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Assessing the state-of-knowledge of bees and their pollination services in Colombia

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Abstract. Understanding the state of knowledge of pollinators and their interactions with plants is critical for planning and developing effective conservation strategies. Despite the many challenges in studying bee diversity and pollination services in Colombia, this contribution represents a preliminary effort to quantitatively assess existing information gaps. This is particularly important in regions of high biodiversity that have historically been understudied and are now facing significant environmental pressures from human activities. Based on a review of the literature, we present the first quantitative assessment of bee biodiversity, bee-plant interactions, and pollination services in Colombia. We analyzed 88 publications and extracted data across the following categories: i) bee diversity, ii) bee-plant interactions, and iii) assessment of pollination services. For each bee and plant species documented, we recorded taxonomic and geographic information, resulting in a total of 8,099 records. Most records report information on bee diversity (58%), followed by bee-plant interactions (29%), and assessments of pollination services (13%). Most records correspond to corbiculate bees (Apidae) from modified ecosystems in the Andean region, particularly at lower elevations. Studies evaluating pollination services are limited and tend to rely on qualitative methods. The implications of these results, taxonomically and geographically skewed towards common taxa and Colombia's most populated areas, are discussed in the context of ongoing efforts to conserve pollinator populations in the country.

INTRODUCTION

The interactions between plants and bees are critical for the functioning of ecosystems due to the key role bees play in plant reproduction. Long evolutionary processes have shaped the close ecological associations between floral rewards and bees, as these insects exclusively use pollen and nectar to feed their brood (Waser & Ollerton, 2006). Complex networks of mutualistic interactions underlie these relationships

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and influence the diversification, maintenance, and ecological functionality of plant and pollinator lineages (Thompson, 2006; Ollerton *et al*., 2011). Furthermore, these mutualistic interactions provide ecosystem services through crop production, which is worth over $200 billion annually worldwide (Gallai *et al*., 2009). Pollination services benefit human societies by contributing to food security, improving the livelihoods of rural communities, and supporting biological diversity in agricultural and natural ecosystems (Kremen *et al*., 2007; Lautenbach *et al*., 2012).

Recently, populations of both wild and managed bee species have declined due to agricultural intensification, deforestation, invasive species (including plants, pathogens, and other bees), pollution, and the excessive use of pesticides (Potts *et al*., 2010; Goulson *et al*., 2015). These environmental stressors have driven shifts in pollinator dynamics, foraging behavior, body size, and generation time (Aizen & Feinsinger, 2003; Bhattacharya *et al*., 2003; Bartomeus *et al*., 2013), resulting in changes to the diversity, intensity, and efficiency of pollination interactions. Although the ecological consequences of these changes have yet to be demonstrated, the impact on the pollination interactions may have adverse, cascading effects on biodiversity at multiple spatial and temporal scales (Biesmeijer *et al*., 2006; Burkle *et al*., 2013). Therefore, understanding the link between bee diversity and ecological processes is essential for conserving their ecological services.

Bees comprise over 20,000 species across 350 genera and are distributed in all continents except Antarctica (Michener, 2007). In the Neotropical region, bees represent half of the pollinating insects, exhibiting high degrees of ecological specialization (Roubik, 1995). Although about 5,000 species have been described from the Neotropical region, this number likely underestimates the true diversity of the region (Roubik, 2001; Gonzalez & Engel, 2004; Moure *et al*., 2007; Freitas *et al*., 2009). There is still little information about bee population dynamics in the Neotropics, their interactions with plants, and whether they are experiencing population declines (Giannini *et al*., 2012).

The tropical Andes, a region spanning Bolivia, Colombia, Ecuador, Peru, and Venezuela, is of unparalleled diversity, as it comprises the highest and most diverse fauna and flora in the world (Allen & Gillooly, 2006; Bovarnick *et al*., 2010). Among these countries, Colombia is the second megadiverse country globally, comprising approximately 10% of the world's biodiversity in an area that is less than 1% of the Earth's landmass. This remarkable biodiversity is due to Colombia's five biogeographical regions (Amazon, Andean, Caribbean, Orinoquía, and Pacific), each characterized by a unique set of climatic and ecological conditions. High ecosystem diversity at the regional level contrasts with the lack of biological inventories in those areas, revealing a tremendous underestimation in current biodiversity accounts (Rangel, 2012). Knowledge gaps in pollination involve the distribution and abundance of pollinators, the associations with plant species, and the estimation of pollination outcomes (Ballantyne *et al*., 2015; IPBES, 2016).

Five of the seven bee families recognized worldwide are presently known in Colombia: Andrenidae, Halictidae, Colletidae, Megachilidae, and Apidae. More than 600 species in about 100 genera are known in the country (Nates-Parra & Gonzalez, 2000; Smith-Pardo, 2003; Smith-Pardo & Ruiz, 2008; Ascher & Pickering, 2016). Despite having preliminary checklists (Nates-Parra & Gonzalez, 2000; Gonzalez & Engel, 2004; Gonzalez *et al*., 2012), Colombia's bee fauna is still in the early stages of exploration. There is also limited information on ecological interactions and pollination services, which prevents the development of viable and effective management strategies for their conservation.

In this study, we aim to quantitatively assess the state of knowledge of bee diversity and their pollination services in Colombia. We reviewed public information and analyzed scientific literature spanning 41 years (1976–2017), focusing on records of bee diversity, bee-plant interactions, and the assessment of pollination services.

Taking a temporal, geographical, and ecosystem-based approach, we identify and discuss knowledge gaps that may help guide current conservation efforts and policy decisions in the country. The methodological framework we employed may also help conduct similar studies in understudied regions of the world where undocumented bees are likely declining.

MATERIAL AND METHODS

Bibliometric analysis

We conducted a literature search for projects that were both local and international in scope. We searched the database catalog of the Library Alfonso Barrero Cabal, S.J., through Pontificia Universidad Javeriana, and also accessed the libraries of Luis Ángel Arango, Biblioteca Nacional de Colombia, Biblioteca Pública Piloto de Medellín, Politécnico Grancolombiano, Pontificia Universidad Javeriana - Cali, Universidad Central, Universidad de Antioquia, Universidad de Bogotá Jorge Tadeo Lozano, Universidad de la Sabana, Universidad de los Andes, Universidad de Manizales, Universidad del Rosario, Universidad del Valle, Universidad El Bosque, Universidad Nacional de Bogotá, Universidad Pontificia Bolivariana, Universidad Santo Tomás, Universidad Tecnológica de Pereira, as well as international databases and search engines such as Academic Search Complete (EbscoHost), Agriculture Journals (ProQuest), AGRIS, Biology Journals (ProQuest), Latindex, ScienceDirect (Elsevier), Science Journals (ProQuest), Scopus, SpringerLink, Redalyc, Google Scholar and Zoological records.

We performed searches in Spanish and English in the Topic field with the words 'Colombia' and 'biodiversity', along with the following Keywords: "bees, biology, crops, crop pollination, ecology, ecosystem services, flora, and pollination". The 'Topic' field retrieves results from the title, abstract, author's keywords, and a set of common words obtained from the references cited in each consulted study. We also included our own published (85% of total records) and unpublished data (15% of total records).

We reviewed the literature over a 41-year period, from 1976 to 2017, corresponding to the earliest identified publications through the time of this study. All search results were saved as text files and compiled in a structured database. For each entry, we recorded the title, publication year, authors, and publication type (scientific papers, books, conference summary, or Undergraduate, Master, or Phd theses). Each publication was categorized into one of three main groups based on the type of information it provided: bee diversity, bee-plant interactions, and assessment of pollination services. Publications related to bee taxonomy were classified under 'bee diversity', while those discussing bee-plant interactions were categorized under 'bee-plant interactions'. Publications focusing on the pollination of crops or plant species of commercial significance were categorized under 'assessment of pollination services'. For the latter two categories, we recorded the specific bee and plant species involved, along with relevant assessments. For each bee species and plant interaction mentioned in a publication, we recorded the names of both the bee species and plants, in addition to the geographical information. We followed the higher-level classifications of bees by Michener (2007). For higher-level classification of plants, we followed the guidelines established by Haston *et al*. (2009) and Chase *et al*. (2016).

We followed Arbeláez-Cortés (2013) to assess the error of omission in our data. This process involved conducting an additional search in the Web of Science for studies published from 1976 to 2017 that included 'Colombia' as a central topic. We refined our search by focusing on the categories 'bee diversity', 'bee-plant interactions', 'ecological interactions', and 'assessment of pollination services', analyzing the keywords independently and in combination. To ensure the precision of our research, we select only the most relevant results regarding Colombia.

Data analysis

We analyzed each information category from temporal, geographic, and ecological perspectives. For the temporal analysis, we focused on the year of publication to trace the changes in information patterns. Our geographic analysis categorized each publication by location, documenting the department (*i.e.*, the first administrative level in the Colombian political division) available for most publications. With this information, we evaluated the knowledge across natural regions. Unfortunately, we were unable to use geographic coordinates, as only 14% of the publications included this information. From an ecological perspective, we analyzed the relationships between bees and plants, focusing on their interactions and associations with cultivated plants. We aimed to highlight these interactions by visualizing bee diversity alongside the plants documented. In this process, we considered the number of bees, the number of plants involved in interaction reports, and the number of publications that assess pollination services, thereby illustrating the distribution of this information.

To analyze the ecological interactions between bees and plants, we evaluated bipartite networks to characterize the specialization outlined in the section Assessing the state-of-knowledge (see below). For the evaluation of pollination services, we categorized the methodologies of each publication according to the types of assessments reported: Type I involved data collection of flower visitors, followed by cleaning and counting all the pollen grains (Ashman & Stanton, 1991); Type II consisted of the direct observation of visitor activity on the flower, resulting in a record of pollinated stigmas, as well as fruit and seed production (Dafni *et al*., 1987); and, Type III calculated the number of fruits divided by the number of pollinated flowers, multiplied by 100 (Dafni *et al*., 2005). We analyzed bee-plant interactions in crops, considering the genera of crops reported worldwide and the relationship of bee species associated with these reports. The names of bee species and plants were verified using the following platforms: Bold Systems (http://v3.boldsystems.org), Encyclopedia of Life (https://eol.org/), GBIF - Global Biodiversity Information Facility (https://www.gbif.org), Tropicos (https://www.tropicos.org), The Plant List (http://www.theplantlist.org), and Catálogo de plantas de Colombia (Bernal *et al*., 2016).

ASSESSING THE STATE-OF-KNOWLEDGE. We analyzed each category of analysis (diversity, bee-plant interactions, assessment of pollination services) and assigned them to Colombia's natural regions, which are classified based on topography, climate, and soil type. These regions are the Caribbean (Atlantic), Pacific, Orinoquia, Amazonia, Andean, and Insular regions (IDEAM *et al*., 2007; IGAC, 2017). Within each natural region, we considered the departmental administrative divisions (IGAC, 2017) to illustrate the geographic distribution of records for each category.

We conducted a comparative analysis of bee diversity across each natural region using asymptotic diversity estimates based on Hill numbers: species richness ($q = 0$), Shannon diversity ($q = 1$), and Simpson diversity ($q = 2$) (Chao *et al*., 2014; Hsieh *et al*., 2016). Our approach involved extrapolation and rarefaction procedures based on the available records (Chao & Jost, 2012). Additionally, we employed visual methods that focused on the overlap of 95% confidence intervals, using 500 bootstrap replicates (Hsieh *et al*., 2016). The analysis used the R package iNext R (Hsieh *et al*., 2016).

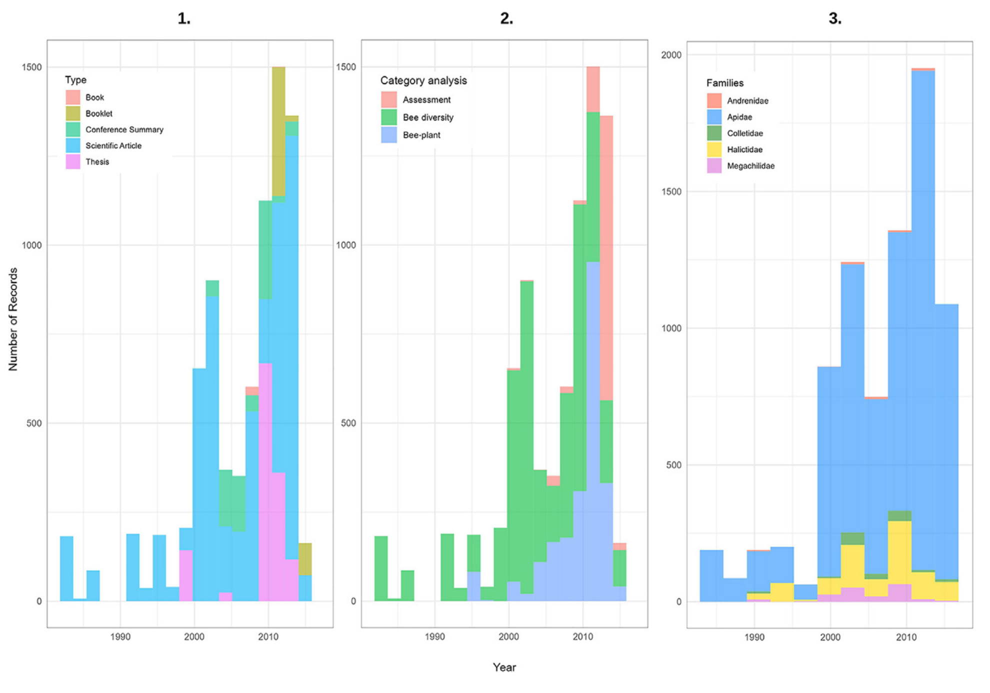
We examined bee-plant interaction networks to characterize the specialization through a bipartite network (Bascompte & Jordano, 2007). Due to the large size of our data, we included all records that focused on bee genera and plant families. The interactions were analyzed using the connectance metric, which is defined as the ratio of observed interactions to the total number of possible interactions. Additionally, we utilized the H2′ metric to assess the specialization of network interactions (Blüthgen *et al*., 2006; Dormann *et al*., 2008; Jordano *et al*., 2009).

Data retrieval, management, and analysis were performed using R version 3.1.3 (R Core Team, 2014), employing packages: *circlize* (Gu *et al*., 2014), *vegan* (Oksanen *et al*., 2014) *bipartite* and *ggplot2* (Wickham, 2016). Mapping activities were conducted using ArcMap v10.5 (ESRI, 2011).

RESULTS

Our database encompasses 8,099 records drawn from 269 publications from 1976 to 2017. Of these, 6,171 records (76%) provided species names sourced from 63 publications. The types of records include scientific articles (5,544), books (25), conference summaries (741, unpublished data), and undergraduate or Master theses (1,319) (Fig. 1, Table S1). A substantial 59% of these records were related to bee diversity. In contrast, 26% focus on bee-plant interactions, while 15% involve studies assessing bee-plant interactions (Fig. 2).

From a temporal perspective, individual data points from publications (hereafter referred to as records) for the analysis categories were scarce (approximately 1 to 2 per year) in the 1980s, with a focus on bee diversity, resulting in a total of 182 records. In the mid-1990s, the emphasis on diversity continued, expanding to include studies on bee-plant interactions. This shift resulted in approximately 1 to 6 publications annually, documenting 347 records in the bee diversity category and 85 records in the bee-plant interaction category. Between 2000 and 2017, a notable upward trend in publications related to diversity (3,873 records), interactions (2,270 records), and assessment (1,022 records) rose from 1 to 18 (Fig. 2). This increase in research output and documentation across the three domains paralleled a growth in the number of researchers and collaborative networks aimed at enhancing the understanding of bees in Colombia (Table S1).



Figures 1–3. Annual records detailing the state of knowledge about bees in Colombia from 1976 to 2017. **1.** Records arranged by types of publications. **2.** Records by each category of analysis: diversity, bee-plant interactions, and assessment of pollination services. **3.** Records by bee family (See text for further explanation).

Bee diversity

Our analysis includes a total of 8,099 records from five families (Andrenidae, Apidae, Colletidae, Halictidae, and Megachilidae), 13 subfamilies, 34 tribes, 126 genera, and 640 species with binomial descriptions and 114 morphospecies documented as "sp" (754 species in total). Most of these records involve corbiculate bees, including the tribes Apini (honey bees), Bombini (bumble bees), Euglossini (orchid bees), and Meliponini (stingless bees), which were consistently studied over the 41-year analysis period. During the 1980s and onwards, the species reported in the literature were limited to the family Apidae. By the 1990s, the five families were recorded in varying proportions (Fig. 3), with Apidae receiving the most attention, followed by Halictidae. Conversely, Megachilidae, Colletidae, and Andrenidae had the fewest records with 184, 137, and 40, respectively. The majority of species were predominantly obtained from the Andean region, specifically from Antioquia (18%), Cundinamarca (15%), and Boyacá (10%). In contrast, the departments of Arauca in the Orinoquia region and Cordoba and La Guajira in the Caribbean region demonstrated a significantly lower number of bees, with only 4, 9, and 5 records, respectively (Fig. 4).

From a geographical perspective, our analysis revealed that only 14% of the assessed publications included geographic coordinates. This category of studies included all-natural regions of the country, with significant variation among them. The Andean region displayed the highest proportion of bee diversity (5,105 records), primarily concentrated in the departments of Antioquia (1,436), Cundinamarca (1,185), and Boyacá (824). The Amazon region had 893 records, mainly in the departments of Amazonas (368) and Caquetá (144). The Orinoquia region accounted for 791 records, predominantly from the department of Meta (417). In contrast, the Caribbean, Pacific, and Insular regions contributed significantly fewer records, with 593, 325, and 2, respectively (Fig. 4). It is noteworthy that Boyacá, Cundinamarca, and Antioquia are the most studied departments, each with over 900 records, while Arauca, La Guajira, Córdoba, Guainía, and Guaviare are the least studied, with fewer than 20 records each. Most of these records were from elevations ranging from 160 m.a.s.l. to 2,759 m.a.s.l.

Significant differences were observed among the various natural regions based on Hill numbers (Fig. 5). The rarefaction and extrapolation curves, derived from species records identified in the bibliometric analysis, indicated that the Andean region exhibited the highest levels of species richness and diversity, significantly exceeding the values found in other regions. The Amazon and Orinoquia regions demonstrated similar patterns of richness and diversity, as did the Caribbean and Pacific regions. In contrast, the Insular region did not yield significant findings. Unlike species richness, the Shannon and Simpson diversity estimates derived from the extrapolation and rarefaction curves were statistically lower in regions outside the Andean region. Furthermore, the rarefaction and extrapolation curves suggested that the completeness of the evaluated records was consistent across all metrics, with coverage values remaining within the 95% confidence interval without any overlap. Most extrapolation and rarefaction curves relied on records indicating that richness and diversity indices stabilized at approximately 500 samples, except in the Andean region, which had many records. Although the curves did not stabilize for this region, it can be inferred that more comprehensive records of diversity and abundance are needed to enable a more thorough evaluation.

Bee-plant interactions

We documented 2,355 records of at least one mutualistic interaction between bees and plants. Most records on these interactions are from the Andean region (Antioquia, Boyacá, and Cundinamarca) (Fig. 4) and were published between 2000 and 2017. In total, we documented 162 bee species, including 116 with binomial descriptions and 46

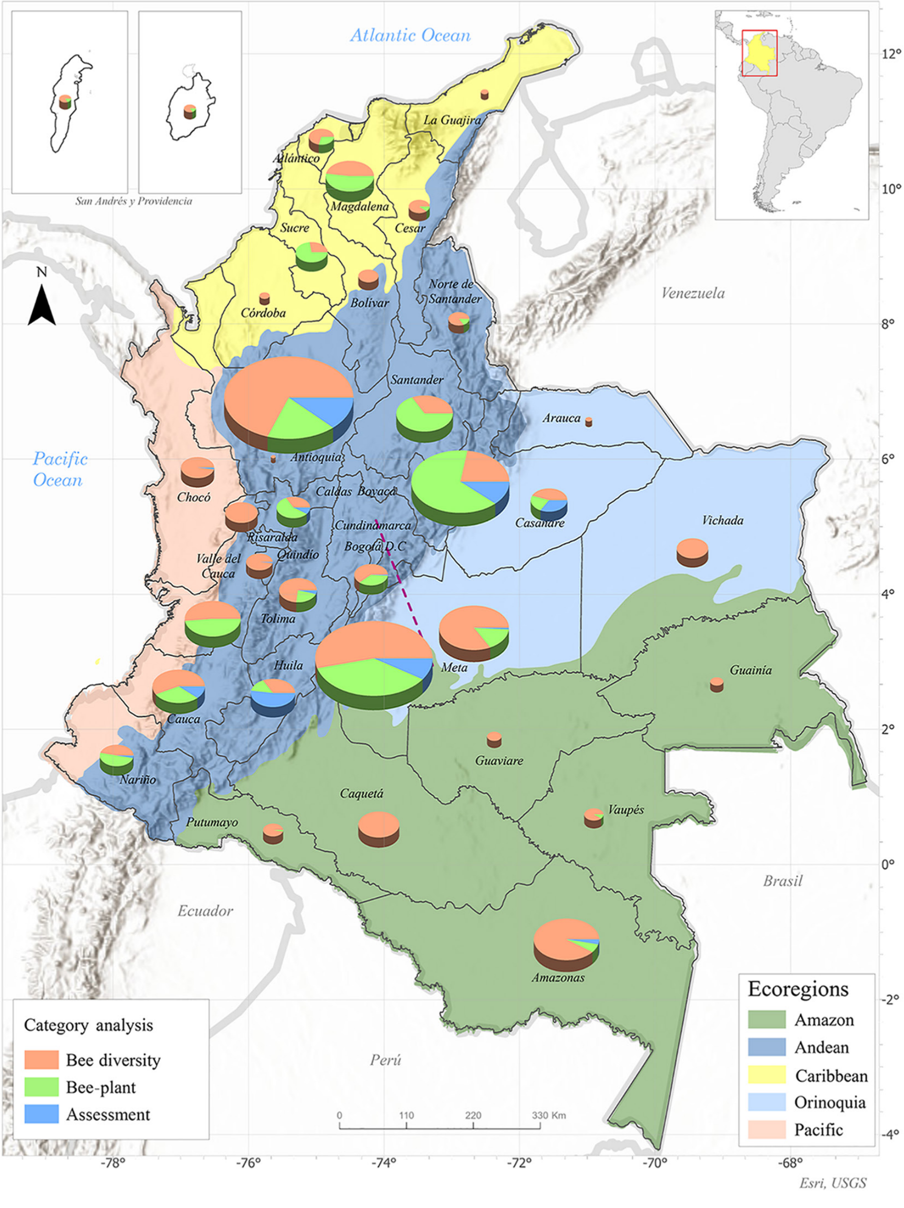


Figure 4. Map of Colombia depicting its ecoregions with insert indicating geographical location in South America. Black lines indicate the boundaries of departmental administrative divisions. Within each department, the distribution of recorded data is represented as proportions for the three analysis categories.

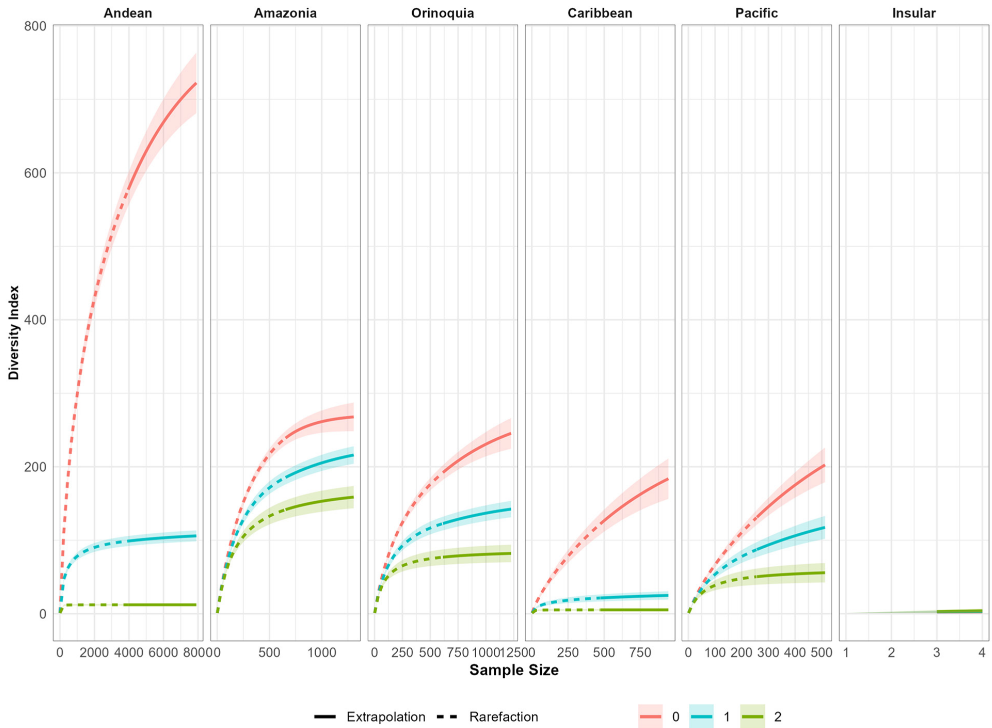


Figure 5. Comparative analysis of bee diversity indices across Colombia's natural regions based on the rarefaction and extrapolation of Hill numbers. Each natural region is presented individually, showcasing the indices as follows: species richness (q = 0) is represented in red, Shannon diversity (q = 1) in blue, and Simpson diversity (q = 2) in green. The 95% confidence intervals are depicted with shading along each line.

classified simply as "sp", spanning across 50 genera and representing all five families. Among these, the following five genera from Apidae had the highest numbers of documented plant interaction records: *Apis* Linnaeus (1,337 records), *Trigona* Jurine (891 records), *Euglossa* Latreille (511 records), *Melipona* Illiger (487 records), *Centris* Fabricius (370 records), *Xylocopa* Latreille (213 records), and *Bombus* Latreille (183 records).

A total of 476 plant species of 297 genera and 107 families have been documented in both natural and experimental conditions. Among these, 132 taxa from 54 genera across 26 families are of agricultural significance. This notable group includes widely recognized crops such as coffee, tomatoes, bell peppers, oranges, squash, and palms. The plant genera with the most bee interactions were *Attalea* Kunth, *Bactris* Jacq. ex Scop. and *Geonoma* Willd, collectively accounting for 585 records within the Arecaceae. Next, we found the most information for *Passiflora* L. with 221 records (Passifloraceae), *Solanum* L. with 170 records (Solanaceae), *Coffea* L. with 113 records (Rubiaceae), *Mimosa* L. with 110 records (Fabaceae), *Miconia* Ruiz & Pavón with 107 records (Melastomataceae), and *Piper* L. with 80 records (Piperaceae).

Analyzing bee-plant interaction networks through a bipartite framework revealed distinct relationships among 129 bee genera and 109 plant families. The highest specificity in these interactions corresponds to the most significant nodes, represented in the graphs as the thickest areas, which underscores their critical role in pollination services for specific floral resources. An assessment using the H2′ metric indicated a

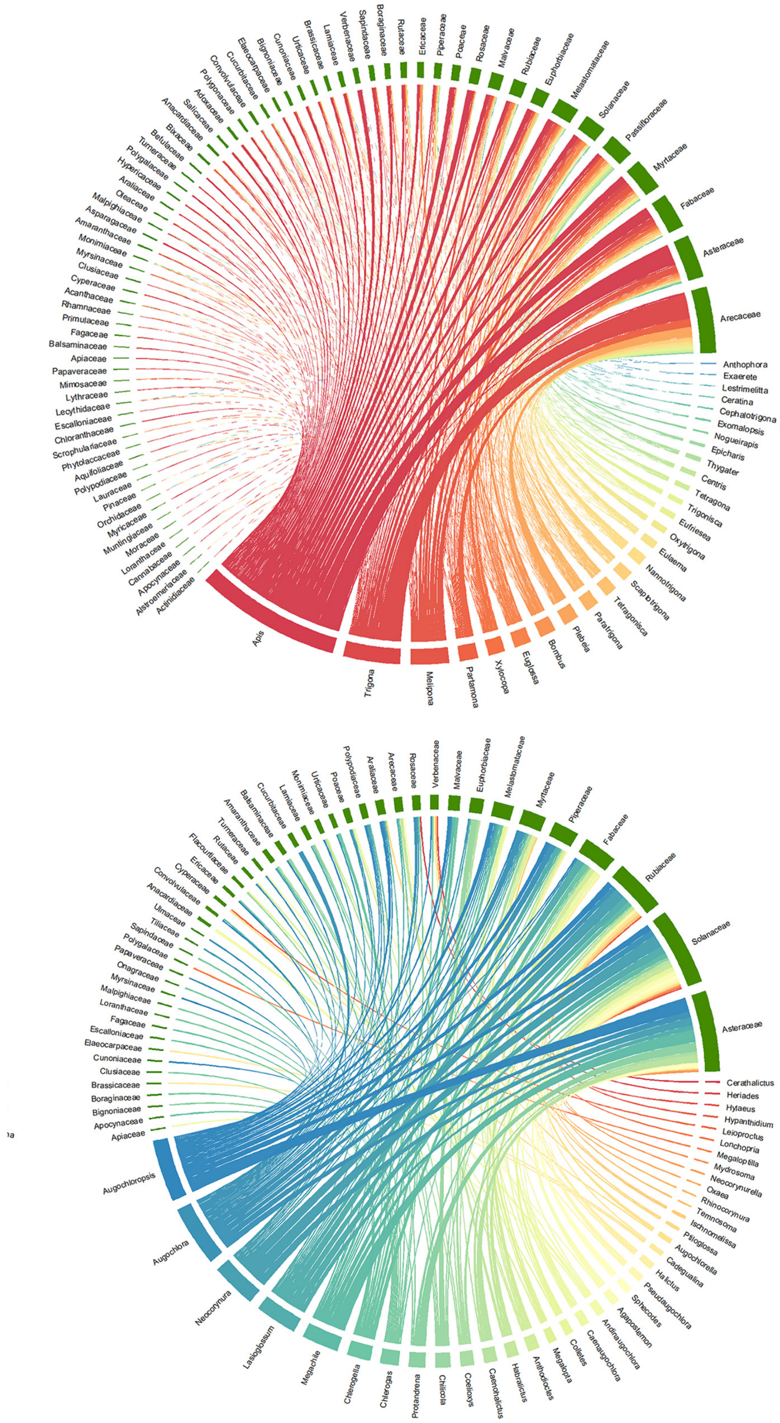


Figure 6. Bipartite networks illustrating ecological relationships between bee genera and plant families. The thickness of nodes and links are proportional to the number of records of ecological relationships. The top figure shows the interaction strengths among genera within the bee family Apidae, with a gradient from red to green, where green represents plants. The bottom figure shows the interaction strengths of genera from the bee families Andrenidae, Colletidae, Halictidae, and Megachilidae, with a gradient ranging from blue to green, where green represents the interaction with plants. Colors were sourced from the RColorBrewer package, employing the Spectral color palette.

generalist pattern in bee-plant interactions, with Apidae showing an H2′ value of 0.2. Apidae accounted for the most significant number of bee-plant interactions, totaling 6,969 records, primarily involving generalist genera such as *Apis* (1,341 records), *Trigona* (1,039 records), and *Melipona* (547 records). These interactions were mainly with the plant families Arecaceae, Asteraceae, and Fabaceae (Fig. 6, Table S2). In contrast, Andrenidae, Colletidae, Halictidae, and Megachilidae, with a combined total of 1,130 records, exhibited fewer interactions, primarily focused on the interactions between *Augochlora* (129 records), *Neocorynura* (80 records), and *Augochloropsis* (72 records) with plants in the families Asteraceae, Solanaceae, and Rubiaceae (Fig. 6, Table S2).

Assessment of pollination services

Regarding the pollination service assessments, we identified 1,022 records in publications that document 115 bee species from 50 genera, belonging to five families. The first studies on pollination assessment appeared in 2000, with a notable increase in publications between 2012 and 2015 (Fig. 2). A significant proportion of the records were reported in the Andean region, specifically from the departments of Antioquia and Cundinamarca, which represent 155 (11% of all records) and 89 (8% of all records), respectively.

All three types of pollination service assessments were represented in these records, with Type II having the highest number of records at 978, followed by Type III at 383 and Type I at 213. Upon evaluating each reported assessment type, we found no significant differences in the geographic distribution of records (Type I, $p = 0.295$; Type II, $p = 0.536$; Type III, $p = 0.141$). These results indicate a comparable range of ecological interaction studies among the families and regions of Colombia.

Most records belong to the introduced honey bee, *Apis mellifera* L., and the native bees *Bombus pauloensis* (Franklin), *Nannotrigona melanocera* (Schwarz), *Trigona amalthea* (Olivier), and *Trigona fulviventris* (Guérin-Menéville). The plant families Arecaceae, Fabaceae, Malvaceae, Myrtaceae, Passifloraceae, Rubiaceae, and Solanaceae were commonly recorded in our dataset (Tables S3 and S4).

Pollination services to plants of commercial interest included records from studies in: *Euterpe precatoria* Mart. (palmito) (5%), *Phytelephas macrocarpa* Ruiz & Pav. (tagua) (5.5%), *Cucurbita moschata* Duchesne (squash) (5%), *Psidium guajava* L. (guava) (13.26%), *Passiflora edulis* Sims (passion fruit) (8%), *Passiflora ligularis* Juss. (granadilla) (5%), Coffea arabica L. (coffee) (16%), *Citrus sinensis* (L.) Osbeck (orange) (4%), and *Solanum tuberosum* L. (potato) (13%) (Table S3).

The number of plant genera with agricultural interest reveals that among the 55 genera records and 234 genera of non-agricultural interest, the information concerning bee-plant interactions was primarily found within a narrow range of publications (≈ 1 to 50) (Fig. 2). There are few records of these interactions, likely because research has predominantly focused on the same species of plants and bees. The least documented genera of bees (from 0 to 10 records) out of the 541 publications are primarily those not of agricultural interest. In contrast, the genus *Solanum* stands out with the highest number of associated bee species, with 499, followed by *Attalea*, which has 489 reported interactions.

DISCUSSION

This study represents an initial effort to quantitatively assess the state of knowledge of bee diversity, their interactions with plants, and their role as pollinators in Colombia. We have gathered and analyzed publications and records of bees from the literature, focusing on three key categories: bee diversity, bee-plant interactions, and assessment of pollination services. Our results highlight significant gaps in knowledge about the bee fauna in different natural regions and administrative divisions of the country. Compared with other countries, Colombia's bee fauna is still in the early stages of exploration, as evidenced by the regular discovery of new taxa (Gonzalez *et al*., 2012).

Most records come from the Andean region, particularly from human-dominated landscapes in the departments of Antioquia (1,434) and Cundinamarca (1,282), where major universities and research centers are located. Notably, 14 of 32 departments in Colombia have fewer than 40 bee records (Fig. 5), highlighting that most ecosystems and habitats in the country remain unexplored for bee diversity. The Andean region is known for its high endemism and species richness, attributed to its topographic complexity, diverse altitudinal gradients, and numerous geographically isolated valleys. This suggests that many species may be discovered even in well-studied regions. Conducting large-scale ecosystem experimental studies is critical to improve our knowledge of the impacts of global climate change on Andean diversity (Báez *et al*., 2016). This pattern seems to align with broader reports on the biological diversity of the Andes, highlighting the urgency of assessing the threats and vulnerabilities faced not only in the Andean region but also across other regions of the country. It also highlights the need to develop comprehensive inventories that increase taxonomic knowledge.

However, the abundance of records found in the literature from the Andean region does not necessarily indicate that this area harbors the highest bee diversity in the country. This result could be an artifact of increased sampling efforts in this biogeographic region. In contrast, the Caribbean region, which comprises extensive dry forests and deserts, is underrepresented in the literature. Local biologists have often characterized it as a "barren biodiversity area" compared to the Chocó or Amazon regions (Pennington *et al*., 2018). However, recent studies have shown a diverse and unique melittofauna, exhibiting high levels of endemism and complex taxonomic composition that parallels that of the region's flora (Gonzalez *et al*., 2012; Florez *et al*., 2015), emphasizing the need for more significant sampling efforts in this area. Biological research in this region is key, as these dry tropical forests are facing some of the fastest rates of habitat destruction globally (Vieira & Scariot, 2006; Gonzalez, 2014). Comprehensive sampling efforts throughout the country, using systematic and standardized methodologies, are essential for better documenting bee diversity in Colombia and determining whether the biodiversity patterns observed are a genuine biological phenomenon or the result of sampling biases.

Our analyses clearly show strong taxonomic biases. Most records are from species of corbiculate bees, most of which are social, abundant, and frequently encountered in ecosystems or easily captured through baits (*e.g*., Euglossini) (Nates-Parra, 2006). Collectively, these taxa represent approximately one-third of the known bee species of Colombia, suggesting that two-thirds of the country's melittofauna remains largely undocumented. A major constraint to improving our understanding of the bee biodiversity of Colombia is the limited number of scientists with expertise in the local fauna (Freitas *et al*., 2009). Even among corbiculate bees, it is still not clear how many and which species occur in Colombia. For instance, the number of reported bumble bees varies from 9 to 12 species. Names of species commonly used in the current Colombian bee literature [e.g., *Tetragonisca angustula* Illiger] are likely from species that do not occur in the country (Moure *et al*., 2007; Gonzalez *et al*., 2013). Our results call for improving the documentation of knowledge about the diversity of Colombian bees. This could increase the volume of publications output in the coming years, mainly by including laboratory and field notebooks and scientific collections, some of which have data available, providing additional sources of information on Colombian biodiversity.

We found that studies focusing on the identity of bee-plant interactions and the quantification of pollination services provided by bees were underrepresented in the literature. Overall, the lack of knowledge of the bee fauna, their interactions with plants and their level of specialization, and their value as pollinators in Colombia, has some negative consequences with practical implications. First, natural areas in Colombia, as in many other countries in tropical areas, are experiencing accelerated deforestation rates (Armenteras *et al*., 2017; González *et al*., 2018). This situation implies that many bee species are lost before being described to science. Second, we have limited background information to (1) understand whether bee and plant communities' interactions have changed through time, and (2) predict how changes in bee populations will impact plant reproduction in the future (Nates-Parra & Gonzalez, 2000). Parallel declines of pollinators and plants have been documented in Europe and North America (Biesmeijer *et al*., 2006; Burkle *et al*., 2013), and these studies have facilitated the development of pollinator conservation plans with economic support from government agencies (*e.g*., US Pollinator Research Action Plan, European Pollinator Initiative). Therefore, generating information about bee pollinators in Colombia will be necessary to drive policy changes. Third, there is a poor understanding of bee diversity's ecological and economic value for crop pollination services (Garibaldi *et al*., 2013). According to the three types of evaluation of the pollination service, the highest reports corresponded to Type I (relative effectiveness, involved the collection of flower's visitors, cleaning and counting all pollen grains), indicating a scarcity of studies that evaluate the role of native pollinators in the production of fruits and seeds in the country. The gaps in information about assessing pollination services are evident, and it is urgent to develop a database of the state of pollination in their territories, similar to those in North America, Europe, and even Africa (Pantoja *et al*., 2014). Without this information, it is impossible to implement appropriate and effective management practices to enhance crop pollination when needed, in political and practical terms, allowing for viable management aimed at conserving pollination services.

Even though our data show increased scientific knowledge about bees over the last 41 years, significant gaps still exist. We hope this work highlights areas that should be emphasized for future research efforts. A comprehensive understanding of the taxonomic diversity of bees within the country poses a key challenge to advancing bee ecology, evolution, pollination biology, and environmental economics. Integrating molecular approaches, such as DNA barcoding, with traditional taxonomic methods should lead to more accurate species delimitation (Schmidt *et al*., 2015). However, studies that use these techniques are scarce in the country (Prada *et al*., 2009; Pires & Marinoni, 2010; Ramírez *et al*., 2010). Additionally, analyzing the melittofauna in the context of climate change and its impacts on pollination services (*e.g*., crop phenology, pollinator etiology), along with evaluations in agroforestry systems and best management practices at various scales (*e.g*., ranging from individual farms to broader agricultural landscapes), as well as assessments of the effects of land-use change, could contribute to a comprehensive multi-scale assessment of pollination services and the health of bee populations.

More significant efforts should be made to understand bee diversity, ecological interactions with plants, and contributions to ecosystem services. Creating publicly available databases that centralize all existing information about bees in the country is imperative. Such repositories will guide future efforts to document the diversity and ecological roles of these insects in Colombia, assess their conservation status as pollinators, and reinforce the Colombian Pollinators Initiative (Moreno-Villamil *et al*., 2018).

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SUPPLEMENTAL MATERIAL

Table S1. Summary of literature records from 1976 to 2017 on the state of knowledge about bees in Colombia. The table shows the literature identified for each year, including its analysis category and the number of reported records.

Table S2. Bee–plant interaction records in Colombia, organized by bee taxonomy and plant family.

Table S3. Plant species recorded for bees in the categories of bee diversity, bee-plant interactions, and assessment of pollination services.

Table S4. Number of records for bee families and genera from the literature review.

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