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A framework and case study to systematically identify long-term insect abundance and diversity datasets

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Abstract

Biodiversity is in crisis, and insects are no exception. To understand insect population and community trends globally, it is necessary to identify and synthesize diverse datasets representing different taxa, regions, and habitats. The relevant literature is, however, vast and challenging to aggregate. The Entomological Global Evidence Map (EntoGEM) project is a systematic effort to search for and catalogue studies with long-term data that can be used to understand changes in insect abundance and diversity. Here, we present the overall EntoGEM framework and results of the first completed subproject of the systematic map, which compiled sources of information about changes in dragonfly and damselfly (Odonata) occurrence, abundance, biomass, distribution, and diversity. We identified 45 multi-year odonate datasets, including 10 studies with data that span more than 10 years. If data from each study could be gathered or extracted, these studies could contribute to analyses of long-term population trends of this important group of indicator insects. The methods

†Deceased prior to final manuscript completion (September, 2021) but made significant intellectual contributions to the project with expectation of co-authorship.

developed to support the EntoGEM project, and its framework for synthesizing a vast literature, have the potential to be applied not only to other broad topics in ecology and conservation, but also to other areas of research where data are widely distributed.

KEYWORDS

damselflies, dragonflies, evidence synthesis, insect decline, insect population trends, Odonata, systematic map

1 | INTRODUCTION

At multiple levels of biological organization, from genes to populations to ecosystems, biodiversity is being lost at a rate that is transforming every region of the planet (Barnosky et al., 2012). Insect declines have been reported in nearly all habitats from the Arctic (Gillespie et al., 2020; Høye et al., 2013; Loboda et al., 2018) to the tropics (Roubik, 2001; Salcido et al., 2021); in developed areas (Theng et al., 2020), wildlands (Forister et al., 2021), and nature reserves (Hallmann et al., 2017; Rada et al., 2019); and across taxa from hoverflies (Hallmann et al., 2021) to dragonflies (Nakanishi et al., 2018) to butterflies and moths (Conrad et al., 2006; Fox, 2013; Thomas et al., 2004; Wagner, Fox, et al., 2021; Warren et al., 2021). Propelling these declines are a multitude of threats including habitat destruction, agricultural intensification, climate change, invasive species, and more (see Cardoso et al., 2020; Harvey et al., 2020; Wagner, 2020; Wagner, Grames, et al., 2021). Insect population trends are spatially, temporally, and taxonomically complex (Montgomery et al., 2020), and in addition to the many reports of insect declines, recent studies have also described insect population increases (Høye et al., 2021; van Klink et al., 2020a, 2020b; Wagner, Fox, et al., 2021; Warren et al., 2021) or a lack of discernible directional change over time (Boyes et al., 2019). To understand how insect population and biodiversity trends vary across taxa, space, and time, and to better understand the relative importance of different threats in driving those trends, it is necessary to go beyond the results of individual studies and systematically synthesize available demographic evidence for insects without bias.

Collating and analyzing long-term insect population and diversity datasets are essential first steps towards a synthetic and balanced understanding of global insect population and diversity trends. Identifying these datasets is challenging, however, because the literature is vast and widely distributed. Datasets documenting long-term insect population and biodiversity trends are scattered across many scientific disciplines, with much coming from medical entomology (e.g., Shone et al., 2014), agricultural and natural resource sciences (e.g., Kim & Kwon, 2019), and community ecology (e.g., Yukawa et al., 2006), as well as conservation and biodiversity studies (e.g., Bartomeus et al., 2013; Seibold et al., 2019). Due to the diversity of purposes for which long-term insect data are collected, they are often not described as such by the authors; rather, insect population data may be framed as data on food availability (e.g., Gardarsson & Einarsson, 2008; Hong et al., 2016), disease vectors (e.g., Fairbairn & Culwick, 1950), agricultural pests (e.g., Ouyang et al., 2014), pollinator communities (e.g., Smith-Ramírez et al., 2014), water quality indicators (e.g., Cooper et al., 2014), and more. It is therefore necessary to search broadly for studies that contain long-term insect population and diversity data and to use rigorous methods to ensure that available evidence is systematically accumulated.

Rigorous methods of evidence synthesis were first introduced to conservation biology over two decades ago (Pullin & Knight, 2001) and have existed for nearly half a century in fields such as medicine and public health (Glass, 1976; Gurevitch et al., 2018). These methods involve specific steps to ensure syntheses are as comprehensive, repeatable, and objective as possible. Taking a systematic approach to reviewing scientific literature and identifying studies for meta-analyses (Foo et al., 2021) overcomes limitations of traditional literature reviews, which often fail to be comprehensive and focus on subsets of data, with potential for biased conclusions. Despite the advantages of taking systematic approaches to reviewing the literature and the prevalence of guidelines and standards to follow (Koricheva et al., 2013), most reviews in ecology and conservation biology continue to be conducted in an unsystematic manner that lacks reproducibility, often due to ad hoc or poorly designed data gathering methods (Grames & Elphick, 2020; Haddaway et al., 2020). One approach to address this issue, especially for broad topics, is to begin evidence synthesis projects with a systematic map.

In a systematic map, the goal is not to provide an overview, test hypotheses, or develop a deeper understanding of a topic, but rather to identify and catalogue studies and datasets on a particular topic in a searchable database; in other words, to "map" the relevant research literature. Systematic map databases can be used to identify where in the world studies on a topic have taken place, which systems have been studied the most, what research methods are most commonly employed to study a topic, which researchers are working on a topic and how they are connected, and other metadata about the way research on a particular topic has been conducted. By identifying and cataloguing studies in a common framework, systematic maps provide a rigorous foundation that can then be further investigated to address specific research questions through qualitative and quantitative syntheses, and can also be used to identify gaps in the literature that are priorities for new primary research (James et al., 2016). Applying conventional systematic mapping methods to large topics can be time-consuming and requires sustained funding, however, necessitating a new approach for topics as broad as tracking changes in insect abundance and diversity.

The Entomological Global Evidence Map (EntoGEM) project was initiated in 2019 to address the challenge of identifying and integrating data to understand long-term insect population and diversity trends. The project consists of an open collaborative research network and an interconnected series of modular subprojects that can be harnessed to identify and catalogue multi-year data sources that represent diverse taxa, habitats, and geographic regions in a way that is unbiased, comprehensive, and transparent. This will inform more robust assessments of global insect population and biodiversity trends. Here, we present the EntoGEM framework, describe the aims and methods of the project in more detail, and present results from the first completed EntoGEM taxonomic subproject on dragonflies and damselflies (Odonata). While the focus of this paper is to introduce EntoGEM and describe the first subproject, the methods and framework shared here are broadly applicable to any discipline where systematic synthesis is needed to address subjects with large or scattered data resources.

2 | METHODS

2.1 | Establishing the EntoGEM project

The EntoGEM project is a community driven evidence synthesis project. It was designed to be an open and flexible project, taking an approach that allows a diverse community of researchers and other stakeholders to collaborate on a topic. It differs from traditional syntheses in that the core team coordinates, rather than leads, the process and does not restrict who is part of the community. The community is open and anyone with an interest in the topic is welcome to participate in decision-making and to use the results of the synthesis effort. Additionally, project protocols, decisions, and data are made publicly available to facilitate community re-use or adoption by other, similar projects (Nakagawa et al., 2020).

To establish the general framework for the EntoGEM project (Figure 1), we developed a protocol defining the project objectives, what types of dataset we would include in the database, how we would find and screen articles, what metadata we would extract from each study, and how we would ensure consistency across project participants. We drafted an initial project protocol, which we then distributed to entomologists, conservation biologists, and experts in synthesis methods to gather feedback. We incorporated feedback from this community of researchers into a final protocol and archived it in a public repository, with one subsequent revision to clarify what types of datasets would be included in the database (Grames, Montgomery, et al., 2019). The protocol and general methods used in the EntoGEM project are summarized below; additional details are available in the archived protocol (Grames, Montgomery, et al., 2019).

2.2 | Eligibility criteria for studies included in the EntoGEM database

When planning the project, we developed a set of criteria describing what types of studies and datasets would be included in the database (the searchable systematic map of studies meeting all inclusion criteria and their associated metadata) based on their potential to contribute to understanding short- and long-term insect population dynamics and drivers of change. To meet the EntoGEM inclusion criteria, articles needed to document more than 1 year of data on insect populations or communities that were not the subject of direct management. We were only interested in nonmanaged insect populations, and thus we excluded, for example, studies of pesticide effectiveness or conservation actions specifically designed to benefit insect populations unless there was a control plot from which population trends could be analyzed or nontarget insects were also sampled. The way in which researchers quantified and reported insect population and diversity trends had to fall into, or be easily converted into, one or more of: occurrence, abundance, range size, diversity indices (e.g., Shannon diversity, species richness), or biomass. We did not include studies with data at scales below the whole individual, such as morphological, genetic, or metabolomic studies. For investigations of geographic range, studies had to include prior sampling to be included; presence-only records at new locations were not included. Years of data collection did not necessarily need to be consecutive, but did need to span at least 13 months (see Grames, Montgomery, et al., 2019 for full definitions).

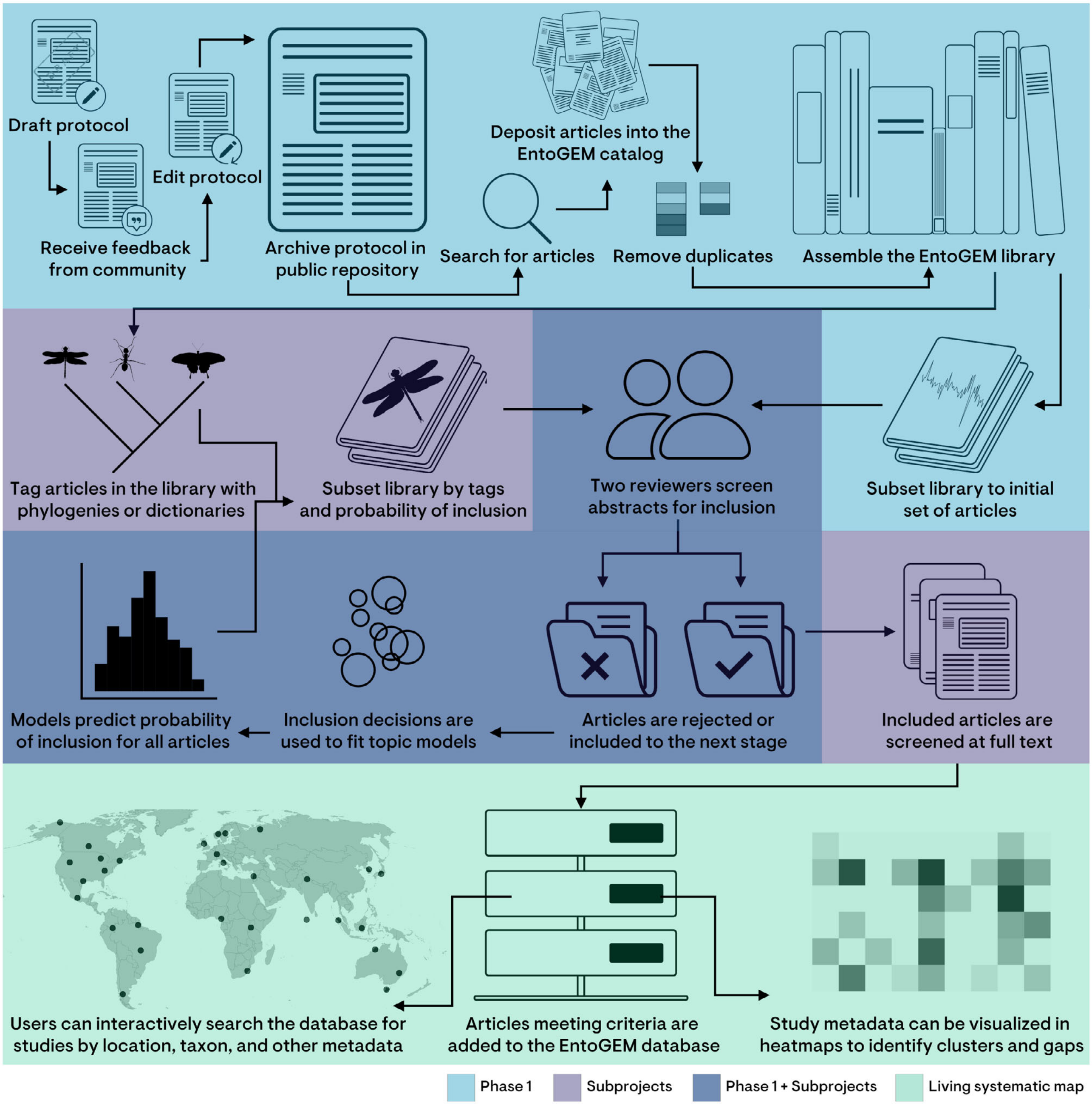

FIGURE 1 Conceptual model representing the workflow and stages of the EntoGEM project. Stages completed during the first phase of the project are highlighted in green. Subprojects, including the completed project on odonates, ongoing projects, and as-of-yet uninitiated projects are highlighted in purple. Because some steps, such as updating the topic model predictions, are done in multiple phases of the project, they are highlighted in both green and purple. The final phase of the project (light blue) is the creation of the living systematic map database, which is updated as subprojects are completed, that can then be used to initiate meta-analyses on research clusters and identify priorities for primary research to fill gaps

2.3 | Phase 1a: Literature search and library assembly

To identify studies meeting the EntoGEM criteria, we designed a search strategy for locating published and gray literature. When designing a search strategy for any type of review, there is a trade-off between the sensitivity of a search, or its ability to retrieve all relevant studies, and its specificity, or its ability to retrieve only relevant studies. Our strategy prioritized a comprehensive search to reduce the risk of omitting studies that met our criteria (i.e., high sensitivity), even though this increased the number of irrelevant papers retrieved by the search (i.e., low specificity). Using a combination of expert opinion, web scraping for insect common names, and automated search strategy development with the R package litsearchr (Grames, Stillman, et al., 2019, 2020), we developed a search string (Grames, Montgomery, et al., 2019, Appendix 1, Table A2) containing >1500 synonyms for "insect" or for specified insect groups, which we paired with 44 terms indicating population or biodiversity responses (e.g., "abundance," "species richness"), and 43 terms, including proximity operators, indicating time series data (e.g., "long-term," "over time," "population trend").

We searched 16 bibliographic databases and one thesis database in the first phase of the project (Table S1), with an additional 30 bibliographic databases and over 250 gray literature sources (see Grames, Montgomery, et al., 2019, Appendix 3) to be searched in later phases. The initial searches were carried out between August and December 2019. We recognize that many datasets exist in formats outside of scientific articles housed in bibliographic databases (e.g., in repositories such as the Global Biodiversity Information Facility or records of national monitoring schemes), however, we restricted our search to bibliographic sources for the first phase of the project because the datasets described within published papers are not necessarily already indexed. Given the urgent nature of the research topic, the first phase was designed to identify highly relevant articles as quickly as possible to provide a springboard for more comprehensive meta-analyses. We assembled all search results into the EntoGEM library (the bibliographic records for all articles considered by the project) using custom functions that are now contained in the R package synthesisr (Westgate & Grames, 2020). To identify duplicate records of the same article (e.g., when retrieved from multiple databases), we first checked the search results for studies with identical titles, abstracts, or DOIs. To identify duplicate records with minor formatting differences due to database rules or typographical errors (e.g., including species scientific names in parentheses rather than italicizing them, or misspelling a word when the article was indexed), we used the optimal Damerau-Levenshtein distance for partial string matching (Damerau, 1964; Levenshtein, 1966). We allowed adjacent characters to be transposed and set a threshold of five for the maximum number of insertions, deletions, or character substitutions to map one record to another. For records identified as duplicates, we removed all but a single instance from the assembled library.

2.4 | Phase 1b: Screening and article prioritization

In the first phase of the EntoGEM project, we screened a prioritized subset of articles from the assembled library (Figure 1). Initially, article prioritization was somewhat ad hoc and intentionally biased towards studies with long-term datasets. This approach to prioritization allowed us to have enough articles that contained multiple years of insect data to create the project infrastructure early on, knowing that over time, as more subsets were completed, the bias introduced by this selection process would disappear. We selected articles where the title, abstract, or keywords contained terms such as "long term" or "multi-decadal" rather than more generic terms like "changes." We uploaded this set of articles to the screening platform SysRev (Bozada et al., 2021), where participants in the EntoGEM project could screen articles by titles and abstracts to determine if they met inclusion criteria. Each article in the first phase of the project was screened by at least two reviewers who had completed an initial training to assess comprehension of the inclusion criteria. In cases where it was unclear if articles met the full EntoGEM criteria, reviewers were instructed to promote articles to the full-text stage of screening as a precaution. When two reviewer inclusion decisions were not in agreement, a third party with a low false negative error rate (one of EMG, DHB, GAM, or NGT) resolved the conflict.

Because our search strategy aimed to increase sensitivity at the expense of specificity, we retrieved many irrelevant articles (e.g., searching for *changes* in *insect abundance* also retrieves studies on *changes* in gene *abundance* in *Drosophila*). To reduce the burden of manually screening papers to assess their relevance, we took a quasi-automated approach. Following completion of the initial phase of screening, we used the manual article inclusion decisions on the first priority set of articles to train topic models predicting whether articles were likely to be included or excluded based on the terms and phrases appearing in their titles and abstracts. The predictions from these models were then used to filter the remaining articles in the library and prioritize relevant articles for future manual review. To do this, we used the R package litsearchr v1.0.0 (Grames, Stillman, et al., 2019, 2020) to identify terms and phrases in article titles and abstracts while removing stopwords (e.g., "and," "how," "some") and irrelevant terms (e.g., "abstract authors," "copyright") to create a cleaned body of text. Using the cleaned text, we created a document-feature matrix containing counts of each key term or phrase appearing in the title and abstract of each article. Using the inclusion status for each article as the outcome of interest and the document-feature matrix as predictors, we conducted a logistic LASSO regression using the R package glmnet v4.1.1 (Friedman et al., 2010). We first set aside a random 70% of the dataset for model training and used cross-validation within that set of articles to select the optimal penalty parameter (λ). We then predicted the probability of inclusion for articles in the set-aside 30% of the data. To select the optimal threshold in predicted probability of inclusion that maximized exclusion of true negatives while minimizing the exclusion of true positives to make the screening process more efficient, we calculated the proportion of true negatives and true positives that would be excluded at each threshold in the predicted probability of inclusion from 0 to 1 in intervals of 0.01. We defined the optimal threshold as the point where the difference between the proportion of true negatives and true positives excluded was at its maximum. Because of model sensitivity to the articles randomly selected for the training dataset, we repeated this procedure 20 times and calculated the mean probability across all iterations. We used this probability as a cutoff for model predictions on new datasets that were not part of the training or test datasets created in the first phase of the EntoGEM project. To reduce false negative error rates introduced by this approach, the topic models and predictions are periodically updated as subprojects are finished, and new predictions are made for all articles in the EntoGEM library.

2.5 | Odonata subproject: Taxonomic tagging and article prioritization

Because of the volume of literature and the diversity of insects, we have begun to subdivide the EntoGEM library into a series of modular, interconnected subprojects based on specified focal taxa, regions, and research questions. Each subproject has its own leadership and aims, but there is coordination across subprojects and all results feed back into the central EntoGEM systematic map database. The first completed subproject on odonates is described here to exemplify the approach—as noted above, the methods and guiding principles apply across subprojects and other subjects where systematic maps or reviews are desired.

To identify articles on dragonfly and damselfly population trends, we first compiled a list of terms and synonyms for insects based on phylogeny and common names. We combed BugGuide.net, the Entomological Society of America Common Names Database (ESA, 2019), and the Global Biodiversity Information Facility backbone (GBIF Secretariat, 2017), and organized insect scientific and common names into a hierarchical dictionary, where each level of the dictionary represents an increasingly higher taxonomic resolution. At the highest level are insect orders, followed by sub- and infraorders, and so on for family-group categories. We used this dictionary and the R package topictagger v0.0.9 (Grames, 2020) to create a document-feature matrix, where each row represents one bibliographic record (including the title, abstract, and keywords) for each article in the EntoGEM library, and each column represents an insect taxon and all its nested synonyms from the dictionary. Articles where all the taxon tags matched a single order were assigned to that taxonomic subproject; articles tagged as multiple taxa were assigned as community studies which will be distributed into multiple taxa-specific projects when screened. Not all articles include taxon names in the title, abstract, or keywords, and we were unable to tag any taxon for 35% of articles. These articles are not assigned to taxon-specific subprojects and will be screened and added to the systematic map database at a later time. For the case study presented here, we selected all articles that matched only to Odonata. We then applied the topic models described above to this subset to predict how likely it was that each article would be included by reviewers, and selected articles with a probability of inclusion greater than the predetermined threshold from cross-validation of the topic models.

2.6 | Odonata subproject: Article screening and metadata extraction

The set of odonate articles that topic modeling identified as likely to meet our inclusion criteria was screened by eight reviewers using titles and abstracts, as described above. At the full-text stage of screening, two reviewers independently read the methods section of each article to determine if it met the EntoGEM criteria. For articles that met all criteria, reviewers extracted the following metadata: geographic location of data collection, habitat type, type of population or diversity response (e.g., abundance, species richness), insect sampling methods used, years of data collection and time series length(s), insect orders studied, and data availability (see Grames, Montgomery, et al., 2019 for details).

For articles where the two independent reviewers disagreed on study inclusion, years of data collection, or taxa studied, a third party resolved conflicts. We did not require independent reviewers to reach consensus for other types of metadata where different terms can be used to represent the same idea. For example, one reviewer may describe the sampling method as a visual survey, and another as a line transect count; one reviewer may say the community response was species richness, and another may say alpha diversity. Rather than resolving these minor conflicts by a third party, we created hierarchical dictionaries for habitat types, response types, and sampling methods (Table S2). We then re-tagged these metadata for each article using the reviewers' tags and the R package topictagger v0.0.9 (Grames, 2020) to create consistent labels. For example, studies where reviewers assigned the sampling method as a dip net, kick net, or D-frame net were all reclassified as "aquatic net" by the dictionary.

3 | RESULTS

3.1 | Phase 1a-b: Search, assembly, screening, and prioritization

After the first phase of searching, we retrieved 617,026 results across 17 databases (Figure 2). We automatically removed 486,191 duplicate articles based on exact matches and string distance, resulting in 130,835 articles used in the remaining stages of the EntoGEM project. From this set of articles, 7091 were prioritized for the first phase of screening based on their likelihood of containing long-term data. In this initial set of articles, 1657 were manually marked as definitely meeting criteria, 1598 were marked as being unclear if they met criteria, and 3836 were marked as definitely not meeting criteria. When developing topic models, we grouped the 1598 articles for which there was uncertainty with the 3836 rejected articles and compared them to those articles for which there was no doubt about inclusion to increase the precision of the models. Across 20 iterations (Figure 3), the optimal threshold (i.e., maximal exclusion of true negatives with minimal exclusion of true positives) for probability of inclusion ranged from 0.15 to 0.25 (mean = 0.19). Because we created the odonate subset prior to iteratively running the topic models and based it on a single iteration, we (somewhat arbitrarily) used 0.20 as the threshold for probability of inclusion. The topic models are updated as EntoGEM participants make

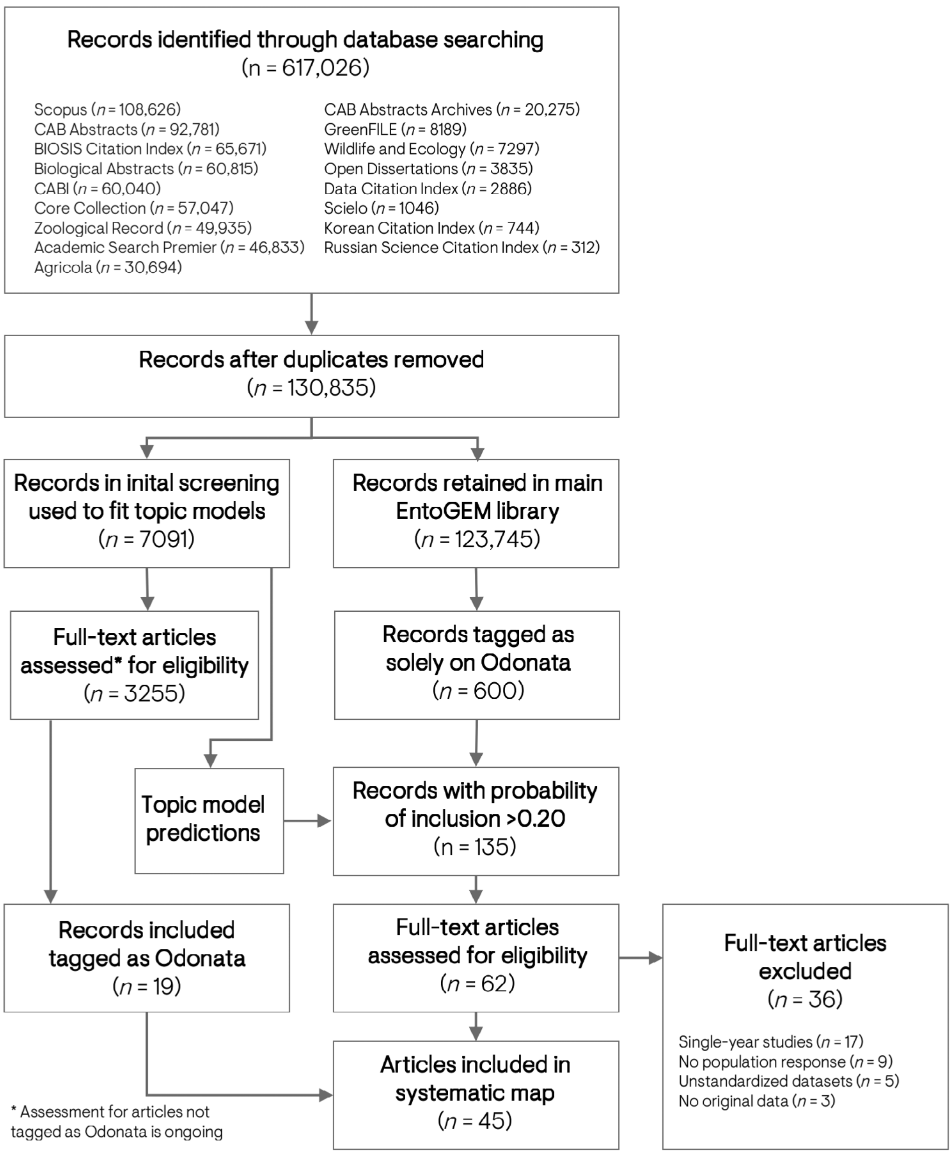

FIGURE 2 PRISMA flowchart indicating the flow of search results through the EntoGEM library search and assembly, data processing, and screening stages

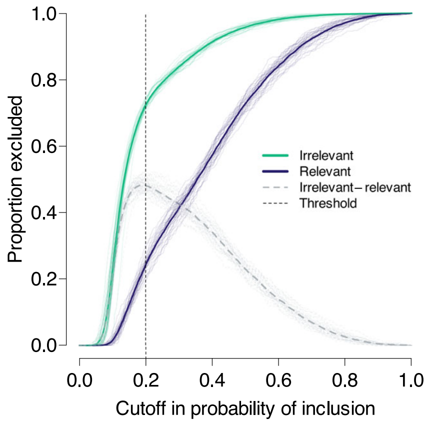

FIGURE 3 Topic model predictive performance at different thresholds for probability of inclusion. The green line indicates the proportion of irrelevant articles that would be properly excluded at that threshold (true negatives) and indigo indicates the proportion of relevant articles that would be incorrectly excluded (false negatives). Light-gray dashed lines indicate optimal probabilities, based on maximizing the rate of exclusion for true negatives and minimizing the rate of exclusion of true positives across the 20 model iterations. The dashed vertical line indicates the selected threshold of 0.20

inclusion decisions on more articles and predicted probabilities of inclusion shift over time as the models gain more information. This means that articles that were initially excluded by the models could become higher priorities for manual screening in future phases of the projects, including additional odonate articles.

3.2 | Odonata subproject: Taxonomic tagging, article prioritization, and screening

Within the set of 123,745 unscreened articles retained in the EntoGEM library (i.e., the EntoGEM library excluding articles already screened in the first phase of the project to create the topic models; Figure 2), 600 articles were automatically tagged as having Odonata as the only focal taxon. We predicted the probability of inclusion for each of these articles using the results of the latest available topic models, using a threshold of 0.20 for the predicted probability of inclusion, resulting in 135 articles that were manually screened in duplicate. Although the topic models only produced a modest reduction in manual screening hours for the relatively small Odonata subproject, a ca. 78% reduction in effort will have a substantial payoff for larger subprojects. After title and abstract screening, 62 articles were passed to full-text screening, of which 27 met all inclusion criteria (Figure 2) and were included in the systematic map database. Most articles excluded at the full-text screening step (Figure 2) were dropped because they were single-year studies (n = 17, 49% of the excluded group), lacked a population or biodiversity response (n = 9, 26%), did not include uniformly collected data or data from control plots (n = 5, 14%), or did not contain any original data (n = 3, 9%). Because the articles used in the first phase of the EntoGEM project to develop the topic models were not included in the automatic taxa tagging and had been previously screened, we added articles from this phase that were identified as Odonata at full-text screening to the systematic map database, resulting in a total of 45 studies (Table 1).

3.3 | Odonata subproject: Characteristics of included studies

Included studies on odonates were mostly conducted in Europe (n = 20, 44%), North America plus Hawaii (n = 11, 24%), and Asia (n = 8, 18%) with three studies conducted each in Latin America and Africa, and none from South America or Australasia (Figure 4a). Most studies included in the database took place over 2–4 years (n = 25, 55%), with the most frequent duration being 2 years (n = 14, 31%). Study lengths ranged up to 36 years (mean = 7.3) and 10 (22%) studies spanned >10 years (Figure 4b). Several time series contained gaps or were snapshot studies comparing two 1-year datasets separated by many years (n = 9, 21%), especially for time series >10 years (n = 5, 50%). Although we did not extract time series data from studies because, at this stage, EntoGEM is focused only on documenting potential data sources, we found that data were only fully available—either through public repositories or displayed in tables and figures—for a few studies (n = 8, 18%), with an equal number of studies containing partial data in tables and figures (n = 8, 18%). Most studies (n = 29, 64%) did not make time series data available or include a statement of data availability, although effect sizes may still be calculable from summary statistics.

Thirty-three (73%) studies included data only on odonates, and the remaining 12 studies also included data on communities of insects—these collectively represent 15 additional orders that were not detected by taxon tags based on abstracts alone. Diptera (n = 12), Coleoptera (n = 11), Trichoptera (n = 9), Ephemeroptera (n = 9), Hemiptera (n = 8), Plecoptera (n = 5), and Megaloptera (n = 5) were most commonly included; 1–2 studies also included data on Neuroptera, Lepidoptera, Hymenoptera, Thysanoptera, Orthoptera, Mantodea, Heteroptera, and Dermaptera. Not surprisingly, most studies took place in aquatic systems such as rivers, ponds, and lakes

TABLE 1 Characteristics of studies included in the first release of the odonate EntoGEM subproject

References	Study location	Habitat description	Sampling methods	Response type	First year	Last year	Max. time series (years)	Taxa reported
Anderson (2009)	Maldives	Urban	Visual survey	Abundance	2002	2007	6	Odonata
Baba et al. (2019)	Japan	Paddy fields	Visual survey	Abundance	2012	2013	2	Odonata
Baker (1986)	Canada: Ontario	Pond	Net sampling; microhabitat samples	Abundance	1983	1984	2	Odonata; Diptera
Ball (2014)	Oman	Wadi bed	Net sampling	Abundance	2012	2013	2	Odonata
Bam et al. (2018)	USA: Louisiana	Saltmarsh	Net sampling	Abundance	2013	2014	2	Odonata; Orthoptera; Thysanoptera; Coleoptera; Hymenoptera; Lepidoptera; Diptera;
Banks and Thompson (1987)	United Kingdom	Pond	Hand collecting	Abundance	1983	1984	2	Odonata
Bond et al. (2007)	Mexico: Chiapas	River	Net sampling	Abundance; diversity	2001	2002	2	Coleoptera; Diptera; Ephemeroptera; Hemiptera; Megaloptera; Odonata; Plecoptera; Trichoptera
Bried and Hinchliffe (2019)	Canada: Alberta	Wetland	Net sampling	Abundance	2011	2017	1	Odonata
Carbone et al. (1998)	Canada: Ontario	Lake	Structural trap	Abundance; occurrence	1987	1994	7	Megaloptera; Coleoptera; Hemiptera; Trichoptera; Odonata; Ephemeroptera; Plecoptera; Diptera
Crowley and Johnson (1982)	USA: Tennessee	Pond in a city	Net sampling	Abundance; biomass	1977	1979	3	Odonata
Córdoba-Aguilar and Rocha-Ortega (2019)	Mexico: Morelos	Riverbank	Visual survey	Abundance	2002	2016	1	Odonata
Danell and Sjoberg (1982)	Finland	Lake	Net sampling; emergence trap	Occurrence; abundance	1974	1979	6	Ephemeroptera; Odonata; Heteroptera; Hymenoptera; Coleoptera; Trichoptera; Diptera
Dolný et al. (2018)	Slovakia	Raised bog	Visual survey	Abundance; diversity	2001	2017	17	Odonata
Domeneghetti et al. (2015)	Italy	Ponds on an estate	Visual survey	Abundance	1997	2012	2	Odonata
Donath (2007)	Germany	Old coal mine site	Unknown	Occurrence	1976	2005	9	Odonata

(Continues)

TABLE 1 (Continued)

References	Study location	Habitat description	Sampling methods	Response type	First year	Last year	Max. time series (years)	Taxa reported
Dronen Jr (1978)	USA: New Mexico	Permanent ponds	Microhabitat samples	Abundance	1971	1973	3	Odonata
Englund (1999)	USA: Hawaii	River	Net sampling	Abundance	1992	1998	unknown	Odonata
Fincke (1999)	Panama	Neotropical forest	Visual survey	Occurrence	1992	1993	2	Diptera; Odonata; Hemiptera
Flenner and Sahlén (2008)	Sweden	Lake	Net sampling	Abundance	1996	2006	1	Odonata
Goffart (2010)	Belgium	Not reported	Visual survey	Occurrence	1989	2000	12	Odonata
Harabiš (2016)	Czechia	Pond and forest	Net sampling	Abundance	2014	2015	2	Odonata
Hickling et al. (2005)	United Kingdom	Not reported	Unknown	Geographic range	1960	1995	10	Odonata
Julka et al. (1999)	India: Himachal Pradesh	Stream	Flow intercept trap	Density; diversity	1989	1991	3	Ephemeroptera; Odonata; Plecoptera; Hemiptera; Megaloptera; Coleoptera; Trichoptera; Diptera
Kéry et al. (2010)	Switzerland	Not reported	Visual survey	Occurrence	1999	2000	2	Odonata
Le Rouzic et al. (2015)	Sweden	Ponds in an agricultural landscape	Hand collecting	Abundance	2000	2011	12	Odonata
Lowe et al. (2009)	United Kingdom	Pond in a park	Net sampling	Abundance	2005	2006	2	Odonata
Lubertazzi and Ginsberg (2010)	USA: Rhode Island	Wetland	Visual survey	Diversity	2004	2005	2	Odonata
Moore (1989)	USA: Colorado	Human-made pond	Visual survey	Abundance	1984	1987	4	Odonata
Munyuli et al. (2007)	Uganda	Tropical savannah and farm field	Visual survey; pitfall trap	Abundance; diversity	2002	2003	2	Diptera; Coleoptera; Hemiptera; Odonata; Neuroptera; Mantodea; Dermaptera
Nagel et al. (2010)	Canada: Ontario	Marsh	Emergence trap	Abundance	2002	2008	5	Odonata
Niba and Samways (2006)	South Africa	Wetland	Visual survey	Abundance; diversity	2000	2003	4	Odonata
Nurminen et al. (2018)	Finland	Aquatic system	Flow intercept trap	Biomass	2007	2012	6	Diptera; Coleoptera; Ephemeroptera; Megaloptera; Odonata; Trichoptera

TABLE 1 (Continued)

References	Study location	Habitat description	Sampling methods	Response type	First year	Last year	Max. time series (years)	Taxa reported
Perez-Bilbao et al. (2013)	Spain	Coastal lagoon	Net sampling	Diversity; abundance	2007	2008	2	Coleoptera; Hemiptera; Diptera; Odonata; Ephemeroptera; Trichoptera
Raebel et al. (2010)	United Kingdom	Farm ponds	Visual survey	Abundance	2006	2008	3	Odonata
Schneider et al. (2013)	Israel	River	Unknown	Occurrence	1986	2010	1	Odonata
Skevington and Carmichaeu (1997)	Canada: Ontario	Not reported	Hand collecting; flight intercept trap	Occurrence	1991	1996	5	Odonata
Staentzel et al. (2019)	France	River	Flow intercept trap	Diversity	2014	2017	4	Ephemeroptera; Plecoptera; Trichoptera; Coleoptera; Odonata; Diptera
Takahashi et al. (2010)	Japan	Pond	Visual survey	Abundance	2005	2009	5	Odonata
Termaat et al. (2010)	Netherlands	Not reported	Unknown	Occurrence	1980	2003	24	Odonata
Usio et al. (2017)	Japan	Farm ponds	Visual survey	Diversity	2006	2008	1	Odonata
Van Dijk et al. (2013)	Netherlands	Aquatic system	Microhabitat samples	Abundance	2004	2009	6	Coleoptera; Diptera; Ephemeroptera; Hemiptera; Odonata; Trichoptera; Lepidoptera; Neuroptera
Vick (1999)	Cameroon	Tropical montane streams	Flow intercept trap; emergence trap	Occurrence	1995	1998	Unknown	Odonata
Watanabe et al. (2008)	Japan	Artificial wetland	Visual survey	Abundance	2003	2006	4	Odonata
Wellenreuther et al. (2012)	Sweden; Finland	Not reported	Visual survey	Abundance	2007	2009	3	Odonata
Yamada et al. (2019)	Japan	Pond	Net sampling	Abundance	2014	2015	2	Odonata

Note: Metadata refer to sites where odonates were surveyed over multiple years, so may be a subset of the total data reported in an article. Maximum time series length refers to the longest continuous series of years in which data was collected with no annual gaps or missing data.

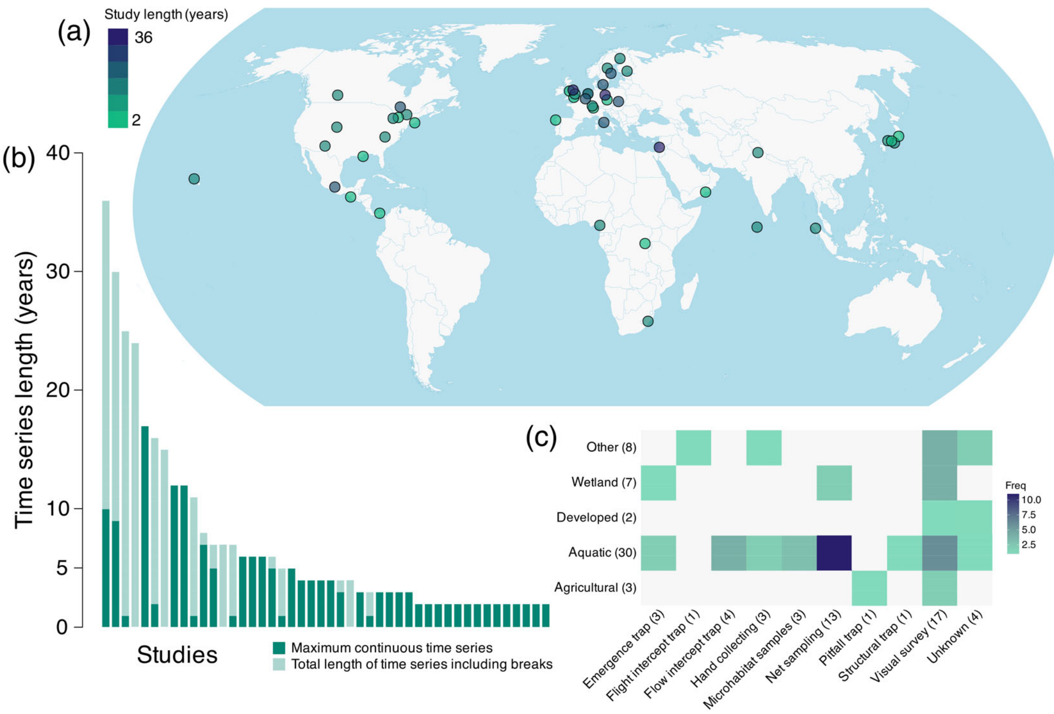

FIGURE 4 Characteristics of long-term Odonata population and diversity datasets. (a) Approximate study locations based on site information included in original papers, colored by total length of time series inclusive of gaps in sampling, where green denotes short studies and indigo denotes longer studies. (b) Distribution of study lengths; each bar represents a single study and the height of the bar indicates time series length inclusive of gaps (light green), and only for the maximum continuous time series length from each study (dark green). (c) Counts of studies by habitat type (y-axis) and type of insect sampling method used (x-axis); lack of studies is shown in light gray, with a color ramp to indicate an increasing number of studies where green is few studies and indigo is the most studies

($n = 26$, 58%) or wetland types ($n = 7$, 16%); five studies did not report this information, and other studies were described by the authors as taking place in urban, industrial, forested, and agricultural settings. Insects were mostly sampled using visual surveys ($n = 16$, 36%), net sampling ($n = 15$, 31%), and flow intercept traps ($n = 5$, 11%). Other collecting methods used by studies in the database include: hand collecting, microhabitat samples, emergence traps, structural traps, flight intercept traps, and pitfall traps (Figure 4c), not all of which targeted odonates because some studies sampled multiple taxa.

4 | DISCUSSION

Understanding insect population trends and their drivers is a key challenge in addressing biodiversity loss and prioritizing research and conservation actions. Because insects are ubiquitous in terrestrial and freshwater systems, highly diverse (Dirzo et al., 2014; Gaston & Fuller, 2007, 2008; Stork, 2018), represent core components of many trophic webs (Schoenly et al., 1991), and provide essential ecosystem services (Losey & Vaughan, 2006; Winfree et al., 2015), many researchers and collaborative groups are working to understand long-term trends and trajectories in insect abundance and diversity through new monitoring initiatives and standards (Montgomery et al., 2021). Given the urgent nature of the insect decline problem, though, we cannot wait decades for the results of new monitoring initiatives to identify taxa and regions with the greatest need for conservation action (Forister et al., 2019). We need to collate and harness existing, unexamined data to inform decisions regarding conservation actions, monitoring needs, and future research initiatives. Some recent attempts to synthesize literature on this topic have been criticized because of major shortcomings, in part due to the volume and widely scattered nature of demographic data for insects. The EntoGEM framework presented here addresses many of these challenges by searching the literature using a systematic, rigorous, and repeatable method and a community-driven approach to expand the collection of datasets that can be assessed to address insect population and diversity trends.

By searching broadly, the approach taken by EntoGEM addresses one of the biggest challenges in synthesizing evidence for insect population and biodiversity trends: that the literature is vast and scattered among different subfields with data collected and reported to meet different objectives. This problem is not unique to this topic; syntheses on broad topics often fail to be comprehensive or rely on (often biased) subsets of evidence due to time and resource constraints. When search strategies do not match the stated goals of a synthesis, conclusions can be biased and misleading. For example, in their review of insect trends, Sánchez-Bayo and Wyckhuys (2019) selected search terms that biased their results towards studies that found declines. The result was a distorted picture of insect population trends that garnered substantial criticism from the scientific community (Grames & Elphick, 2020; Komonen et al., 2019; Montgomery et al., 2020; Mupepele et al., 2019; Simmons et al., 2019; Thomas et al., 2019; Wagner, 2019). This example is a useful illustration of how search strategies will fail to capture relevant studies when not well designed to thoroughly explore the literature. Authors of primary research articles often do not consider the role their work might play in future syntheses (Hennessy et al., 2021), and as such may not describe their research using the keywords that synthesists and meta-analysts subsequently use to search the literature. To address this problem, we used a semi-automated approach that allowed us to expand our selection of search terms based on methods designed to identify missing synonyms in fields that lack standardized keywords (Grames, Stillman, et al., 2019), rather than simply relying on an initial preselected set of terms. Our approach has enabled us to identify many studies that have not been included in recent synthesis attempts. For example, we examined 53 commentaries, perspectives, and reviews published since 2017 that mention "insect decline" or similar terms, and none cited any of the 10 studies with more than 10 years of data identified by the odonate subproject. Although the larger EntoGEM project is just in its early stages, it has already identified more than 100 such studies with data spanning more than 10 years, suggesting potential for much larger gains as the project proceeds (Grames, Amano, et al., 2020).

Debate about what constitutes evidence for insect decline has been considerable in the scientific literature in recent years (Didham et al., 2020). Because insect population numbers are highly variable, with densities sometimes spanning orders of magnitude from one generation to the next, it is not surprising that we have much to learn about the estimation of trends over time. This is especially true because the literature on animal time series modeling has been dominated by work with vertebrates, where population fluctuations are less extreme and stochastic than for invertebrates. Discussion in particular revolves around how long time series need to be to detect trends (Cusser et al., 2021), how snapshot (or revisit sampling designs) should be analyzed to assess long-term change (Stuble et al., 2021), how many sampling sites are necessary, and which sampling methods yield the most reliable results (Montgomery et al., 2021; Prendergast & Hogendoorn, 2021). Other key issues include which taxa should be incorporated into aggregate indices, how to account for pests and invasive species (Desquilbet et al., 2021), and what variables are the best indicators of population trends (Hallmann et al., 2021).

Acknowledging a diversity of opinion, we designed the EntoGEM project to be flexible enough to accommodate the different definitions and criteria that researchers may use. For instance, rather than using an arbitrary threshold in the number of years of data a study must have, we opted to include all studies with data points in two or more years (at least 13 months apart). First, two data points are the minimum to estimate change, and any other cutoff would be arbitrary. Second, evidence for decline (or lack thereof) can be inferred from a few time series with many data points across decades/generations, or from many time series with a few data points (Gerrodette, 1987; Vellend et al., 2017), and lowering the threshold for inclusion may broaden the sample sufficiently to compensate. Third, many datasets tracking insect population and biodiversity trends make comparisons to historical datasets; to gauge whether these snapshot studies represent true changes in diversity, it is necessary to have a benchmark of between-year variability for comparisons of any 2 years of data. Similarly, we did not restrict the insect taxa studied, sampling methods used, or other aspects of study design, instead tagging this information as metadata in the database. Sampling effort metadata are not included in the EntoGEM database due to the highly varied nature in which primary study authors report this information; however, we emphasize that these metadata are critical to extract when using studies from the database for meta-analyses. We thus leave it up to researchers using the EntoGEM database to make their own decisions about what types of studies to include and welcome methodological comparisons using different subsets of the database to evaluate how decisions made during the synthesis process affect conclusions.

To make the articles identified by the EntoGEM project widely accessible, we developed an interactive, web-based platform (https://entogem.shinyapps.io/living-map/) where users can interrogate the database. The platform was designed for three primary functions: (1) visualizing what types of datasets exist, (2) identifying knowledge clusters and gaps, and (3) providing access to the EntoGEM database. On the platform, users can interactively produce graphics showing where studies have been conducted, time series length and total study duration, which taxa have been studied, sampling methods used, habitat types, and so on. We anticipate that the ability to search and visualize the database in this way will become increasingly useful as the number and diversity of studies continues to grow, as it will become an essential tool for identifying clusters of similar studies. These clusters can also be visualized on the platform with heatmaps, helping point towards specific topics for which there exists sufficient data with potential for more quantitative synthesis (e.g., meta-analysis). Conversely, research gaps can be identified in the same way and may become research priorities. The platform also lets users download the bibliographic data for studies matching their selected criteria to facilitate future work. The EntoGEM: Odonata subproject is completed for now, however, many other projects are ongoing and regular updates will be made as topic model predictions are updated and more articles are screened. Users should remain alert to biases in the developing EntoGEM database, such as taxonomic biases depending on which subprojects have been completed, geographic biases based on which languages have been searched, and the bias towards single-taxon over community studies in the initial subprojects due to limitations of automatic taxa tagging and lack of standardized reporting of focal taxa in article titles, abstracts, and keywords. To facilitate reproducibility, we will archive stable versions of the database periodically in permanent, publicly accessible archives and referenced with a DOI.

It is estimated that up to one-third of articles in conservation biology are published in languages other than English (Amano et al., 2016) and that ignoring this literature could bias understanding (Amano et al., 2021; Konno et al., 2020). Systematically excluding studies by searching only in English can change the conclusions of syntheses and bias results towards developed regions, especially North America and Europe, that do not represent global trends. Of particular importance to global insect population and diversity trends would be the omission of many studies from the tropics where most insect diversity is located (Stork, 2018; García Robledo et al., 2020). In the first phase of the EntoGEM project, databases were searched only in English, which may explain why we found no data on odonates from South America and very little from Central America. Expansion of EntoGEM to incorporate the results of searches in other languages would remove a key limitation of the current version of the database, and is a major goal for future work. Adding searches in Spanish and Portuguese would help to identify studies in Latin America, and adding other languages may improve representation for Africa and Asia. The nuances of ecological terms make selecting search terms (Grames, Stillman, et al., 2019) across languages challenging, however, because direct translations are often not possible. It is thus critical for searches to be developed by researchers who are academically fluent in each language to generate appropriate search strategies (Chu et al., 2012). For the full EntoGEM project, we aim to conduct searches in additional languages by partnering with researchers who speak those languages and thereby also build a more inclusive community of researchers working on the project (Grames, Montgomery, et al., 2019).

The EntoGEM project is still in its infancy. Over the coming months and years, we will be compiling recovered studies documenting long-term insect population and biodiversity trends to facilitate future syntheses and comparisons across taxa. Our goal is for the EntoGEM database to be a central clearinghouse for everyone working to understand insect population and diversity trends. Researchers will be able to access and contribute to the database, use it as a resource when selecting studies for synthesis projects, find potential collaborations with groups working on similar questions, and identify gaps in knowledge to prioritize future studies. As the project continues to develop, the diversity of datasets indexed in the database will grow. Ultimately, our goal is not just to identify evidence, but to help researchers coordinate across projects to conduct rigorous analyses to understand insect population and biodiversity trends, in turn informing identification of priorities for conservation action across the globe.

Insect abundance and diversity is not the only topic with a vast and scattered literature for which there is heated debate about what constitutes evidence. The framework that we outline here can be applied to a multitude of questions on broad topics within conservation, as well as in areas such as public health, social justice, and other fields coping with abundant and scattered evidence on large and nuanced topics. EntoGEM's community-driven approach to synthesis reduces the burden of effort by sharing workload and resources across groups and reducing bias by considering varied perspectives when making project decisions. All project materials are open, transparent, and publicly accessible to facilitate broad community interaction. We encourage researchers working on similarly broad topics to adopt and adapt the community-driven approach and automated methods we have developed to make the EntoGEM project feasible. Using these methods, it is possible to conduct unbiased syntheses on broad topics while facing time and resource constraints, estimate how much evidence is missed by conventional syntheses, and work towards a more open and collaborative approach to research synthesis.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

AUTHOR CONTRIBUTIONS

All authors in this publication made substantial contributions to developing the ideas, designing the methods, collecting the data, and editing the manuscript. *Conceived the idea and designed the methods*: Eliza M. Grames, Graham A. Montgomery, Lynn V. Dicks, Tanner A. Matson, Shinichi Nakagawa, Morgan W. Tingley, David L. Wagner, Thomas E. White, Paul Woodcock, Chris S. Elphick, Douglas H. Boyes, Nigel G. Taylor. *Collected essential data*: Kit S. Prendergast, Douglas H. Boyes, Nigel G. Taylor. *Wrote the manuscript, created figures, and lead the analysis*: Eliza M. Grames. *Lead interpretation of the data*: Eliza M. Grames, MLF, David L. Wagner, Chris S. Elphick. *Reviewed and edited the manuscript*: Eliza M. Grames, Graham A. Montgomery, Lynn V. Dicks, Matthew L. Forister, Tanner A. Matson, Shinichi Nakagawa, Kit S. Prendergast, Nigel G. Taylor, Morgan W. Tingley, David L. Wagner, Thomas E. White, Paul Woodcock, Chris S. Elphick.

DATA AVAILABILITY STATEMENT

Code to reproduce the topic models, metadata extracted for articles included at full text, and code to reclassify metadata post hoc are archived (Grames, 2022: https://doi.org/10.5281/zenodo.6382704).

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