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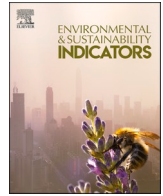
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Beescape and BeeSpatial: Making multi-scale environmental indicators of bee habitat accessible across audiences

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ABSTRACT

Pollinators, especially bees, provide a key ecosystem service by facilitating flowering plant reproduction and crop production. Supporting bee populations requires an understanding of land cover, foraging and nesting resources, insecticide loading and toxicity, and climate trends in the landscape. However, datasets necessary for assessing bee habitat quality are not conveniently located, interoperable, or readily accessible. Further, stakeholders have differing needs and technical capacities. We developed two complementary web applications that tailor access to bee habitat indicators for a large geographical region, the conterminous United States: 1) *Beescape* provides bee habitat quality indicators at user-selected locations and is designed from feedback by its main intended users: beekeepers, growers, gardeners, scientists, and conservationists. *Beescape* enables dynamic visualizations of landscape conditions impacting bees to support bee colony and habitat management and general awareness of the local status and relative importance of these factors. 2) *BeeSpatial* gives researchers and geospatial analysts additional data layer selections, functions for multi-location data extraction, and access to underlying geospatial data files to conduct subsequent analysis and processing. To meet its intended users' needs, *BeeSpatial* returns reproducible data queries at large volumes for research workflows. Together, these applications extend access to an integrated set of bee habitat quality indicators across audiences, though we note limitations for each indicator that users should consider. This framework can be applied to other global regions and conservation management contexts, where key geospatial indicators are relevant for a range of stakeholders and supporting spatial data and models exist but are not broadly accessible.

1. Introduction

The composition and quality of habitats, as well as climate indicators, are key factors that influence the distribution, health, and community composition of species that provide essential ecosystem services across space and time (Schellhorn et al., 2015). Insect

pollinators, primarily bees, are vital to the reproduction of 80% of all flowering plants and to the yield of 75% of food crops (Klein et al., 2007; Ollerton et al., 2011). Like many other insect taxa, bee populations have declined due to a variety of anthropogenic drivers operating across spatial and temporal scales, e.g., habitat loss, pesticide exposure, and changing weather patterns (Dicks et al., 2021; Janousek et al., 2023).

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Studies increasingly point to the importance of multiple landscape drivers for bee health (Gray et al., 2024; McNeil et al., 2020) and wild bee diversity and abundance (Janousek et al., 2023; Kammerer et al., 2024). Key information includes land cover, foraging and nesting resources, insecticide loading and toxicity, short-term weather patterns, and long-term climate trends. This information is vital to effective decision-making, for both management of domesticated honey bees and conservation of wild bees. For example, research studies have demonstrated the role of climate shaping wild bee abundance and richness (Kammerer et al., 2021), pesticides driving bumble bee population declines (Janousek et al., 2023), and lack of floral resources and nesting habitats increasing bumble bee pathogen loads (McNeil et al., 2020).

The ability to access and deploy geospatial indicators is an essential capacity that enables decision makers and researchers to better understand the resources and threats bees encounter as they forage in a landscape, as well as their associated pollination ecosystem services over space and time. Many stakeholder groups are interested in better managing and conserving pollinator populations, including beekeepers, growers, conservationists, urban planners, land managers, and members of the public (Dicks et al., 2013; Kleinman and Suryanarayanan, 2020; Turo and Gardiner, 2019). These stakeholders focus on different pollinator species and manage different types and sizes of landscapes. Beekeepers, for example, manage bees for honey production and pollination services, while growers benefit from the pollination services of both managed and wild pollinators.

However, the data needed for spatial analyses are typically distributed across different sources and require specialized knowledge of spatial analysis methods and geographic information systems (GIS) software for access and interpretation. Contemporary GIS tools are powerful and flexible, but they require significant training to implement, as users must understand how to acquire, analyze, and visualize spatial data (Rogers et al., 2025). These barriers limit the ability of scientists to leverage spatial data to uncover new insights into how environmental factors influence species abundance and distribution, and limit the ability of stakeholders and policymakers to use existing data to better manage and support bees and their habitats (Dwyer et al., 2025). Furthermore, the needs of users who wish to incorporate spatial data into scientific analyses may differ from those of beekeepers or local stakeholders that use spatial data for informed decision making. For example, researchers might focus on comparing specific variables over a range of sites across broad spatial extents, while growers or beekeepers may be more interested in exploring a particular site or focal area in detail. Addressing the needs of different user groups is essential for developing effective tools for both research and management (Lacey and Nelson, 2023).

To address these differing needs, we developed two geospatial web applications designed to enable users to visualize and query multiple indicators relevant to the ecology and health of bees and other pollinators, bringing together and applying multidisciplinary findings in landscape ecology, environmental toxicology, and environmental economics. These tools broaden the accessibility of regionwide geospatial indicators published in peer-reviewed scientific literature that cover the conterminous United States (approximately 8,000,000 km²). *Beescape* (latest version as of June 2026: *Beescape NexGen*, <https://beescape.psu.edu/>) is a web-based decision-support tool that helps users visualize and learn how their landscape supports bees. *BeeSpatial* (<https://beesuite.psu.edu/beespacial/>) is a research-focused companion tool to *Beescape* that provides deeper access to the underlying datasets, including historical data. *Beescape* and *BeeSpatial* are tailored based on needs assessment work with their target user groups, and they support a subset of key tasks for those users without requiring them to complete technical training.

These tools are free to use and represent the collaborative contributions of all the authors, who are scientists and developers from multiple disciplines across several universities and research institutions. Our research team has implemented the concept of user-centered design, a

common method in cartography and human-computer interaction (Robinson et al., 2005), where, at multiple stages of the development process, researchers test the tool with users (Houtman et al., 2025; Prestby et al., 2023; Robinson et al., 2021). The complementary designs of *Beescape* and *BeeSpatial* have emerged from this process. We summarize information for effective and appropriate use of these tools and their data, as well as lessons from their development that can be applied to similar platforms aiming to share large-scale spatial ecological data across broad audiences.

2. Geospatial indicators of bee habitat quality

We synthesize and serve key bee habitat data layers from the research literature within the complementary frameworks of *Beescape* and *BeeSpatial* (Fig. 1). Prior work has demonstrated how land use and land cover data can be translated into specific indices of bee habitat quality, including potential nesting and floral resources (Koh et al., 2016) and crop insecticide loading (Douglas et al., 2022), as well as potential ecosystem service provided by pollination (Jordan et al., 2021). Further, ancillary data on weather trends and citizen science observations can provide contextual insights for local management and variations in species abundance and richness. In the following sections, we overview each included data layer's methodology and usage considerations to guide practitioners and scientists in using these tools appropriately and interpreting their outputs effectively.

2.1. Base land cover

Beescape and *BeeSpatial* host the Cropland Data Layer (CDL), which provides crop and natural land cover information for the conterminous US (Boryan et al., 2011). This data layer is also the basis for indices of floral and nesting resources, crop insecticide toxic load, and economic value of pollinators. The CDL datasets are produced by the US Department of Agriculture National Agricultural Statistical Service (USDA-NASS) through supervised classification of remote sensing data (Sentinel 2 and Landsat) and US Geological Survey elevation and land cover data, using crop field data from the Farm Service Agency (FSA) and regional agricultural ground reference datasets for training and validation (Li et al., 2024). Historically, the CDL has been available at a 30 m resolution, but since 2024 it is produced at both 10 and 30 m resolutions (USDA-NASS, 2026). Land cover from the CDL is represented in *Beescape* using the most current 10 m version aggregated to broad thematic categories to support legibility. *BeeSpatial* supplies either aggregated or original CDL land cover data from as far back as 2008 at 30 m resolution, which is the data format shared across all years of availability (Fig. 1a).

Usage considerations. The modeling methods used to create the CDL have documented accuracy considerations. The CDL is intended as a satellite-adjusted statistical census of crop area that is essentially a regression of the ground reference information, mainly from the FSA Common Land Unit (CLU) survey, which is biased towards subsidized crops (USDA-NASS, 2026). As a result, the most common crops by planted area (corn, soybeans, and winter wheat) have the highest accuracies (>90%), while crops like vegetables and fruits with lower planted areas have lower accuracy (<60%, Lark et al., 2021). Across all crops, the area-weighted average accuracies are around 90% for most years. Also reflecting FSA CLU sampling intensity, major growing areas in the central US have the highest cropland accuracies, while less dominant agricultural regions in eastern, southern, and western US have lower accuracy. Outside of crops, land cover accuracies range from 47 to 90%, with the highest values for developed areas, open water, shrublands, and non-mixed forest classes. Regionally, non-crop accuracies are better outside of the northern and southern Great Plains regions of the central US. The accuracy considerations of the CDL in turn apply to the indices of bee nesting and forage resource, insecticide use and toxicity, and pollination economic value, which rely on CDL land cover

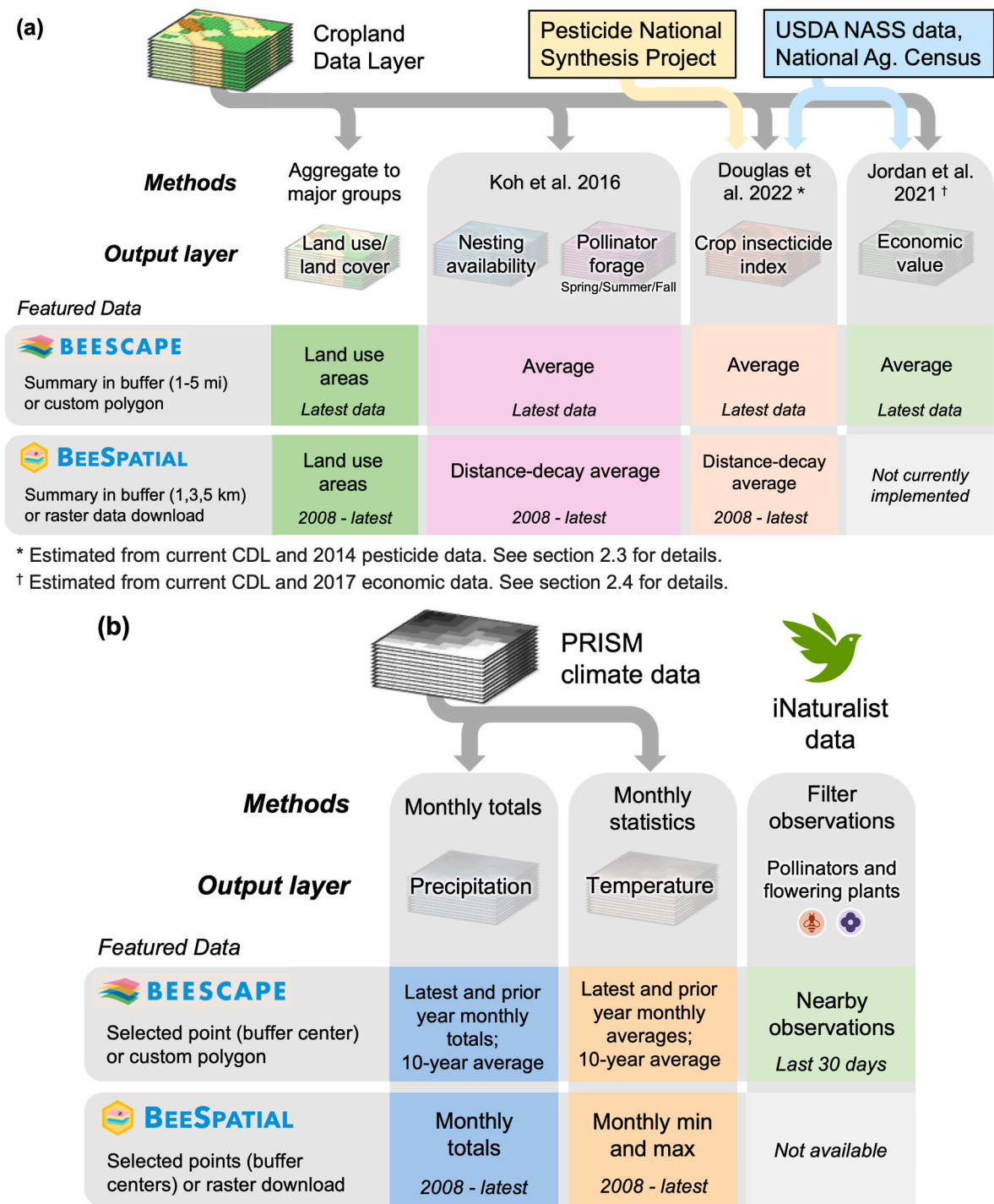


Fig. 1. Featured data, sources, and processing for *Beescape* and *BeeSpatial* applications. (a) Land use, nesting and forage resources, potential insecticide toxicity, and economic value of pollination are summarized by area-based methods. (b) Temperature, precipitation, and citizen observation data are available by points. *BeeSpatial* also provides users with historical and underlying raster data, where available.

information.

2.2. Bee nesting and forage resources

The nesting and forage indices (Fig. 1a) predict the availability of nesting habitat and floral resources in spring, summer, and fall seasons for wild bees using the CDL land cover categories based on Koh et al. (2016). Index estimates are based on aggregated expert opinion of the value of major CDL land cover categories as floral resources and as nesting habitat for ground, cavity, stem, and wood nesting bee guilds.

These indices can also be used to model relative bee abundance patterns in the landscape, which have been demonstrated to correlate with field-collected data (Kennedy et al., 2013; Lonsdorf et al., 2009). *Beescape* represents habitat indices on a scale of 0-100 for legibility, while *BeeSpatial* scores use the original formulation in Koh et al., (2016), which ranges from 0 to 1.

Usage considerations. The confidence distributions around expert-based index estimates are reported in Koh et al. (2016), although they are not represented in *Beescape* and *BeeSpatial*. Aside from uncertainty from variability in expert agreement, another source of uncertainty

stems from the potential variability in quality within the same land cover class from one location to another. Further, habitat estimates derived from the parent CDL data resolution and classes may not sufficiently capture important small habitats, for example small natural areas and urban gardens, which can still significantly benefit pollinators, even at patch sizes of 40–500 m² (Donkersley et al., 2023). Finally, the nesting and seasonal foraging indices represent resources as a single value for each land cover type, which makes assumptions that generalize across bee species within a community. Both *Beescape* and *BeeSpatial* follow Koh et al. (2016) and take the average of the estimated resource values for ground, cavity, stem, and wood nesting bee guilds for each land cover class.

2.3. Insecticide use and toxicity

The insecticide index (Fig. 1a) summarizes typical insecticide use patterns in agricultural crops and translates them into insecticide toxic load, i.e., the hazard to insect pollinators, with honey bees as a proxy (Douglas et al., 2022). Total applications of common insecticide active ingredients were sourced from the USGS Pesticide National Synthesis Project (Wieben, 2020) and converted to yearly application rates for each active ingredient by crop group and state, using crop acreage data (USDA-NASS, 2025). Application rates were then converted to numbers of contact and oral lethal doses to honey bees (LD₅₀) per area, based on toxicity literature (Douglas et al., 2020). The aggregate number of lethal doses applied per area was estimated by summing across all insecticide active ingredients applied on each crop group, specific to state and year. Contact and oral dose values were averaged and scaled for interpretability to represent 10¹⁰ lethal doses per hectare of each crop group, state, and year combination. These values for each crop group and state were applied to CDL land cover data to form the insecticide index in *Beescape* and *BeeSpatial*. Further data and code to generate additional pesticide indicators are available in Douglas et al. (2022).

Usage considerations. The insecticide index is best suited for characterizing patterns of typical insecticide use and comparing these patterns between locations or years. The index is not intended to quantify insecticides at any specific location because actual insecticide application rates may vary across fields, while estimates are based on average use patterns by state, year, and crop groups (Douglas et al., 2022). These estimates apply to agricultural land only, so non-agricultural lands such as urban areas and unmanaged lands do not contribute to the estimate of insecticide toxic load value. Insecticide loading in urban areas is difficult to estimate because pesticide reporting for these areas is lacking (Sponsler et al., 2019). That said, regional case studies suggest that pollinator exposure tends to be lower in urban than in agricultural areas, though these patterns are not uniformly lower and are likely compound-specific (Benner et al., 2023; Botías et al., 2017; Lawrence et al., 2016; Tsvetkov et al., 2017).

Pollinator exposure to active ingredients depends on the spatiotemporal overlap in activity with insecticide application and persistence in the landscape (Sponsler et al., 2019). Since these layers represent annual insecticide use, they best reflect hazards to species whose activity extends over more of the growing season. Further, lethal dose values reflect acute toxicity, rather than chronic exposure; they also assume additive effects of active ingredients and use the honeybee as a surrogate species. Finally, although seed-applied insecticides contribute significantly to bee hazard, comprehensive insecticide application rates including both spray and seed applications are only available for most states annually up to 2014, and unavailable in the state of California (Douglas et al., 2020). We applied the 2014 application rates to CDL land covers of later years since this is the most updated information available (Douglas et al., 2022). After 2014 and for the state of California, the insecticide index likely represents a more conservative estimate of toxic load, given increasing trends in seed-applied insecticide use in the US (Douglas et al., 2020).

2.4. Economic value of pollination

The economic value of contribution by pollinators is available based on the pollinator dependence of each crop present in the CDL and the value of that crop in US dollars (Fig. 1a). We take the approach of Jordan et al. (2021), who estimated pollinator dependence coefficients of individual crops based on a survey of crop pollination studies, which was used to supplement previous reviews of pollinator dependence. The pollinator dependence coefficient is the proportion of final crop yield attributable to pollinators, which was used to convert the reported crop yield and price of crops in the National Agricultural Statistics Service data to an estimate of pollinator contribution (in US dollars) to insect-pollinated crops in all the continental US counties for that year. This was in turn converted to a per-area value using reported harvested area by county from the 2022 USDA Agricultural Census. The per-area value of pollinator contribution for each crop was then used to reclassify the CDL crop land cover classes to their pollinator-contributed values. These values are currently only available on *Beescape*.

Usage considerations. Our estimates of economic value are intended to be used in *Beescape* by growers, beekeepers, and policymakers for relative quantifications and comparisons of the contributions by wild pollinators to the agricultural sector (Jordan et al., 2021). These estimates assume that the production values of crops were dependent on yield, to which pollination partly contributes. However, production value also depends on environmental, agronomic, technological, and other factors, which may vary independently of pollination. Broader economic impacts of pollination decline are not quantified, such as costs due to compensatory increases in resource use (Garratt et al., 2018), the loss in pollination for nonagricultural plants and ecosystems (Ollerton et al., 2011), and the long-term sustainability and stability of food production (Allen-Wardell et al., 1998). Estimates reflect prices during the last agricultural census (2017) and do not adjust for inflation.

2.5. Climate data

Climate data comes from the PRISM Climate Group at Oregon State University as 4-km resolution gridded monthly average temperatures and monthly precipitation totals (Daly et al., 2008). *Beescape* presents the current year trend alongside both the previous year and the ten-year average at a monthly interval (Fig. 1b) to help users account for abnormal weather that may impact forage availability or winter survival rates. *Beescape* updates monthly trends based on the release schedule of the PRISM source repository, which publishes preliminary monthly statistics on the 15th of the following month (NACSE, 2026). *BeeSpatial* hosts monthly total precipitation and monthly maximum and minimum temperature from 2008 up to the most recently available full-year dataset. *BeeSpatial* climate datasets are finalized versions of PRISM data, which are only published following a six-month period of quality control checks (NACSE, 2026).

Usage considerations. Gridded climate models have documented biases and uncertainties: temperature estimates are typically more accurate than precipitation; estimates in topographically complex regions (e.g., mountains) are less accurate; and extremes in temperature and precipitation are less well represented in the gridded data (Behnke et al., 2016). The coarser spatial resolution of this data may not reflect microclimatic conditions of some sites, which depend on local landscape features at a smaller spatial scale (Lembrechts et al., 2019).

2.6. Citizen observation data

Beescape users can also view records of flowering plants and bees (epifamily Anthophila) in the last 30 days (Fig. 1b), obtained from the application programming interface of iNaturalist, a crowdsourced species identification and organism occurrence recording tool (iNaturalist, 2024). These records are intended to convey the current phenological context to users by highlighting recent observations of seasonal events

such as flowering (Barve et al., 2020) as they interactively explore the landscape with *Beescape*. For example, a beekeeper may use this feature to understand plants that may be contributing to current local honey flows.

Usage considerations. Plant and insect observations from iNaturalist are subject to observer biases and possible identification error (see Hughes et al., 2021). These include geographic biases towards areas with higher human populations and near roads, and taxonomic biases towards charismatic groups and common species. Information on occurrence of bees and floral resource plants are for visual reference only and therefore only available on *Beescape*. Citable research-grade iNaturalist records are available through the Global Biodiversity Information Facility (GBIF), an international data infrastructure that standardizes, aggregates, and makes publicly available biodiversity observation records (GBIF: The Global Biodiversity Information Facility, 2020).

3. Serving bee habitat data in audience-specific applications

The selection and presentation of the data available on the *Beescape* and *BeeSpatial* applications reflect their intended audience. While *Beescape* presents information designed to be interpreted directly by stakeholders, *BeeSpatial* functions as a starting point for subsequent statistical and spatial analysis by expert users. *Beescape* displays the most current land cover data and derived indices (nesting and floral resources, insecticides, and economic value) at the highest available resolution (10 m) and returns a simple average for these indices within the selected buffer area. *BeeSpatial* hosts historical index data back to 2008 at 30 m resolution for congruency across datasets. For buffer-based index calculations, *Beescape* presents simple averages within buffers, while *BeeSpatial* summarizes values using an exponential distance-decay function that weights areas closer to the buffer center, as implemented in Lonsdorf et al. (2009), which better reflects the movement behavior of bees (Williams et al., 2012). To illustrate these applications in practice, we describe examples of their intended usage by target audiences.

3.1. Beescape usage

Beescape provides visualizations of key factors influencing bee health

and productivity, making it a relevant tool for a broad array of users (Houtman et al., 2025; Prestby et al., 2023; Robinson et al., 2021). Conservation practitioners can use the tool to visualize floral and nesting resources over an area of interest, while policymakers interested in supporting local beekeepers or wild bee habitat can quantify the economic value of pollinators to highlight contributions they make to local agricultural systems. Here we focus on the potential use for a beekeeper (Houtman et al., 2025; Robinson et al., 2021).

A beekeeper can use *Beescape* to examine land use patterns within the expected foraging range of an apiary location and estimate forage resources in the spring, summer, and fall (Fig. 2). This information can help predict nectar and pollen availability, anticipate honey flows, and identify periods when gaps in floral resources may call for supplemental feeding. The beekeeper can also compare the potential economic contribution of their bees to surrounding crops among candidate hive locations in their available landscape. The insecticide index reflects the insecticide toxic load from typical use for crops in the surrounding landscape, which can help the user understand potential impacts on colony health and performance. Temperature and precipitation data identify conditions, such as drought or heavy rains, that impact flowering phenology and in turn affect foraging and honey flows (Jentsch et al., 2009; Smith et al., 2021). By comparing current and past-year climate trends, beekeepers can also anticipate potential overwintering mortality (Calovi et al., 2021; Gray et al., 2024). *Beescape* also provides users with a snapshot of currently flowering plants contributing to local honey flows and simultaneously foraging bee species through iNaturalist observations. These results can be downloaded and saved as a report card in a pdf format.

3.2. BeeSpatial usage

BeeSpatial is designed to integrate into a reproducible research workflow. As an example, to investigate the influence of landscape factors on wild bumble bee pathogen loads, McNeil et al. (2020) calculated spring and summer floral resources, insecticide toxic load, and precipitation within a 2-km buffer around 59 bumble bee sampling sites for 2018 and 2019. *BeeSpatial* allows researchers to make similar queries for their own points within the extent of the conterminous US, for a wide range of available spatial layers, with historical data from

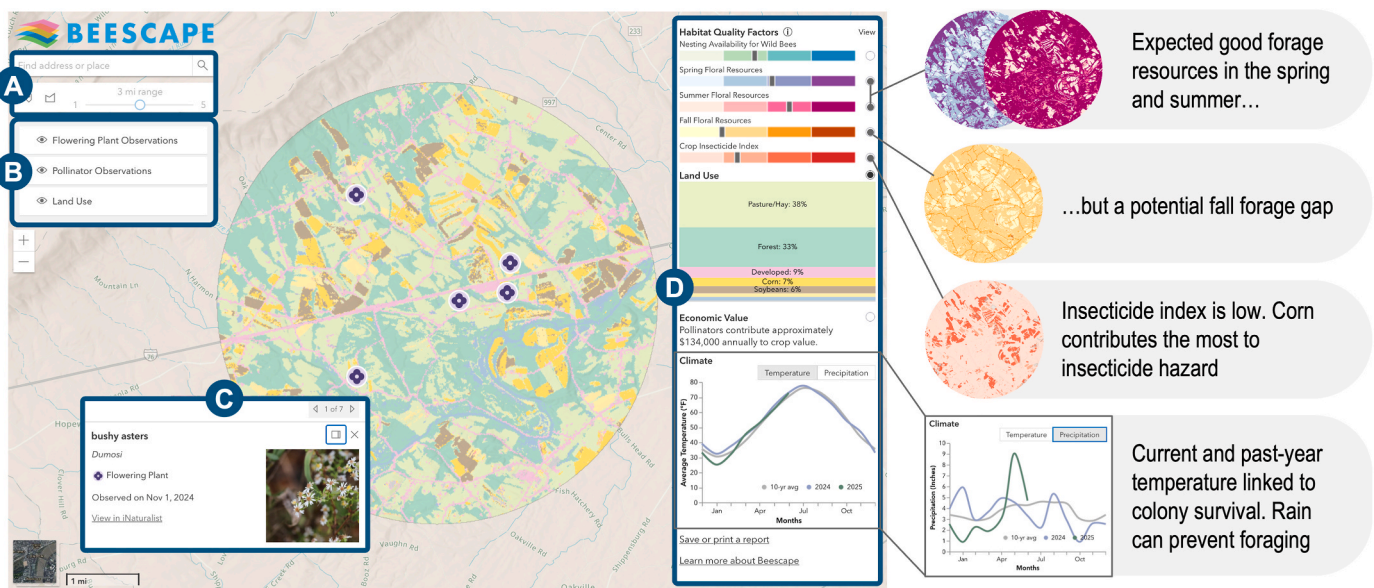


Fig. 2. *Beescape* user interface. (A) Location controls allow the user to input their location and set the buffer size for summarizing the surrounding landscape. (B) Map viewing controls to show/hide observations from iNaturalist and landscape data overlays. (C) Pop-up window shows more information on individual observations from iNaturalist. (D) Pollinator habitat scores, land use, economic value, and climate data dashboard. Selecting data in the dashboard changes the data overlay in the map or the dashboard; example interpretations of this information are shown on the right.

2008 up to the most recently released year. Users can also access the underlying gridded raster data, which provides continuous data coverage over a geographic area of interest for direct geospatial processing, analysis, and visualization.

To use *BeeSpatial*, users upload their own set of coordinates (using coordinate reference system WGS 1984, EPSG:4326) or select from a preset list of state and county boundaries in the conterminous US (Fig. 3a). Users select variables in bulk by specifying a series of target data layers and dates (Fig. 3b). Once the query-based data extractions

are completed, the user downloads the resulting data from the final page of *BeeSpatial* (Fig. 3c) for further analysis and visualization. A data query based on uploaded points returns a table of results, while a boundary selection produces a zipped directory containing the tif raster files of the selected data layers, clipped to the target administrative boundary. A demonstration of these workflows in *BeeSpatial* can be found at <http://climateecology.github.io/beespatal-tutorial/>.

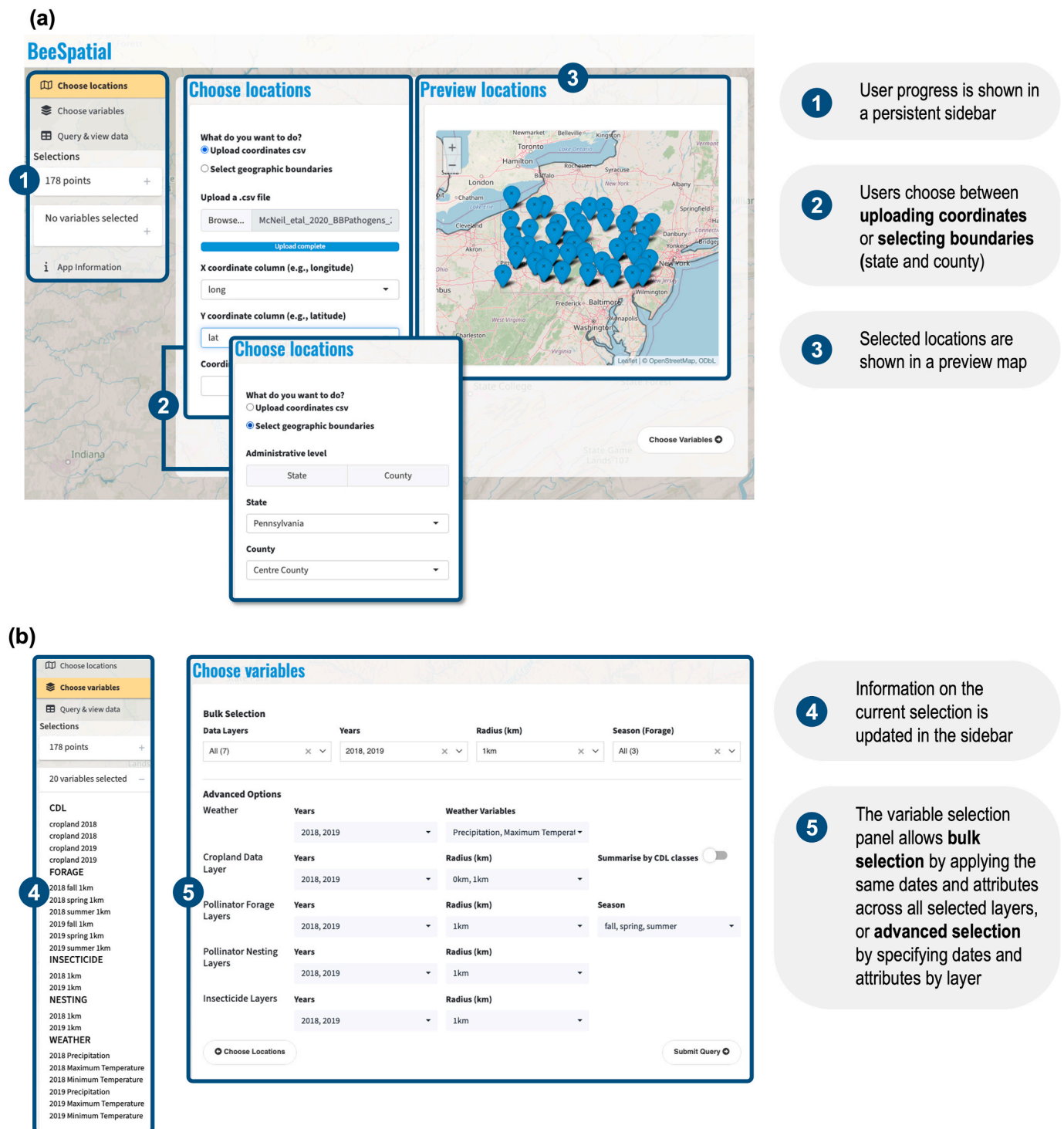


Fig. 3. *BeeSpatial* workflow. (a) Users begin the process by specifying the type of location information they will input. (b) Users next select the desired variables. (c) Once location and variable selections are complete, the user submits their query and downloads the data.

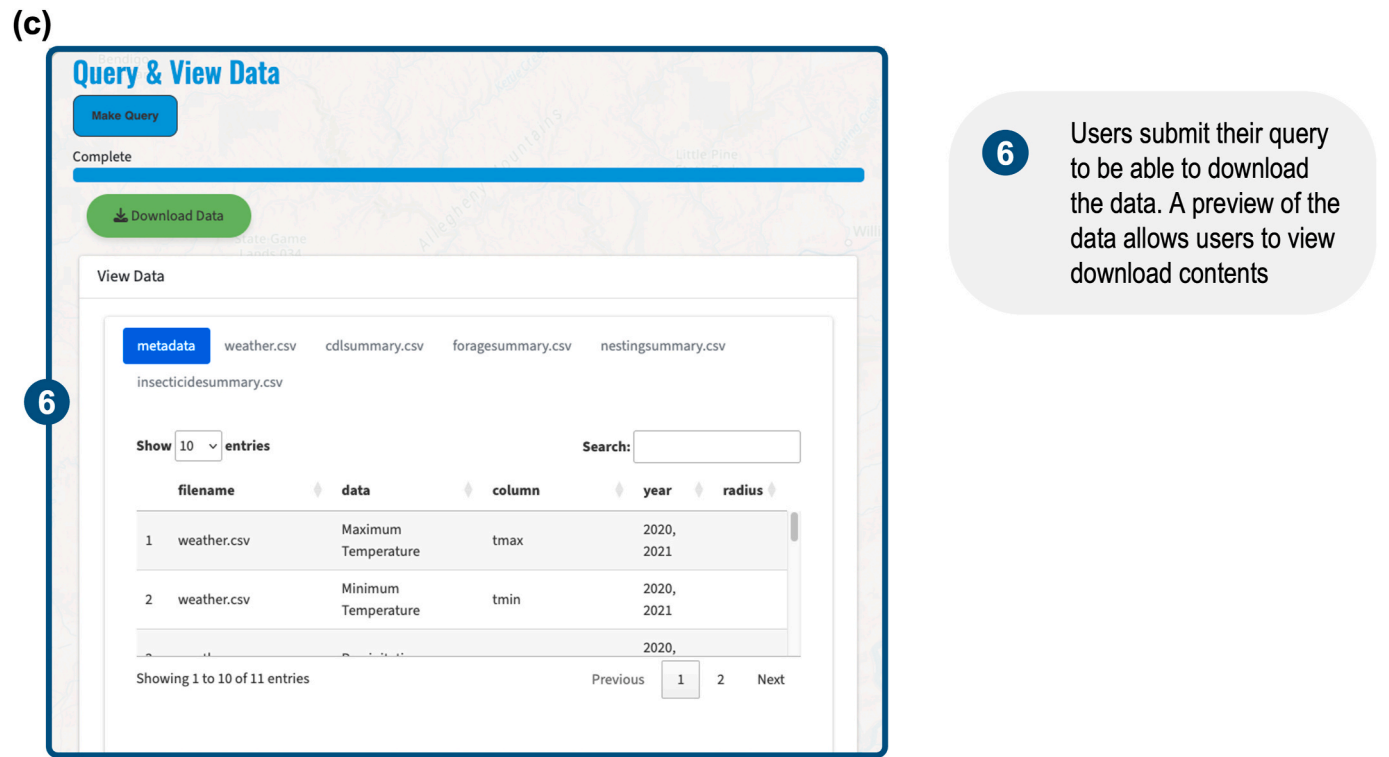


Fig. 3. (continued).

4. Beescape and BeeSpatial design and development

The architectures of *Beescape* and *BeeSpatial* deliberately differ in their approach to serving data, based on user feedback and needs. *Beescape* encourages interactivity and so its architecture prioritizes responsiveness. Therefore, *Beescape* is a browser-based web application using a client-side web mapping feature that allows the user to responsively query geospatial information and quickly see results based on their selections (Fig. 4a). *Beescape* uses the ArcGIS application programming interface, Vega, and D3 JavaScript libraries to access and

visualize geospatial data stored on a server. Results are calculated immediately in the browser upon the user's selection, which reduces the response time and encourages user engagement and exploration.

On the other hand, since *BeeSpatial* is intended to be part of a data analysis workflow, it emphasizes reproducibility with standardized and potentially high-volume outputs. *BeeSpatial* conducts geoprocessing on the server side (Fig. 4b), using geospatial and data-processing R packages (“exactextractr” v0.10.0, Baston, 2024; “terra” v1.7-78, Hijmans, 2025; “sf” v1.0-19, Pebesma, 2018; R Core Team, 2024). *BeeSpatial*'s user interface is programmed with the R package “shiny” (Chang et al.,

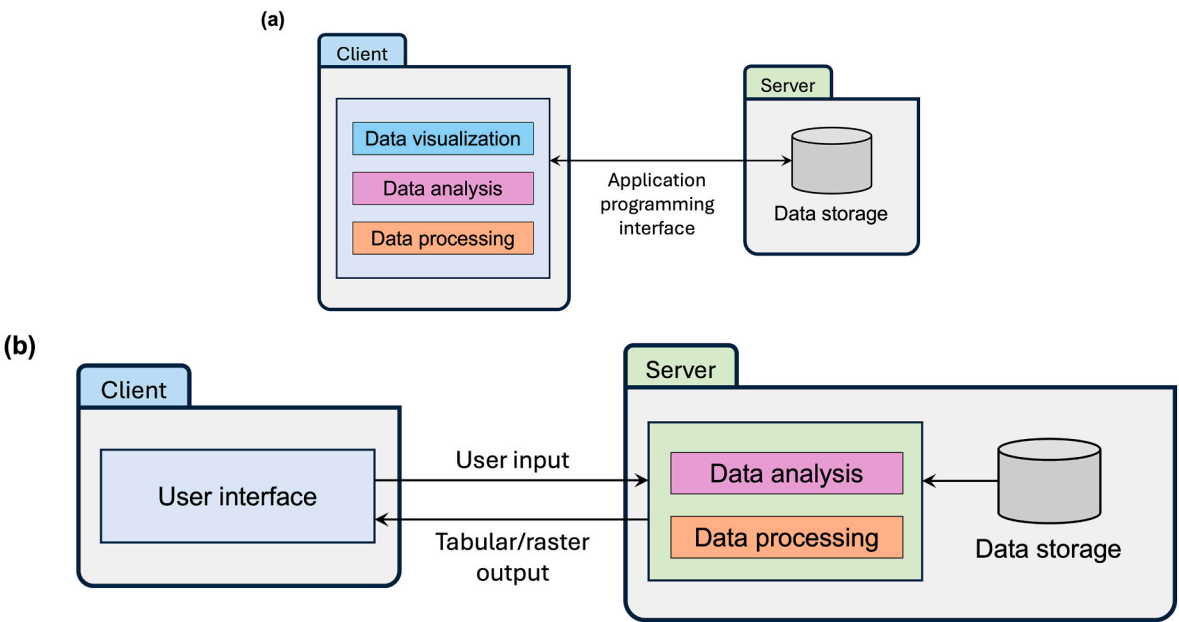


Fig. 4. Comparison between *Beescape* and *BeeSpatial* architectures. (a) *Beescape* performs its calculations on the client's browser, speeding up results. (b) *BeeSpatial* performs geoprocessing on the server using R, which can be integrated into a reproducible workflow.

2025). The use of R code for geoprocessing means that *BeeSpatial* follows a reproducible workflow understandable by researchers who can share their methodologies and replicate results. The server side of *BeeSpatial* uses cropping and masking geoprocessing functions to subset an area from national-scale raster datasets or buffering and extraction functions to query and then summarize cell values. Due to the potential volume and complexity of these geoprocessing tasks, outputs are downloaded by the user rather than dynamically displayed in the web browser.

The design of *Beescape* followed an iterative development informed by user-centered design methods (Robinson et al., 2005) involving a series of workshops that explored the application's usability and utility (Houtman et al., 2025; Prestby et al., 2023; Robinson et al., 2021). Paying attention to user needs and feedback is critical for the effective design of decision support tools, and can increase their impact (Lacey and Nelson, 2023). Based on user feedback from early workshops (Prestby et al., 2023; Robinson et al., 2021), the first version of *Beescape* was redesigned to the current version (*Beescape NexGen*), which users have rated as easier to use and more effective (Houtman et al., 2025).

The lessons from the user-centered design process are applicable for developing similar knowledge sharing and decision support platforms. One important finding fundamental to gaining audience acceptance was the importance of ensuring that users understand the purpose of the platform's data layers, especially for users without academic backgrounds. For example, workshops revealed that when practitioners such as beekeepers and growers did not understand the bee habitat data, they preferred interpreting habitat information directly from land cover, even though the nesting and floral resource layers were built to provide this information (Prestby et al., 2023). Users also desired transparency about how indices were created and, in some cases, distrusted information if local-scale land cover data did not match their own knowledge (Houtman et al., 2025; Prestby et al., 2023). While designers can provide background information about data processing on the platform, addressing the inherent uncertainties of spatial data is an important continuing challenge. This could be met by emphasizing landscape-level habitat quality summaries rather than pixel-level accuracy and introducing spatial uncertainty representations in future developments. While we found that users often preferred to see more granular information, e.g., recent weather trends rather than long-term averages, and specific land cover types rather than broad groups (Prestby et al., 2023), this has to be balanced against feedback from users that they could be overwhelmed with overly detailed information (Robinson et al., 2021).

The specific needs of different user groups identified through the user-centered design process inspired additional features in *Beescape* and the development of *BeeSpatial* as a separate application. *Beescape* users wanted a way to share results outside of the application, leading to the addition of a report card feature in the latest iteration (Houtman et al., 2025); while interest in more information on local flowering plants and pollinators led to the addition of iNaturalist data (Prestby et al., 2023). On the other hand, *BeeSpatial* fulfills the needs of conservationists and scientists who wanted access to more data, such as historical datasets (Prestby et al., 2023).

In a recent review, Dwyer et al. (2025) found that *Beescape* contrasts with other decision-support tools for pollinators in agricultural landscapes in that it is built with feedback from its intended stakeholders and is designed to be accessible to users with little or no specialized GIS capabilities. They also found that many of the tools they reviewed focused on domesticated honey bees and featured North American or European regions. While many of the data layers in *Beescape* and *BeeSpatial* are applicable to beekeepers and reflect their feedback, the bee nesting resources layer is designed to specifically assess wild bee habitat suitability. Other layers, such as land cover, forage resources, climate data, and insecticide index also apply to wild bees and can be adapted to study impacts on non-bee pollinators, which can contribute 25-50% of flower visits (Rader et al., 2016). On the other hand, *Beescape* and other pollinator decision-support tools could increase their impact by integrating with wider decision-support systems and incorporating social,

economic, and institutional drivers (Dwyer et al., 2025). Nevertheless, to our knowledge, *Beescape* and *BeeSpatial* are the only geospatial platforms that serve multifaceted bee habitat data for the conterminous United States.

While the focus of *Beescape* and *BeeSpatial* is supporting bees, bee habitat, and pollinator ecosystem services in the United States, the overall approach and framework could be readily adapted to other contexts, such as other global regions, or for bird or other wildlife management. High resolution datasets that could support similar geospatial platforms are available globally for generalized land cover, pesticide application rates, and weather (Brown et al., 2022; Fick and Hijmans, 2017; Maggi et al., 2019), while crop-specific datasets of land cover exist regionally, for example for Europe or Brazil (EEA, 2024; Souza et al., 2020). Regional distributions of bee forage plants could be developed from citizen science records, including for regions with less available data, such as Africa (Nganso et al., 2025). Based on our own experiences developing the *Beescape* and *BeeSpatial* applications and building the underlying indicator datasets, we recommend further habitat assessments involving regional specialists to characterize land cover resource values and working with local stakeholders to ensure the relevance and usability of geospatial data platforms for targeted users.

5. Conclusions

We have developed *Beescape* and *BeeSpatial* as complementary applications that support management and conservation of domesticated and wild bees by presenting indicators of habitat quality and economic value, as well as data on land use, citizen science observations, and climate integrated from multiple sources, making this information accessible and interpretable for a broad range of audiences. These two applications differ in their approaches to data access, reflecting the needs of their target users. *Beescape* focuses on data visualization and exploration by using client-side processing that prioritizes dynamic outputs and interactivity over reproducible workflow. This is useful for users such as beekeepers who wish to explore the landscape for ideal sites and potential bee stressors. In contrast, *BeeSpatial* specializes in providing reproducible results using a workflow that can handle larger volumes of data for predetermined points or areas. Our user-centered design and development process distinguishes these applications as geospatial decision-support tools that lower technical barriers and are tailored to stakeholder needs, an approach that can be applied to other regions and management contexts. By making ecosystem service and habitat conservation data available for a broad range of audiences, from researchers to local resource managers, targeted geospatial platforms such as *Beescape* and *BeeSpatial* enable knowledge sharing for complex landscape conservation issues over their heterogeneous groups of stakeholders.

CRedit authorship contribution statement

Kevin Li: Data curation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Heather Grab:** Data curation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Mark A. Buckner:** Data curation, Software, Writing – review & editing. **Lily Houtman:** Data curation, Methodology, Software, Writing – review & editing. **Melanie Kammerer:** Data curation, Methodology, Writing – review & editing. **Dave McLaughlin:** Data curation, Methodology, Software, Writing – review & editing. **Anais Ostroski:** Data curation, Methodology, Writing – review & editing. **Margaret R. Douglas:** Data curation, Methodology, Writing – review & editing. **Sarah C. Goslee:** Data curation, Methodology, Software, Writing – review & editing. **Vikas Khanna:** Data curation, Methodology, Writing – review & editing. **Eric V. Lonsdorf:** Data curation, Methodology, Writing – review & editing. **Anthony C. Robinson:** Data curation, Methodology, Software, Writing – review & editing. **Christina M. Grozinger:** Conceptualization, Data curation, Funding acquisition,

Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data is available through the web platforms described and linked in the manuscript.

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