.

The ability to visualize the locations of bees across a geographic space is the first priority of a bee tool, but the ability to cross-cut the data points according to ecoregion, land management area, tribe, indigenous lands, state or province, natural protected areas, and county gives a visualization tool incredible flexibility for various land managers tasked with determining which bee species have been documented in the area where they work. These features are all associated with the geospatial coordinates attached to a bee record, and the availability of spatial layers that can be overlaid on top of those coordinates. Spatial layers that contain some assessment of threat (rate of deforestation, climate variability, etc.) could aid in assessing risks to bee species in these areas. Additionally, because specimens are recorded with different levels of precision, having a location range associated with a specimen could aid in accurate interpretation of data.

An additional spatial feature that should be considered in visualization tools is grid cells. While they don't represent any well-demarcated boundary, adding manipulable and scalable grid cells could enhance the ability to count and analyze bees per unit area to get a sense of collection effort for a region and potentially provide a standardized index of abundance. Being able to toggle between grid cells set to standards of 2km x 2km, 30km x 30km, and 100km by 100km would be incredibly useful to those who are looking at changes in bee presence or absence over time. It would also help to highlight hot spots and cold spots (i.e., areas where very little work had been done), which may vary depending on the scale of analysis. Grid cells could also aid in establishing systematic sampling in a region. Last, grid cells facilitate many types of existing statistical spatial analyses.

Having the ability to see predicted bee ranges instead of just bee occurrences would be ideal. Niche modelling is an aspect of a bee visualization tool that would increase its usefulness by filling in information for areas where collection data is minimal. Also known as species distribution modelling, niche modelling predicts the potential distribution of a species in a given geographic area based on the environmental conditions (e.g., temperature, precipitation, land cover types, etc.) that determine the habitats with which the species is associated. Clearly, niche modelling relies on some number of occurrence records in order to accurately identify patterns and relationships between the species occurrences and the environmental conditions. For some rarer species, this is not yet possible; for others, the lack of null data (places where the bee *did not* occur) also limits the accuracy of the model, however, there are statistical methods available to address a lack of null data.

A bee data visualization tool is most effective when it also incorporates attributes of the bee species. Current tools include information on species taxonomy (i.e., family, tribe, genus, etc.), whether a species has been afforded legal protection (a 'listing'), and phenology. The addition of information about nesting habits, links to keys and literature for taxa, and photographs of the species would add usefulness. A number of data portals are working to compile this information (see above). Ideally, this information would be summarized for filtered regions to create, for example, relative abundances of ground nesters, specialists, and social insects.

Specimen-level data are also essential to the analyses that bee scientists need to do. Having information about the sex of the specimen would aid in some analyses. For the purposes of crediting those taxonomists who worked on the specimen identification, having the identifier associated with the species determination listed would be valuable. This also applies to the person who was involved with the collection of the specimen.

Preferably, bee data could be filtered, based on how the data were collected. iNaturalist records add to our understanding of bee occurrences for some species but lack the same level of precision often associated with collected specimens. Having the ability to filter for the collection method would aid in the ability of users to examine the data most applicable to their task. As molecular data become more available, the usefulness of this feature will only increase. This should include the ability to filter for those specimens collected, using different techniques (net, pantrap, malaise trap, or vane trap). Thus, knowing which species were captured with different methods, also provides information on which species were potentially *not* present, given their propensity to be sampled by a given method. Finally, being able to filter for systematic collection efforts over incidental records would also be helpful, especially with respect to the former for documenting changes in community composition, species presence or abundance, with respect to repeated sampling efforts, as discussed above.

4.5 Data Export: How best to share data on bees

Finally, a bee visualization tool must incorporate ways to share what it shows, with a range of users. Users of bee visualization were discussed earlier, but include teachers and their students, land stewards, those creating species status reports, naturalists, and academic bee researchers. This wide array of users may want to learn more about bees, predict bee distributions at a future date, compare areas with each other, or determine the likely "visitors" to a particular plant. For a geospatial tool to be useful across North America, it must, first of all, be communicated in three languages, French, Spanish, and English. It should include Indigenous names of bees as well as common names and Latin names. And it should include 'levels' for analyses, so that someone with any level of understanding of bee biology can find data that are useful and clear. This last point, for making it accessible to those outside of academia or government institutions, means that the maps and other interfaces associated with the tool have to be viewable without licensing. And one additional, coveted output would be downloadable datasets that users could then analyze on their own, if the tools provided were insufficient.

Incorporating community-level statistics in the outputs could aid land managers in understanding lists of bee species generated by a visualization tool. While "laundry lists" of species for a region are of some interest, maximal value comes from being able to interpret the list. Which of these species are surprising? How does this list compare with those of other regions? Has this list changed over time? Using community-level statistics to look at how many different species are in one area (alpha diversity) and how different those areas are from each other in terms of species (beta diversity), as well as how similar or different they are, would help us understand better the information from a bee visualization tool.

Having a geospatial tool that is dynamic and adaptive will ensure its longevity. Having an avenue for providing feedback through a robust survey would aid in seeing that the tool is meeting the needs of its users. Moreover, having multiple managers, with experience in different ecoregions or nations, and with varying priorities, would be helpful; this group could oversee new data inputs, monitor data portals, and add data deliverables as they are designed. This would ensure that the tool is kept up over time, which is particularly important if the tool is hosted on proprietary software—changes by the developers may require frequent updates by the maintainers and proprietary software usually has fewer users overall who can help with troubleshooting, data input, and data extraction, simply as a function of familiarity.

5 Conclusions: The importance of being able to visualize georeferenced bee data

Bees in North America are diverse: across the six families occurring on the continent, they exhibit unique behaviors and preferences, but all play an important role in functioning ecosystems. Understanding bee biology is essential for biodiversity conservation efforts, as it enables researchers to identify and protect critical habitats, manage threats, and preserve this rich and essential insect group. Wrapping our minds around not only the requirements of individual species, but also what it takes to keep entire communities intact, requires a series of tools that allow for the visualization and simplification of vast and varied data.

Through long conversations over the course of nearly two years, researchers identified challenges and potential solutions to gathering and processing available information about bees. Most helpful will be pulling together all available georeferenced data on bees, gathering new data from important areas where bee surveying and monitoring has not been carried out, and viewing that data through one geospatially oriented user interface. Ideally, this user interface would allow one to look at phenological data, plant associations, predicted bee species distributions, interannual variation, and the correlations between bee occurrences and environmental variables. Though the task is big, tools exist today that exemplify all these components, and, with proper support from Canada, Mexico and the United States, supporting a user-friendly bee geospatial tool is a reasonable goal.

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