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REVIEW

Challenges for Quantifying Knowledge Shortfalls on Tropical Pollinators in the Face of Global Environmental Change – Brazilian Bees as a Case Study

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Abstract
Assessing the extent of ongoing pollinator declines and predicting future changes is key to defining priorities and developing adequate policies to mitigate the consequences of such negative trends. Nevertheless, a lack of basic information on species identity, trends, traits, and requirements hinders our ability to make such assessments. Such knowledge gaps are particularly pronounced in tropical regions, which are expected to be severely affected in the upcoming years by climate change. Identifying which taxonomic groups and regions have greater gaps can help direct efforts. Recent studies proposed groups of knowledge to quantify the extent of our ignorance (shortfalls) and proposed methods to quantify them for pollinators. Here, we use Brazilian bees as a case study to evaluate the feasibility of applying these proposed methods to tropical pollinators and provide a first assessment of the extent of these knowledge gaps. While some adaptations were proposed, we evaluated for the first time all seven shortfalls (Linnean, Wallacean, Raunkiaerian, Eltonian, Prestonian, Darwinian, and Hutchinsonian) and the Keartonian impediment. We found that the Linnean shortfall of Brazilian bees is at least five-fold the one recently found for the European countries with the most outstanding shortfalls (i.e., an increase rate of 1% species per year, reaching 3% for certain families). Also, more than half of Brazil's land area (ca. 57.5% of the 50x50 km pixels) lacks known bee records, and most species have less than ten spatially unique known records, indicating the extent of the Wallacean shortfall. Despite these gaps, important sources of information do exist and are just not accessible or spread out. Substantial compilation efforts would be necessary to unite existing information into unique databases. Considerable collaborative efforts and incentives to make standardized data accessible and public are crucial to advance in this field and guide actions to reduce the knowledge gaps.

Introduction

Tropical regions are expected to suffer most from ongoing global climate changes (Hofmann et al., 2021) and are also under large-scale land use changes that negatively affect biodiversity and can worsen the impacts of climate change (e.g., loss of natural habitats, Ferreira et al., 2016; Strassburg et al., 2017). Investment in conservation and restoration policies and actions can reduce these negative impacts on biodiversity (Huang et al., 2019; Sexton & Emery, 2020;

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Romanelli et al., 2022). However, these actions are still limited, and prioritization of certain regions, ecosystems, and species is often necessary (Silva et al., 2023). Significant shortfalls in our knowledge of tropical species greatly limit our ability to define priorities adequately. For a vast number of the described species, we lack information on their distribution (Wallacean shortfall), traits (Raunkiaerian shortfall), interaction patterns (Eltonian shortfall), population trends (Prestonian shortfall), evolutionary relationships (Darwinian shortfall), tolerance to different abiotic conditions (Hutchinsonian shortfall) (full description of shortfalls in Hortal et al., 2015). In addition, the number of undescribed and undetected species is vast in tropical regions (Linnean shortfall, Hortal et al., 2015), and most of those described lack visual representations (Keartonian impediment, Marshall et al., 2024) that can help guide monitoring programs that aim to reduce the shortfalls.

Pollinators are key ecosystem agents that sustain biodiversity by ensuring the reproduction and fruit production of the vast majority of plant species, hence being a vital biotic input for the productivity of many crops (Ollerton et al., 2011; Giannini et al., 2015; Siopa et al., 2024). Recent assessments in Europe (Marshall et al., 2024) and the US (Chesshire et al., 2023) showed that even in regions where bee knowledge is considered to be the most complete (Nieto et al., 2014; Leclercq et al., 2023), shortfalls are still vast. These regions still have high rates of newly described species, and many species lack robust distribution data and information on species traits (Marshall et al., 2024). These assessments help to plan future monitoring actions and research initiatives to address such knowledge shortfalls. While in Latin America, previous works have synthesized information on bee species occurrence at the country level (Silveira et al., 2002; Freitas et al., 2009; Galetto et al., 2022; Moure et al., 2022), it is still unclear how much information we have concerning species trends, abiotic thresholds, traits, interaction patterns, genetic information, among others. Here, we use the native bees of Brazil, which is home to ca. 10% of the described bee species worldwide (Ascher & Pickering, 2023), as a case study and evaluate the potential application of the approaches proposed by Marshall and collaborators (2024) to quantify the extent of the shortfalls highlighted by Hortal and collaborators (2015) and the Keartonian impediment (Marshall et al., 2024). We also discuss the implications of the current state of such shortfalls for evaluating and predicting the impacts of global environmental changes.

How many species of bees are still to be described in Brazil? (Linnean shortfall)

To adequately evaluate how bee diversity is changing in response to global changes, we first need to know how many species exist (or existed) in a given region. Although Brazil has a long history of bee research, starting in the XVII century (Silveira et al., 2002; Pereira et al., 2021), the number of undescribed species (the Linnean shortfall, as defined by Hortal et al., 2015) is still vast. Specialists indicated that, at the beginning of the current century, at least a third of Brazil's bee species were still to be described (Silveira et al., 2002). Defining metrics that allow us to compare the extent of this shortfall with other regions of the world and within Brazil (e.g., comparing biomes, states, or ecogeographic regions) is important for understanding and addressing these knowledge gaps.

The rate of newly described species can be used as an indicator of the Linnean shortfall (i.e., mean annual growth rate of the number of species, Marshall et al., 2024). A country-level assessment of newly described Brazilian bee species (information available in Moure et al., 2022) shows that, for all bee families, the increase in the number of species described in recent years is high (Fig 1). In 2002, Silveira and collaborators (2002) mentioned the existence of 1576 species of bees described for Brazil. In 2007, the Moure's Bee Catalogue listed 1678 species (Moure et al., 2007). Since then, many new species have been described, now reaching 2061 species (Aguiar & Ramos, 2020; Mahlmann, 2020; Aguiar et al., 2021; Ribeiro et al., 2021, 2023, 2024; Santos, 2021; Engel, 2022; Ferrari et al., 2022; Gonçalves & Pereira, 2022; Moure et al., 2022; Nogueira et al., 2022a,b, Vivallo, 2022a, 2022b; Melo, 2022, 2023; Mahlmann & Oliveira, 2023; Werneck, 2023; Lepeco, 2024; Urban & Melo, 2024). We can compare the newly described species from 1990 with those of other regions of the world. In Brazil, 606 species have been described since 1990, i.e., an increase of 41.9% (see Fig 1). Considering all bee species, there was a mean increase of 1% per year (reaching 3.5% for Andrenidae). This rate is much higher than in European countries (Greece has the highest value with 0.17% new species since 1990, Marshall et al., 2024).

The high rate of recently described species indicates that many bee species in Brazil remain undiscovered. Silveira et al. (2002) suggested that at least 3000 species are thought to occur in the country. However, much of the Brazilian territory remains poorly sampled (Freitas et al., 2009; Pereira et al., 2021). Indeed, by compiling the existing bee records on available databases and calculating data density per 50x50 km pixel, we detected that records cover only ca. 42.5% of the Brazilian land area, with generally very low sampling effort within each unit (see Fig 2). Therefore, the total number of bee species occurring within Brazil could be much higher than 3000.

As a complement to the assessment of the Linnean shortfall based on the number of newly described species, evaluations that make use of methods based on accumulation curves using specimens registered in collections, surveys, and sampling events (Colwell et al., 2012; Chao et al., 2021) can be done. Despite the haphazard nature of these types of occurrence data, adjustments can be made to extract meaningful estimates from this type of data (e.g., Carvalheiro et al., 2013). Efforts turned to the large-scale digitalization of bee occurrence records from national and international databases, coupled with applying such methods to well-curated databases, are essential to reach more accurate estimates of the number of bee species in Brazil.

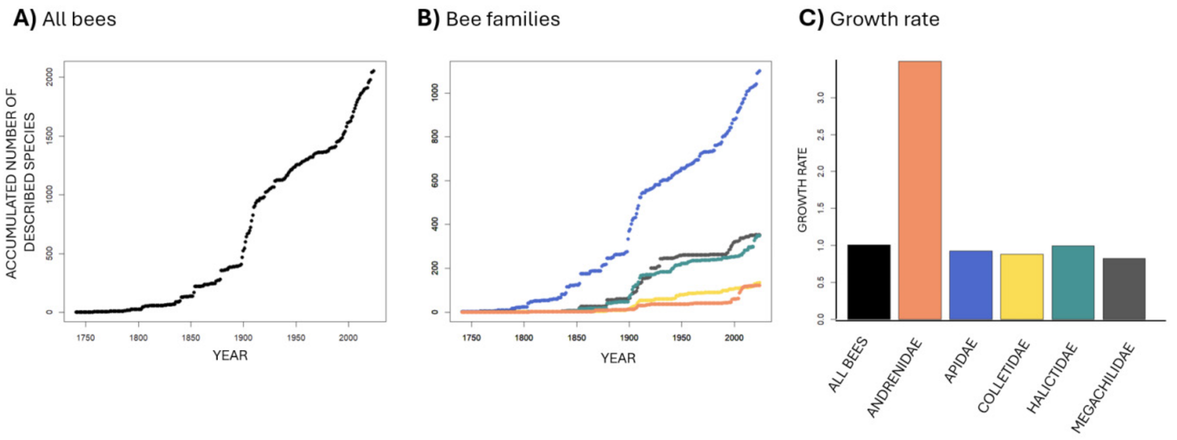

Fig 1. Country-level assessment of newly described Brazilian bee species indicates the Linnean shortfall. Based on the information available in Moure et al. (2022), we present the accumulated number of described species (A - global; B - divided per bee family) from 1700 to the present date and the mean annual rate of newly described species since 1990 (C). Color codes in A and B match with color codes in C.

In Europe, the Linnean shortfall was assessed at the country level (Marshall et al., 2024). Given the continental dimensions of Brazil, conducting assessments at the biome (or ecogeographical region) and state level would complement national level assessments, contributing to guiding future actions aiming to reduce knowledge gaps on this shortfall and all others. Such assessments can help identify where future surveys could most effectively reduce the Linnean and Wallacean (see below) shortfall. Nevertheless, the lack of taxonomists specialized in the different species groups and detailed keys with high-quality images of the important characteristics that separate species is still a significant limitation worldwide (see Isaac et al., 2004; Bortolus, 2008) and specifically for Brazilian bees. Therefore, such efforts must be accompanied by investments in forming new bee taxonomists in Brazil to conduct adequate revisions of the different taxonomic groups and develop informatics and genetic tools to help process large amounts of new information.

Where are Brazilian bee species? (Wallaceaen shortfall)

Knowing species' distribution range is essential to understanding which factors limit the probability of occurrence and extinction, as well as for predicting the impacts of climate change, such as changes in diversity patterns (including functional diversity) and ecosystem service provision (e.g., Giannini et al., 2020). To estimate the lack of information on bee species' geographic distribution (Wallacean shortfall, Hortal et al., 2015), Marshall and collaborators (2024) proposed three methods. The first method compares the discrepancy between the database of wild bee observations and the national checklists for each country. For Brazil, the national checklist (Moure's Bee Catalogue; Moure et al., 2022) is associated with information on geographical location (at the state or even municipality level). So, when integrating such information into databases, all species will have at least one geographically explicit record. A possible adaptation would be to assess the proportion of species in the checklist with more than a given number of acceptable records to assess its distribution correctly. It is well established that species distribution model (SDM) performance depends on the adequate spatial extent of species records (Elith et al., 2006), so the larger the number of well-distributed occurrence points, the better the performance of a distribution model. However, the minimum number of spatially unique records required to run an adequate species distribution model is debatable. In Brazil, 58% of bee species have less than ten spatially unique records, and 74% have less than 20, with many regions still being underrepresented (57.5% of the 50x50 km pixels within Brazil's land area lack known bee records, Fig 2). These values indicate that the extent of this shortfall is large.

The second method proposed by Marshall and collaborators (2024) for accessing this shortfall involves comparing modeled predictions of taxonomic wild bee diversity against observed diversity based on occurrence records. In Brazil, distribution assessments based on SDMs were done for at least 271 species (Giannini et al., 2012, 2013, 2015, 2017, 2020; Maia et al., 2020; Acosta et al., 2024). While this number could be extended to all species having an adequate number of spatially unique records, it is clear that for many bee species, we are still far from knowing their actual distribution.

Finally, the third method is based on calculations of sampling completeness (coverage) for each spatial unit (Marshall et al., 2024), using the iNext package in R (Chao et al., 2021). This method could certainly be applied to the Brazilian bee dataset, but given that many records have an accuracy lower than 50 km (e.g., state-level or municipality level), it may be better to use a larger spatial scale than the 25 km used in Marshall et al. (2024).

How do species differ in terms of genes? (Darwinian shortfall)

Information on genetic diversity is fundamental for adequate evaluations of relationships between species and global diversity patterns (Miraldo et al., 2016). As an indicator

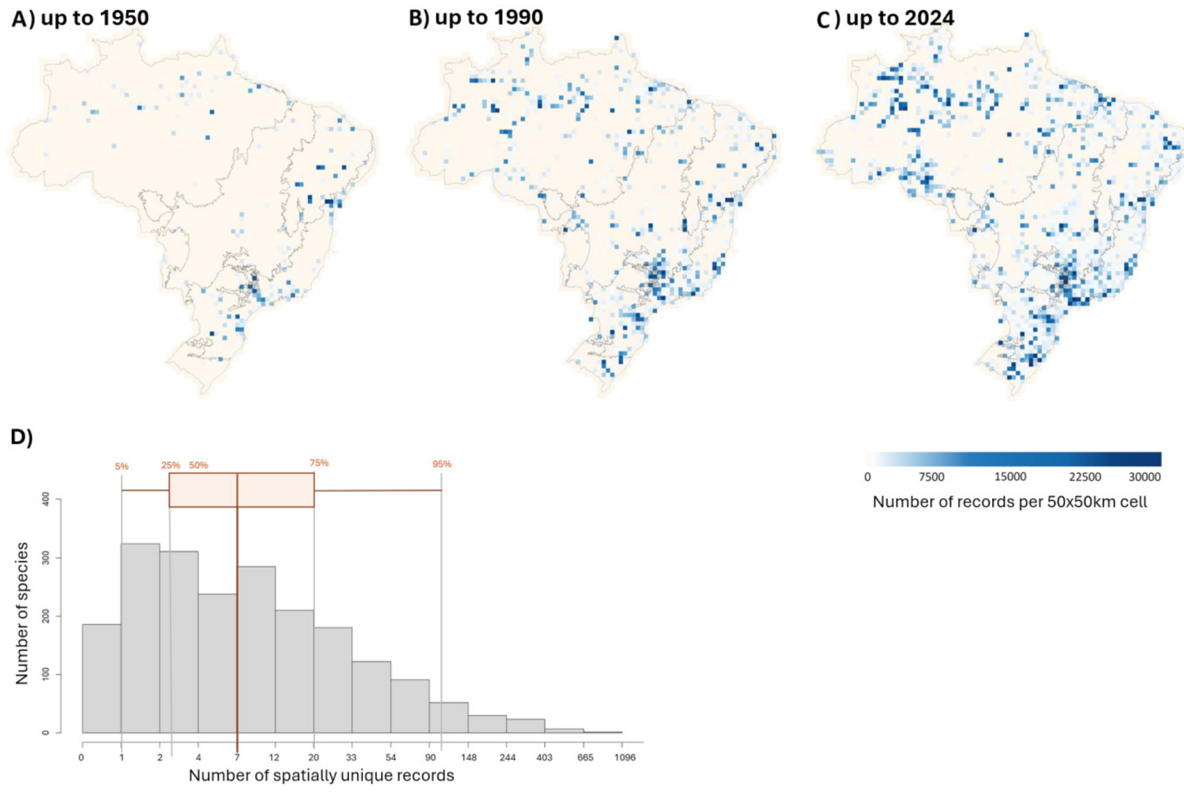

Fig 2. Indicators of the extent of the Wallacean shortfall for Brazilian bees. Maps represent the distribution and density of accumulated occurrence records of native bees in Brazil up to 1950 (A), 1990 (B), and 2024 (C) in each cell of 50 x 50 km. The number of spatially unique records (different coordinates) per bee species at the national level (D) is also presented. The dataset used to build this Figure combined all records with spatially explicit information from available public sources such as GBIF (https://www.gbif.org/), speciesLink (http://splink.cria.org.br), SIBBR (https://www.sibbr.gov.br/), Moure's Bee Catalogue (Moure et al., 2022, https://moure.cria.org.br/), plant-bee interaction database of the Associação Brasileira de Estudos das Abelhas (A.B.E.L.H.A.) (http://abelhaseplantas.cria.org.br). We also added information obtained from national and international entomological collections (Smithsonian National Museum of Natural History, Naturalis Biodiversity Center, Digital Bee Collections Network) and data from digitized scientific articles. All species names were cross-checked with the names and synonyms described in Moure's Bee Catalogue (Moure et al., 2022).

of the absence of knowledge on the evolutionary relationship between species (Darwinian shortfall, Hortal et al., 2015) for European wild bees, Marshall et al. (2024) evaluated how the availability of publicly accessible gene sequences (COI gene sequences from the Barcode of Life Data System, BOLD, https://boldsystems.org/; Ratnasingham & Hebert, 2007) impeded building phylogenies. For Brazil, BOLD currently has 3752 records with sequences of Apidae (representing 171 species), 24 sequences of Colletidae (representing eight species), 20 sequences of Megachilidae (representing nine species), 34 sequences of Halictidae (representing 19 species), eight sequences of Andrenidae (representing four species). This dataset encompasses 211 species, 10% of Brazilian bee species. While data from species that occur in Brazil may have been collected in other countries, just with this brief survey, it is clear that the size of this shortfall is substantial. As Marshall and collaborators (2024) point out, it is possible to build valuable phylogenies at a broad spatial scale using a selection of species (e.g., Almeida et al., 2023; Henríquez-Piskulich et al., 2024) or using Linnaean taxonomic hierarchies (Vereecken et al., 2021a, 2021b; Leclercq et al., 2023). Given the high number of genera requiring revisions (Silveira et al., 2002), this last option may pose a challenge in Brazil.

How are species populations changing? (Prestonian shortfall)

Assessments of bee declines solely based on richness patterns can miss important trends at the population level. Data on population dynamics is fundamental for the early detection of impacts of climate and other global changes. The lack of information on species population dynamics across time and space (the Prestonian shortfall, Hortal et al., 2015) is closely related to the lack of long-term data that allows to estimate changes in species abundance (Cardoso et al., 2011; Hortal et al., 2015) and predict what would happen under scenarios of environmental change. As in Europe (Marshall et al., 2024), the Prestonian shortfall is likely the most significant knowledge gap in wild bee knowledge in Brazil. The tribes Meliponini (stingless bees) and Euglossini (orchid bees) may have better data, as these groups have caught the interest of many researchers for a long time, and scent trap (used for Euglossini) can be used to access their density (e.g., Powell & Powell, 1987; Silva & Rebelo, 2002; Oliveira et al., 2013; Tavares et al., 2013; Nemésio et al., 2015; Tosta et al., 2017).

Given the absence of long-term data for most species, the IUCN Red List was used as a proxy for the absence of meaningful population data to quantify this shortfall in Europe.

In Brazil, only a few species are currently recognized as “in danger or vulnerable to extinction” (EN) including *Melipona capixaba* Moure & Camargo (1994), *Melipona rufiventris* Lepeletier (1836), *Melipona scutellaris* Latreille (1811) and *Partamona littoralis* Pedro e Camargo (2003) (ICMBIO/Brasil, 2022). Most Brazilian bee species have not yet been evaluated, and most likely, data is lacking for many. Indeed, as the authors of the European study point out, data deficiency assessments based on the red list most likely underestimate the extent of this knowledge gap. As an alternative way to assess this shortfall, the European study calculated the number of species without a minimum of three observations for at least ten separate years after 1950 in each province and country to estimate this shortfall. By compiling data from public databases, we detected that in Brazil, only 540 bee species (35%) have occurrence records within Brazil from at least ten different years, the majority having data just for five or fewer years (Fig 3). Even among the bees with data for at least 10 years, if such data does not come from the same region (e.g., state or municipality) assessments on population dynamics are not reliable.

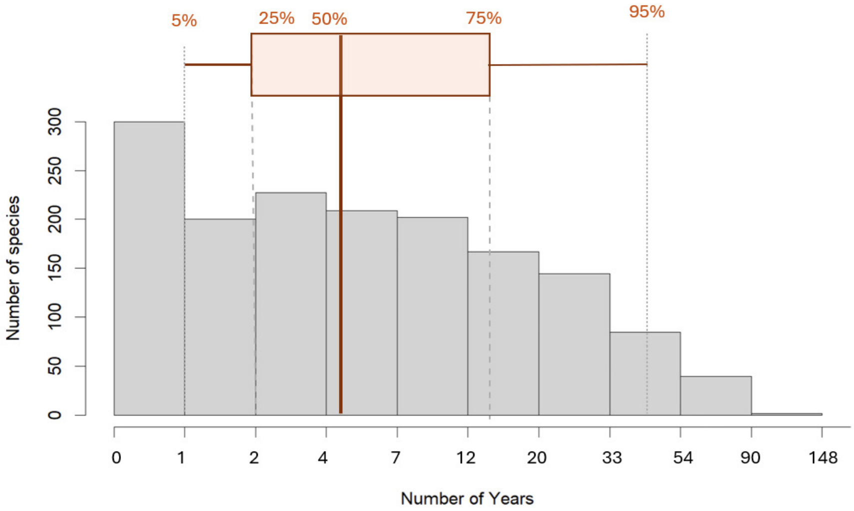

Fig 3. The number of species with enough data to evaluate temporal dynamics of population patterns indicates of the Prestonian shortfall for Brazilian bees at national scale. Data from public databases (same as those used for Fig 1). Histogram of number of years with occurrence data per bee species. The x-axis is presented in log-scale. Half (50%) of the species have data from 5 or less years, 25% have data from 2 or less years and 5% were only registered in a single year.

The extent of the lack of temporal series reinforces the importance of making data occurrence records public and investing more in monitoring schemes. Brazil has a program for long-term monitoring biodiversity (PELD) that started in 1999 (https://www.gov.br/cnpq/pt-br/acesso-a-informacao/acoes-e-programas/programas/peld). However, to our knowledge, only a few sites have collected bee data using Malaise traps or other methods. Investments in long-term schemes with a wider taxonomic range would be important to expand knowledge of such dynamics. Nevertheless, at least for some regions, it may be possible to do these evaluations for some species, and those would be very informative to understand better how bees react to ongoing global changes.

How do species differ in terms of traits? (Raunkiaerian shortfall)

The sensitivity of organisms to climate and other environmental changes varies significantly between species (Burdine & McCluney, 2019), likely depending on their traits (i.e., species-level properties that can be assessed at the individual level). Indeed, species traits influence their response to environmental changes (response traits) and their effect on ecosystem functioning (effect traits) (Suding et al., 2008). For example, body size and sociality level (and colony size) greatly influence species’ foraging range (Greenleaf et al., 2007; Grüter & Hayes, 2022; Kendall et al., 2022) and the ability to control body and nest temperature (Ostwald et al., 2022; Easton-Calabria et al., 2023; Harano & Hrncir, 2023). Pilosity and vibration ability can also be important in thermoregulation (May, 1979; Heinrich, 1993). On the other hand, environmental changes can also affect species traits (e.g., selecting individuals with specific characteristics), affecting their role as ecosystem agents and their responses to future environmental changes. For instance, rising air temperatures can affect body and antenna size and fat content (Fliszkiewicz et al., 2012; Gérard et al., 2023). Therefore, the lack of information on functional trait variation within and between species (i.e., Raunkiaerian shortfall, as defined by Hortal et al., 2015) can hinder evaluations of the consequences of species loss for ecosystem functioning and the provision of ecosystem services, such as crop pollination. Information on species traits can also help define ecological niches (McGill et al., 2006) and geographic ranges (Aguirre-Gutiérrez et al., 2016), addressing other shortfalls mentioned above.

While the description of Brazilian bee fauna started in the XVII century, including important morphological trait data (e.g., size), this valuable information is frequently not publicly available and spread across academic documents, collections, and private annotations from naturalists and researchers. Compiling and standardizing this information in a single database is essential to adequately assess the extent of this shortfall and strategically invest resources to minimize it. Previous studies (Borges et al., 2020) presented compilations of trait data for Brazilian bees, including body size, flight range, distribution, importance as crop pollinators, and sociality. However, there are still important gaps of knowledge for nesting habits (including nesting method, aggregation, and colony size), buzzing capacity, and body size (Fig 4), and lack many other important traits. In Europe, the assessment of the Raunkiærian shortfall does include body size, sociality, and nesting habit, but also includes larval feeding specialization (pollen collection), voltinism (number of generations per year), and pollen transport method (Marshall et al., 2024). Strong collaborative efforts are needed to increase trait coverage of Brazil's more than 2000 bee species. In addition, information on phenology is also important to better understand species' susceptibility to climate changes. In Brazil, few studies have gathered information on phenology (but see Kamke et al., 2011, which gathered data for 64 species of Santa Catarina State). Compiling data from long-term monitoring schemes, where data is collected monthly (e.g., using Malaise traps), is essential for detailed evaluations of activity fluctuations through time.

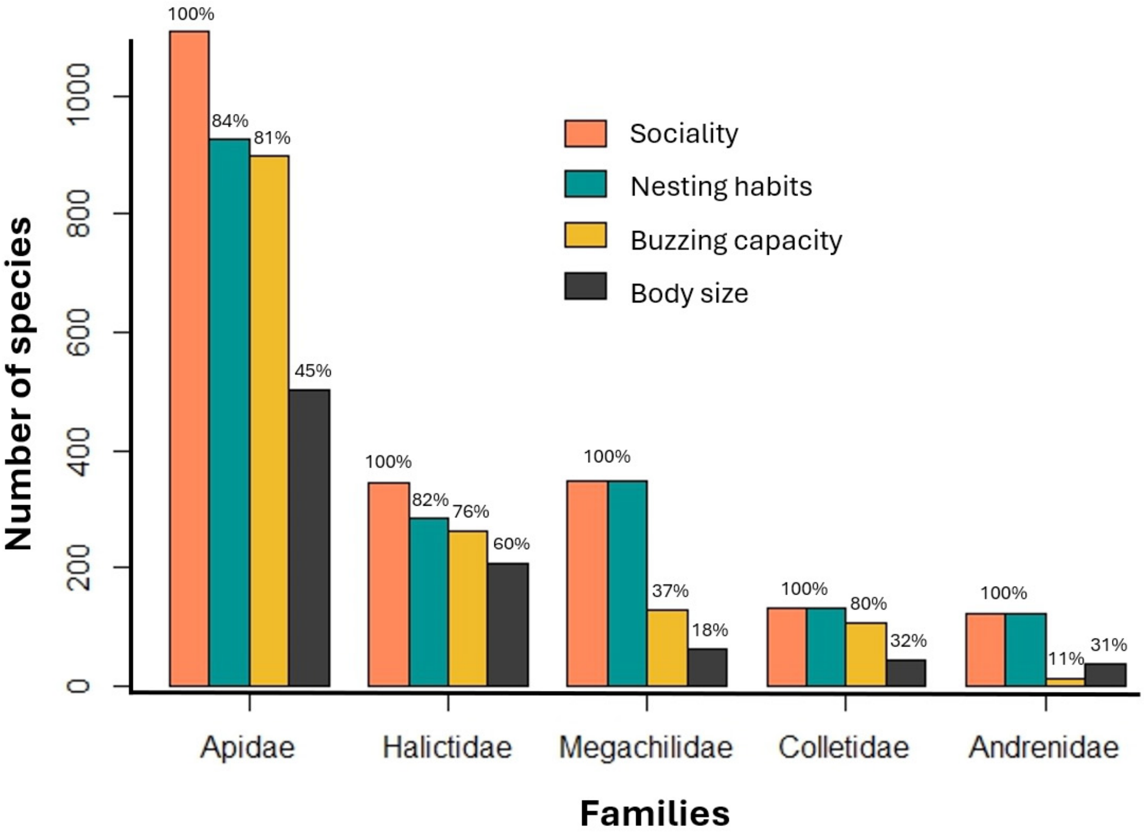

Fig 4. Indicators of the extent of the Raunkiærian shortfall for Brazilian bees. Number of Brazilian bee species with at least some information on sociality, nesting habits, buzzing capacity, and body size listed in public datasets. The information was extracted from the largest compilation of bee trait data published so far in Brazil (Brazilian Bee Trait Database, https://colecaozoologica.icb.ufg.br/p/brazilianbeetraitdatabase). The percentual values indicate the proportion of species within each family with at least some trait information.

How tolerant are species? (Hutchinsonian shortfall)

Information on the extent of knowledge concerning the tolerance of species to changes in abiotic conditions (Hutchinsonian shortfall, Hortal et al., 2015) can be obtained via experimental work testing physiological responses (e.g., Vanderplanck et al., 2019) or evaluating the correlations between bee activity and an environmental gradient (e.g., de Oliveira et al., 2012). Some studies that focused on Brazilian bees evaluated the effects of environmental temperature (e.g., de Oliveira et al., 2012; Hrncir, 2019; Maia-Silva et al., 2021) and pesticides (Barbosa et al., 2015; Lima et al., 2016; Prado et al., 2023, see also Franceschinelli et al., 2023). However, the existing studies are limited to very few bee species, and other environmental stressors are still to be evaluated, e.g., humidity, environmental eutrophication, and other sources of pollution (e.g., stratospheric ozone). Another possible approach to extract information on tolerance thresholds is through species distribution models (SDM, also called environmental niche models, ENM) (e.g., Marshall et al., 2018). As mentioned above (Wallacean shortfall), SDMs have been run for more than 200 Brazilian bee species, and based on those, it would be possible to extract tolerance values for Brazilian bees related to climate. Further SDMs could be run for species with a sufficient number of records.

With whom do species interact? (Eltonian shortfall)

Lack of information on interaction partners between species (the Eltonian shortfall, Hortal et al., 2015) dramatically limits our understanding of how bee species are affected by climate change and other ongoing environmental changes. Bees have multiple interaction partners. They are linked to a diverse set of plant species that they use as floral resources (pollinating or robbing them) and nesting resources in a commensal relation (Memmott et al., 2008). If such resource species are sensitive to specific environmental changes and reduce their abundance or even go locally extinct, the bees that feed on them will decline even if they are not directly affected by the original environmental change. Such propagation of effects through networks of ecological interactions can be even more accentuated if consumers are specialized and propagate to higher tropic levels, such as parasitoids or predators (Carvalheiro et al., 2010; Martins et al., 2024). Changes in such higher trophic levels can also negatively affect bee diversity, as important agents that control populations of bee species that may be more competitive are released, and species with less competitive advantage may go locally extinct due to apparent competition (Morris et al., 2004; Carvalheiro et al., 2008). Moreover, generalist bee species may be able to rearrange their diet in response to climate change (Endres et al., 2021; Morozumi et al., 2022). Overall, information on ecological interactions can be used to build networks and predict the impacts of several ongoing environmental changes, including climate, land use, or biological invasions (Memmott, 1999; Carvalheiro et al., 2008, 2011).

In Brazil, substantial efforts have been made to gather information on flower visitation involving bees (Gazzoni et al., 2021; A.B.E.L.H.A., 2022; REBIPP, 2024). While this type of data can help define the specialization level of adult bees, not all flowers visited by adults will be used as pollen sources, which is the main source of protein for bee larval development (Vaudo et al., 2015). Indeed, the pollen diet of a given bee species may be more specialized than its flower visitation patterns (e.g., *Melipona favosa* was detected to forage on species from at least 27 families but likely only actively collected pollen from species of 17 families, Engel & Dingemans-Bakels, 1980). Defining the lectic status (monolectic, oligolectic, or polylectic) of bee species (pollen specialization) is an important trait used in many ecological studies, and future efforts in gathering information on pollen sources should be a priority when filling knowledge gaps. Some examples of first studies gathering this type of information for South American bees include Engel and Dingemans-Bakels (1980), Silva et al. (2014), and Barth (2004). In addition, several Brazilian bees from the genus *Trigona* evolved diverse diet strategies involving frugivory (Peruquetti et al., 2010) and necrophagy, some species being facultative necrophagous and some authors proposing that some species change to being obligatory necrophagous (Jarau, 2003; Mateus & Noll, 2004; Oliveira et al., 2013), even acting as predators (Mateus & Noll, 2004). Gathering information on such alternative sources of diet is also important.

For European bee species, the Eltonian shortfall was quantified as the number of species with at least one information of diet resources (Marshall et al., 2024). When combining several public sources that have information on bee-plant interactions, we detected information on flower visitation patterns for 676 Brazilian bee species, which means that for more than 67% of the species of bees, we have no information compiled (Fig 5). While further information on foraging habits of Brazilian bees could be obtained from databases from nearby countries that share some species with Brazil, such databases are scarce (but see López-Aliste et al., 2021; Muschett & Fontúrbel, 2022). Among these, 532 species have polyphagous foraging habits, visiting multiple families of plants, and the remaining species do not have enough information to classify them. However, having information on just one interaction partner does not mean sufficient information on how a species is embedded in the complex network of ecological interactions. Moreover, interaction with plants for nesting is also part of this shortfall, as well as interactions between females of different species (e.g., cleptoparasitic bees and their hosts, Antoine & Forrest, 2020) or males for protection overnight (Santos et al., 2014). Finally, information on predators and parasites is crucial to understanding species susceptibility to environmental changes.

In addition to identifying biotic interaction patterns, information on the frequency of interaction and factors that influence such interaction strength is also essential to understanding bee species' susceptibility to environmental changes and consequences for ecosystem services. However, even before the interaction goes extinct, a change in its frequency may lead to intense declines in species fitness, preceding species extinction. Indeed, even if a plant is still visited by its main pollinator species if the frequency of such interaction is rare, it may change the community dynamics with effects on plant fitness (Lázaro et al., 2014; Benadi & Pauw, 2018). Therefore, the Eltonian shortfall could be divided into two components: the identification of partners (Eltonian basis) and the dynamics of such interactions (Eltonian-Hutchinson component). Gathering information on

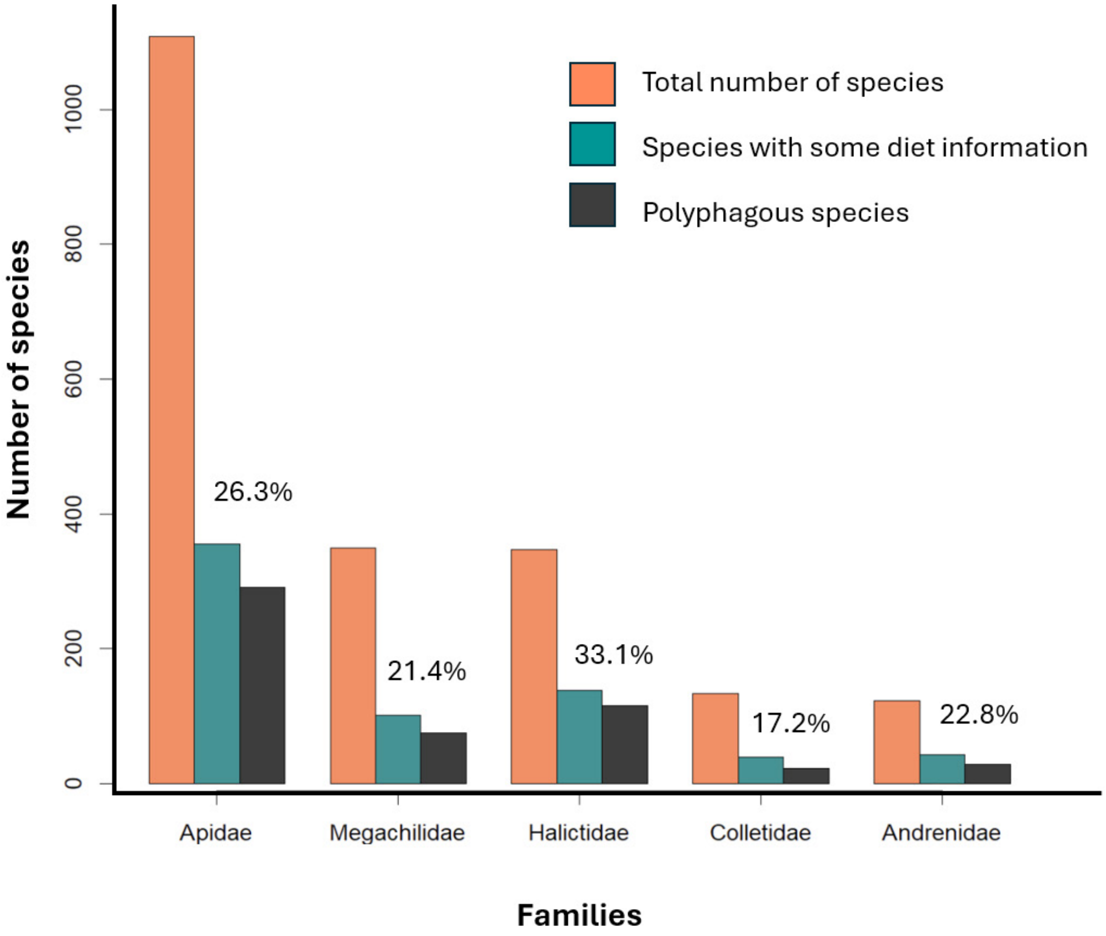

Fig 5. Indicators of the extent of the Eltonian shortfall for Brazilian bees. Number of species with information on at least one interaction partner (only flower visitation events were considered), per bee family. Species with sufficient information were classified as polyphagous (visiting more than one family of plant species). All others do not have sufficient information to be classified in terms of flower visitation partners. Information was obtained from the interaction database of A.B.E.L.H.A (http://abelhaseplantas.cria.org.br/), the currently publicly accessible version of the interaction database of REBIPP (https://rebipp-db.jbrj.gov.br/) and Gazzoni et al. (2021).

quantitative interaction networks involving bees and other flower visitors is essential to cover this second component. In Brazil, there is an established tradition of studying ecological interactions (e.g., Viana et al., 1997; Schlindwein et al., 1998), and many researchers have gathered information on networks involving bees (Campbell et al., 2019). Yet, the comparability of patterns of such networks is compromised by differences in sampling methods and a lack of information on the abundance of resource species (a primary driver of bee choices, Carvalheiro et al., 2014).

What do species look like? (Keartonian impediment)

To cover all of the shortfalls discussed above, it is essential that more people correctly identify the bee species observed and collected. While we depend on professional taxonomists and advanced molecular methods to adequately identify species, the availability of visual representations of species in public sources and imaged-based identification apps can significantly contribute to that. Marshall and collaborators (2024) defined the Keartonian impediment as an indicator of the availability of visual representations of what a species looks like, and they use the absence of high-quality in-situ photographs as a measure using iNaturalist and Flickr.com as reference sources for photos validated by experts (research grade in iNaturalist). For Brazilian bees, at the time of this search (November 2024), iNaturalist had 8802 records marked as 'research grade' belonging to 58 native species belonging to nine tribes (Fig 6). In addition, at least 1132 photographic registers of bees and their nests were available at the date of this data compilation in Cristiano Menezes Fonoteca (https://specieslink.net/col/FCM/). Central and North regions of Brazil are particularly poorly represented, and the tribes Meliponini and Euglossini are those with better representation. Stimulating citizen science programs that involve uploading images of bee species throughout the countries would be fundamental to reducing the extent of this shortfall. On that note, it is worth mentioning that any effort to reduce shortfalls involving non-academic public members, including traditional local communities that have substantial knowledge of native bees (BPBES/REBIPP, 2019), would benefit from a compilation of information on common names used across regions.

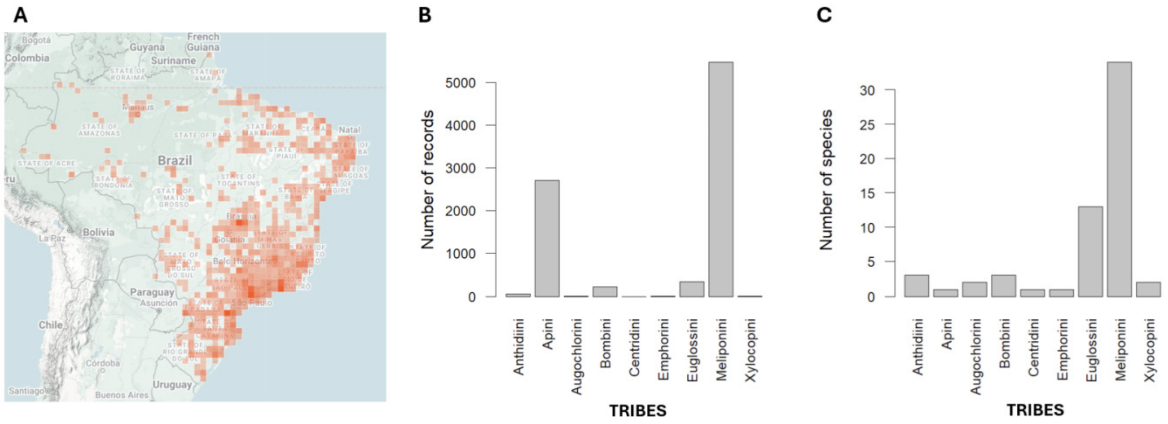

Fig 6. National-level evaluation of the extent of the Keartonian impediment for Brazilian bees. Using records extracted in November 2024 from iNaturalis using the search terms 'bees' and 'Brazil' that were marked as "research grade" (8802 records in total) we present (A) the spatial distribution of records with associated images that have high accuracy in terms of taxonomy, (B) how such records are spread across bee tribes and (C) how many species per tribe are represented. In A, the opacity of each colored square on the map tile is determined by the number of observations in that square; opaquer = more observations.

Concluding remarks

The lack of basic ecological, morphological, and taxonomic information significantly constrains our ability to define priorities for conservation and adequately evaluate and predict the impacts of ongoing global changes. The brief survey of data presented here certainly misses many records stored in non-public databases (including those of national and international museums and many private collections spread throughout Brazil). Nevertheless, the extent of shortfalls for Brazilian bees is much larger than that of other regions where these assessments have been previously done (e.g., Marshall et al., 2024). While the lack of knowledge may sound overwhelming, identifying which groups, regions, and information classes are most affected can help us direct future research and monitoring efforts. Should we prioritize information gathering for all tribes equally? Should the focus be different across biomes? How far are we to have good levels of completeness on traits that influence how species respond to climate change (e.g., body size, vibration ability)? To answer these questions, we need extensive collaborative efforts to (1) compile the thousands of fragments of information that are spread across scientific literature, grey literature, and databases, (2) check and standardize available information so that it is comparable across species, (3) intensify efforts to improve completeness in shortfalls (e.g., digitizing information from individuals in collections within and outside Brazil), defining complementary aims across research groups. Only with that information can we adequately plan to increase field surveys in strategically under-sampled locations.

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References

A.B.E.L.H.A. (2022). Sistema de informação sobre Interações Abelhas-Plantas no Brasil. Available at: http://abelhaseplantas.cria.org.br/. (accessed date: 27 June 2024)

Acosta, A.L., dos Santos, C.F., Imperatriz-Fonseca, V.L., Oliveira, R.C. & Giannini, T.C. (2024). A methodological approach to identify priority zones for monitoring and assessment of wild bee species under climate change. Frontiers in Bee Science, 2: 1-10. https://doi.org/10.3389/frbee.2024.1329844

Aguiar, A.J.C. & Ramos, K.S. (2020). Two new species of Anthrenoides Ducke, 1907 (Hymenoptera: Apidae: Andreninae) with a checklist of Andrenine bees of cerrado savanna. Annales Zoologici, 70: 561-572. https://doi.org/10.3161/00034541ANZ2020.70.4.006

Aguiar, A.J.C., Viana, M.C. & Melo, G.A.R. (2021). A new species of the bee genus *Paratetrapedia* from northeastern Brazil mimic of the stingless bee *Camargoia nordestina* (Apidae, Tapinotaspidini). Revista Brasileira de Entomologia, 65: e20200102. https://doi.org/10.1590/1806-9665-rbent-2020-0102

Aguirre-Gutiérrez, J., Kissling, W.D., Carvalheiro, L.G., WallisDeVries, M.F., Franzén, M. & Biesmeijer, J.C. (2016). Functional traits help to explain half-century long shifts in pollinator distributions. Scientific Reports, 6: 24451. https://doi.org/10.1038/srep24451

Almeida, R.J., Bonachela, J.A. & Lockwood, J.L. (2023). Multiple co-occurring bioeconomic drivers of overexploitation can accelerate rare species extinction risk. Journal of Applied Ecology, 60: 754-763. https://doi.org/10.1111/1365-2664.14376

Antoine, C.M. & Forrest, J.R.K. (2021). Nesting habitat of ground-nesting bees: a review. Ecological Entomology, 46: 143-159. https://doi.org/10.1111/een.12986

Ascher, J.S. & Pickering, J. (2023). Discover life bee species guide and world checklist (Hymenoptera: Apoidea: Anthophila). http://www.discoverlife.org/mp/20q?guide=Apoidea_species (accessed date: 25 June 2024).

Barbosa, W.F., Smagghe, G. & Guedes, R.N.C. (2015). Pesticides and reduced-risk insecticides, native bees and pantropical stingless bees: pitfalls and perspectives. Pest Management Science, 71: 1049-1053. https://doi.org/10.1002/ps.4025

Barth, O.M. (2004). Melissopalynology in Brazil: a review of pollen analysis of honeys, propolis and pollen loads of bees. Scientia Agricola, 61: 342-350. https://doi.org/10.1590/S0103-90162004000300018

Benadi, G. & Pauw, A. (2018). Frequency dependence of pollinator visitation rates suggests that pollination niches can allow plant species coexistence. Journal of Ecology, 106: 1892-1901. https://doi.org/10.1111/1365-2745.13025

Borges, R.C., Padovani, K., Imperatriz-Fonseca, V.L. & Giannini, T.C. (2020). A dataset of multi-functional ecological traits of Brazilian bees. Science Data, 7: 120. https://doi.org/10.1038/s41597-020-0461-3

Bortolus, A. (2008). Error cascades in the biological sciences: the unwanted consequences of using bad taxonomy in ecology. Ambio, 37: 114-118. https://doi.org/10.1579/0044-7447(2008)37[114:ECITBS]2.0.CO;2

BPBES/REBIPP (2019). Relatório Temático sobre Polinização, Polinizadores e Produção de Alimentos no Brasil. Wolowski, M., Agostini, K., Rech, A.R., Varassin, I.G., Maués, M., Freitas, L., Carneiro, L.T., Bueno, R.O., Consolaro, H., Carvalheiro, L., Saraiva, A.M., Silva, C.I., & Padgurschi, M.G.C. (Org.). 1ª edição, São Carlos, SP: Editora Cubo. 184 páginas.

Burdine, J.D. & McCluney, K.E. (2019). Differential sensitivity of bees to urbanization-driven changes in body temperature and water content. Scientific Reports, 9: 1643. https://doi.org/10.1038/s41598-018-38338-0

Campbell, A.J., Carvalheiro, L.G., Gastauer, M., Almeida-Neto, M. & Giannini, T.C. (2019). Pollinator restoration in Brazilian ecosystems relies on a small but phylogenetically-diverse set of plant families. Scientific Reports, 9: 17383. https://doi.org/10.1038/s41598-019-53829-4

Cardoso, P., Erwin, T.L., Borges, P.A.V., New, T.R. (2011). The seven impediments in invertebrate conservation and how to overcome them. Biological Conservation, 144: 2647-2655. https://doi.org/10.1016/j.biocon.2011.07.024

Carvalheiro, L.G., Barbosa, E.R.M. & Memmott, J. (2008). Pollinator networks, alien species and the conservation of rare plants: *Trinia glauca* as a case study. Journal of Applied Ecology, 45: 1419-1427. https://doi.org/10.1111/j.1365-2664.2008.01518.x

Carvalheiro, L.G., Seymour, C.L., Veldtman, R. & Nicolson, S.W. (2010). Pollination services decline with distance from natural habitat even in biodiversity-rich areas. Journal of Applied Ecology, 47: 810-820. https://doi.org/10.1111/j.1365-2664.2010.01829.x

Carvalheiro, L,G,, Veldtman, R., Shenkute, A.G., et al. (2011). Natural and within-farmland biodiversity enhances crop productivity. Ecology Letters, 14: 251-259. https://doi.org/10.1111/j.1461-0248.2010.01579.x

Carvalheiro, L.G., Kunin, W.E., Keil, P., Aguirre-Gutiérrez, J., Ellis, W.N., Fox, R., Groom, Q., Hennekens, S., Landuyt, W.V., Maes, D., de Meutter, F.V., Michez, D., Rasmont, P., Ode, B., Potts, S.G., Reemer, M., Roberts, S.P.M., Schaminée, J., WallisDeVries, M.F. & Biesmeijer, J.C. (2013). Species richness declines and biotic homogenisation have slowed down for NW-European pollinators and plants. Ecology Letters, 16: 870-878. https://doi.org/10.1111/ele.12121

Carvalheiro, L.G., Biesmeijer, J.C., Benadi, G., Fründ, J., Stang, M., Bartomeus, I., Kaiser-Bunbury, C.N., Baude, M., Gomes, S.I.F., Merckx, V., Baldock, K.C.R., Bennett, A.T.D., Boada, R., Bommarco, R., Cartar, R., Chacoff, N., Dänhardt, J., Dicks, L.V., Dormann, C.F., Ekroos, J., Henson, K.S.E., Holzschuh, A., Junker, R.R., Lopezaraiza-Mikel, M., Memmott, J., Montero-Castaño, A., Nelson, I.L., Petanidou, T., Power, E.F., Rundlöf, M., Smith, H.G., Stout, J.C., Temitope, K., Tscharntke, T., Tscheulin, T., Vilà, M. & Kunin, W.E. (2014). The potential for indirect effects between co-flowering plants via shared pollinators depends on resource abundance, accessibility and relatedness. Ecology Letters, 17:1389-1399. https://doi.org/10.1111/ele.12342

Chao, A., Henderson, P.A., Chiu, C-H., Moyes, F., Hu, K-H., Dornelas, M. & Magurran, A.E. (2021) Measuring temporal change in alpha diversity: A framework integrating taxonomic, phylogenetic and functional diversity and the iNEXT.3D standardization. Methods in Ecology and Evolution, 12: 1926-1940. https://doi.org/10.1111/2041-210X.13682

Chesshire, P.R., Fischer, E.E., Dowdy, N.J., Griswold, T.L., Hughes, A.C., Orr, M.C., Ascher, J.S., Guzman, L.M., Hung, K-L.J., Cobb, N.S. & McCabe, L.M. (2023). Completeness analysis for over 3000 United States bee species identifies persistent data gap. Ecography, 2023: e06584. https://doi.org/10.1111/ecog.06584

Colwell R.K., Chao, A., Gotelli, N.J., et al (2012). Models and estimators linking individual-based and sample-based rarefaction, extrapolation and comparison of assemblages. Journal of Plant Ecology, 5: 3-21. https://doi.org/10.1093/jpe/rtr044

Easton-Calabria, A.C., Thuma, J.A., Cronin, K., Melone, G., Laskowski, M., Smith, M.A.Y., Pasadyn, C.L., de Bivort, B.L. & Crall, J.D. (2023). Colony size buffers interactions between neonicotinoid exposure and cold stress in bumblebees. Proceedings of the Royal Society B, 290: 20230555. https://doi.org/10.1098/rspb.2023.0555

Elith, J., Graham, C.H., Anderson, R.P., Dudík, M., Ferrier, S., Guisan, A., Hijmans, R.J., Huettmann, F., Leathwick, J.R., Lehmann, A., Li, J., Lohmann, L.G., Loiselle, B.A., Manion, G., Moritz, C., Nakamura, M., Nakazawa, Y., Overton, J.McC.M., Peterson, A.T., Phillips, S.J., Richardson, K., Scachetti-Pereira, R., Schapire, R.E., Soberón, J., Williams, S., Wisz, M.S. & Zimmermann, N.E. (2006). Novel methods improve prediction of species' distributions from occurrence data. Ecography, 29: 129-151. https://doi.org/10.1111/j.2006.0906-7590.04596.x

Endres, K.L., Morozumi, C.N., Loy, X. et al. (2021). Plant-pollinator interaction niche broadens in response to severe drought perturbations. Oecologia, 197: 577-588. https://doi.org/10.1007/s00442-021-05036-0

Engel, M.S. & Dingemans-Bakels, F. (1980). Nectar and pollen resources for stingless bees (Meliponinae, Hymenoptera) in Surinam (South America). Apidologie, 11: 341-350. https://doi.org/10.1051/apido:19800402

Engel, M.S. (2022). Notes on south american stingless bees of the genus *Scaptotrigona* (Hymenoptera: Apidae), part III: A revised infrageneric classification and new species. Journal of Melittology, 111: 1-29. https://doi.org/10.17161/jom.i111.17013

Ferrari, R.R., Buschini, M.L.T., Diniz, M.E.R., Zhu, C-D. & Melo, G.A.R. (2022). Discovery of *Mourecotelles* (Hymenoptera, Apidae, Colletinae) in Brazil: Nesting biology and pollen preferences of a remarkable new species of the genus. Journal of Hymenoptera Research, 89: 211-31. https://doi.org/10.3897/jhr.89.77485

Ferreira, M.E., Ferreira, Jr. L.G., Latrubesse, E.M. & Miziara, F. (2016). Considerations about the land use and conversion trends in the savanna environments of central Brazil under a geomorphological perspective. Journal of Land Use Science, 11: 33-47. https://doi.org/10.1080/1747423X.2013.845613

Fliszkiewicz, M., Giejdasz, K., Wasielewski, O. & Krishnan, N. (2012). Influence of winter temperature and simulated climate change on body mass and fat body depletion during diapause in adults of the solitary bee, *Osmia rufa* (Hymenoptera: Megachilidae). Environmental Entomology, 41:1621-1630. https://doi.org/10.1603/EN12004

Franceschinelli, E.V., Morais, J.M., Bergamini, L.L., Assis, I.M., Paniago, L.G.F.R., Cardoso, M.D.T., Neto, C.M.S., Marcelo, V.G., Brito, P.V.A. & Carvalheiro, L.G. (2023). Experimental insecticide applications change tomato pollinator assemblages and do not increase fruit production. Agriculture, Ecosystems and Environment, 345: 108310. https://doi.org/10.1016/j.agee.2022.108310

Freitas, B.M., Imperatriz-Fonseca, V.L., Medina, L.M., Kleinert, A.M.P., Galetto, L., Nates-Parra, G. & Quezada-Euán, J.J.G. (2009). Diversity, threats and conservation of native bees in the Neotropics. Apidologie, 40: 332-346. https://doi.org/10.1051/apido/2009012

Galetto, L., Aizen, M.A., del Coro Arizmendi, M., Freitas, B.M., Garibaldi, L.A., Giannini, T.C., Lopes, A.V., Do Espírito Santo, M.M., Maués, M.M., Nates-Parra, G., Rodríguez, J.I., Quezada-Euán, J.J.G., Vandame, R., Viana, B.F., & Imperatriz-Fonseca, V.L. (2022). Risks and opportunities associated with pollinators' conservation and management of pollination services in Latin America. Ecología Austral, 32: 055-076. https://doi.org/10.25260/EA.22.32.1.0.1790

Gazzoni, D.L. (2021). Plantas que os polinizadores gostam. Brasília, DF: Embrapa, 1016p

Gérard, M., Guiraud, M., Cariou, B., Henrion, M. & Baird, E. (2023). Elevated developmental temperatures impact the size and allometry of morphological traits of the bumblebee *Bombus terrestris*. Journal of Experimental Biology, 226: 245728. https://doi.org/10.1242/jeb.245728

Giannini, T.C., Acosta, A.L., Garófalo, C.A., Saraiva, A.M., Alves-dos-Santos, I. & Imperatriz-Fonseca, V.L. (2012). Pollination services at risk: bee habitats will decrease owing to climate change in Brazil. Ecological Modelling, 244: 127-131. https://doi.org/10.1016/j.ecolmodel.2012.06.035

Giannini, T.C., Acosta, A.L., Silva, C.I. Oliveira, P.E.A.M., Imperatriz-Fonseca, V.L. & Saraiva, A.M. (2013). Identifying the areas to preserve passion fruit pollination service in Brazilian Tropical Savannas under climate change. Agriculture, Ecosystems & Environment, 171:39-46. https://doi.org/10.1016/j.agee.2013.03.003

Giannini, T.C., Tambosi, L.R., Acosta, A.L., Jaffé, R., Saraiva, A.M., Imperatriz-Fonseca, V.L., Metzger, J.P. (2015). Safeguarding Ecosystem Services: A methodological framework to buffer the joint effect of habitat configuration and climate change. Plos One, 10:e0129225. https://doi.org/10.1371/journal.pone.0129225

Giannini, T.C., Costa, W.F., Cordeiro, G.D., Imperatriz-Fonseca, V.L., Saraiva, A.M., Biesmeijer, J. & Garibaldi, L.A. (2017). Projected climate change threatens pollinators and crop production in Brazil. Plos One, 12: e0182274. https://doi.org/10.1371/journal.pone.0182274

Giannini, T.C., Costa, W.F., Borges, R.C., Miranda, L., da Costa, C.P.W., Saraiva, A.M & Imperatriz Fonseca, V.L. (2020). Climate change in the Eastern Amazon: crop-pollinator and occurrence-restricted bees are potentially more affected. Regional Environmental Change, 20: 9. https://doi.org/10.1007/s10113-020-01611-y

Gonçalves, R.B. & Pereira, F. W. (2022). New species of the cuckoo bee genus *Austrosphecodes* Michener, 1978 (Hymenoptera: Apoidea: Sphecodini) and a key for Brazilian species. European Journal of Taxonomy, 819: 55-89. https://doi.org/10.5852/ejt.2022.819.1777

Greenleaf, S.S., Williams, N.M., Winfree, R. & Kremen, C. (2007). Bee foraging ranges and their relationship to body size. Oecologia, 153: 589-596. https://doi.org/10.1007/s00442-007-0752-9

Grüter, C., & Hayes, L. (2022). Sociality is a key driver of foraging ranges in bees. Current Biology, 32: 5390-5397. https://doi.org/10.1016/j.cub.2022.10.064

Harano, K. & Hrncir, M. (2023) Big in the tropics - Are there thermal advantages of large body size for carpenter bees in hot climates? Ecological Entomology, 48:358-370. https://doi.org/10.1111/een.13230

Heinrich, B. (1993). The Hot-Blooded Insects. Springer Berlin Heidelberg, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-10340-1

Henríquez-Piskulich, P., Hugall, A.F. & Stuart-Fox, D. (2024). A supermatrix phylogeny of the world's bees (Hymenoptera: Anthophila). Molecular Phylogenetics and Evolution, 190: 107963. https://doi.org/10.1016/j.ympev.2023.107963

Hofmann, G.S., Cardoso, M.F., Alves, R.J.V., Weber, E.J., Barbosa, A.A., de Toledo, P.M., Pontual, F.B., Salles, L.O., Hasenack, H., Cordeiro, J.L.P., Aquino, F.E., Oliveira, L.F.B. (2021). The Brazilian Cerrado is becoming hotter and drier. Global Change Biology, 27: 4060-4073. https://doi.org/10.1111/gcb.15712

Hortal, J., de Bello, F., Diniz-Filho, J.A.F., Lewinsohn, T.M., Lobo, J.M. & Ladle, R.J. (2015). Seven shortfalls that beset large-scale knowledge of biodiversity. Annual Review of Ecology, Evolution, and Systematics, 46: 523-549. https://doi.org/10.1146/annurev-ecolsys-112414-054400

Hrncir, M., Maia-Silva, C., Teixeira-Souza, V.H.S. & Imperatriz-Fonseca, V.L. (2019). Stingless bees and their adaptations to extreme environments. Journal of Comparative Physiology A Neuroethology, Sensory, Neural, and Behavioral Physiology, 205: 415-426. https://doi.org/10.1007/s00359-019-01327-3

Huang, C., Zhou, Z., Peng, C., Teng, M. & Wang, P. (2019). How is biodiversity changing in response to ecological restoration in terrestrial ecosystems? A meta-analysis in China. Science of the Total Environment, 650: 1-9. https://doi.org/10.1016/j.scitotenv.2018.08.320

ICMBIO/Brasil (2022). Ministério do Meio Ambiente. Portaria MMA Nº 148, de 7 de junho de 2022. Altera os Anexos da Portaria nº 443, de 17 de dezembro de 2014, da Portaria nº 444, de 17 de dezembro de 2014, e da Portaria nº 445, de 17 de dezembro de 2014, referentes à atualização da Lista Nacional de Espécies Ameaçadas de Extinção. Available at: icmbio.gov.br/cepsul/images/stories/legislacao/Portaria/2020/P_mma_148_2022_altera_anexos_P_mma_443_444_445_2014_atualiza_especies_ameacadas_extincao.pdf. (accessed date: 22 July 2024).

Isaac, N.J.B., Mallet, J. & Mace, G.M. (2004). Taxonomic inflation: its influence on macroecology and conservation. Trends in Ecology and Evolution, 19: 464-469. https://doi.org/10.1016/j.tree.2004.06.004

Jarau, S., Hrncir, M., Schmidt, V.M., Zucchi, R. & Barth, F.G. (2003) Effectiveness of recruitment behavior in stingless bees (Apidae, Meliponini). Insectes Sociaux, 50: 365-374. https://doi.org/10.1007/s00040-003-0684-2

Kamke, R., Zillikens, A. & Steiner, J. (2011). Species richness and seasonality of bees (Hymenoptera, Apoidea) in a restinga area in Santa Catarina, southern Brazil. Studies on Neotropical Fauna and Environment, 46: 35-48. https://doi.org/10.1080/01650521.2010.538561

Kendall, L.K., Mola, J.M., Portman, Z.M., Cariveau, D.P., Smith, H.G. & Bartomeus, I. (2022). The potential and realized foraging movements of bees are differentially determined by body size and sociality. Ecology, 103: e3809. https://doi.org/10.1002/ecy.3809

Lázaro, A., Lundgren, R. & Totland, Ø. (2014) Experimental reduction of pollinator visitation modifies plant-plant interactions for pollination. Oikos, 123: 1037-1048. https://doi.org/10.1111/oik.01268

Leclercq, N., Marshall, L., Caruso, G., Schiel, K., Weekers, T., Carvalheiro, L.G., Dathe, H.H., Kuhlmann, M., Michez, D., Potts, S.G., Rasmont, P., Roberts, S.P.M., Smagghe, G., Vandamme, P. & Vereecken, N.J. (2023). European bee diversity: Taxonomic and phylogenetic patterns. Journal of Biogeography, 50: 1244-1256. https://doi.org/10.1111/jbi.14614

Lepeco, A. (2024). Contribution to the taxonomy of *Oxytrigona* Cockerell, 1917 (Apidae, Meliponini). Zootaxa, 5506: 369-395.

Lima, M.A.P., Martins, G.F., Oliveira, E.E. & Guedes, R.N.C. (2016). Agrochemical-induced stress in stingless bees: peculiarities, underlying basis, and challenges. Journal of Comparative Physiology A Neuroethology, Sensory, Neural, and Behavioral Physiology, 202: 733-747. https://doi.org/10.1007/s00359-016-1110-3

Mahlmann, T. (2020). A new species of the previously monotypic Neotropical cleptoparasitic bee genus *Rhynostelis*, with notes on *Rhynostelis multiplicata* (Hymenoptera: Megachilidae). Journal of Melittology, 96: 1-8. https://doi.org/10.17161/jom.vi96.13245

Mahlmann, T., Oliveira, F.F. & Oliveira, M.L. (2023). Taxonomy of South American species of *Ceratina* (*Calloceratina*) Cockerell, 1924 with comments on new species-groups proposed for this subgenus (Hymenoptera: Apidae: Xylocopinae). EntomoBrasilis, 16: e1062. https://doi.org/10.12741/ebrasilis.v16.e1062

Maia, U.M., Miranda, L.S., Carvalho, A.T., Imperatriz-Fonseca, V.L., Oliveira, G.C., Giannini, T.C. (2020). Climate-induced distribution dynamics of *Plebeia flavocincta*, a stingless bee from Brazilian tropical dry forests. Ecology and Evolution, 10: 10130-10138. https://doi.org/10.1002/ece3.6674

Maia-Silva, C., Silva, J.P., Freitas, B.M. & Hrncir, M. (2021). Don't stay out too long! Thermal tolerance of the stingless bees *Melipona subnitida* decreases with increasing exposure time to elevated temperatures. Apidologie, 52: 218-229. https://doi.org/10.1007/s13592-020-00811-z

Marshall, L., Biesmeijer, J. C., Rasmont, P., Vereecken, N. J., Dvorak, L., Fitzpatrick, U., ... & Dendoncker, N. (2018). The interplay of climate and land use change affects the distribution of EU bumblebees. Global Change Biology, 24: 101-116. https://doi.org/10.1111/gcb.13867

Marshall, L., Leclercq, N., Carvalheiro, L.G., Dathe, H.., Jacobi, B., Kuhlmann, M., Potts, S.G., Rasmont, P., Roberts, S.P.M. & Vereecken, N.J. (2024). Understanding and addressing shortfalls in European wild bee data. Biological Conservation, 290: 110455. https://doi.org/10.1016/j.biocon.2024.110455

Martins, L.P., Garcia-Callejas, D., Lai, H.R.,Wootton, K.L. & Tylianakis, J.M. (2024). The propagation of disturbances in ecological networks. Trends in Ecology and Evolution, 39: 558-570. https://doi.org/10.1016/j.tree.2024.01.009

Mateus, S. & Noll, F.B. (2004). Predatory behavior in a necrophagous bee *Trigona hypogea* (Hymenoptera; Apidae, Meliponini). Naturwissenschaften, 91: 94-96. https://doi.org/10.1007/s00114-003-0497-1

May, M.L. (1979). Insect Thermoregulation. Annual Review of Entomology, 24: 313-349. https://doi.org/10.1146/annurev.en.24.010179.001525

McGill, B.J., Enquist, B.J., Weiher, E. & Westoby, M. (2006). Rebuilding community ecology from functional traits. Trends in Ecology and Evolution, 21:178-185. https://doi.org/10.1016/j.tree.2006.02.002

Melo, G.A.R. (2022). A revised classification for the Neopasiphaeine line, with the description of new species of the bee tribe Lonchopriini (Apidae, Colletinae). Acta Biológica Paranaense, 51: e86600. https://doi.org/10.5380/abp.v51i1.86600

Melo, G.A.R. (2023). "*Lestrimelitta camposi*, uma nova espécie do grupo limao, com notas sobre as espécies do grupo e uma chave de identificação atualizada". In Estudos Sobre Abelhas e Vespas Brasileiras: uma homenagem ao Professor Lucio Campos edited by Helder Canto Resende, and Hugo de Azevedo Werneck. Viçosa: Universidade Federal de Viçosa. 35-48pp.

Memmott, J. (1999). The structure of a plant-pollinator food web. Ecology Letters, 2: 276-280. https://doi.org/10.1046/j.1461-0248.1999.00087.x

Memmott, J., Gibson, R.H., Carvalheiro, L.G., Heleno, R., Henson, K.S.E., Lopezaraiza-Mikel, M. & Pearce, S. (2008). The Conservation of Ecological Interactions. Insect Conservation Biology (eds A.J.A. Stewart, O.T. Lewis & T.R. New), CABI Publishing, Wallingford, UK, pp. 226-244. https://doi.org/10.1079/9781845932541.0226

Miraldo, A., Li, S., Borregaard, M.K., Flórez-Rodríguez, A., Gopalakrishnan, S., Rizvanovic, M., Wang, W., Rahbek, C., Marske, K.A. & Nogués-Bravo, D. (2016) An anthropocene map of genetic diversity. Science, 353: 1532-1535. https://doi.org/10.1126/science.aaf4381

Morris, R.J., Lewis, O.T & Godfray, H.C.J. (2004). Experimental evidence for apparent competition in a tropical forest food web. Nature, 428: 310-313. https://doi.org/10.1038/nature02394

Morozumi, C., Loy, X., Reynolds, V., Schiffer, A., Morrison, B., Savage, J. & Brosi, B. (2022). Simultaneous niche expansion and contraction in plant-pollinator networks under drought. Oikos, 2022: e09265. https://doi.org/10.1111/oik.09265

Moure, J.S., Urban, D. & Dal Molin, A. (2007). Catalogue of bees (Hymenoptera, Apoidea) in the neotropical region / Organized by Jesus Santiago Moure, Danúncia Urban, Gabriel A. R. Melo. - Curitiba : Sociedade Brasileira de Entomologia, 2007.xiv, 1058p. ISBN 978-85-85729-08-0

Moure, J.S., Urban, D. & Melo, G.A.R. (Orgs) (2022). Catalogue of Bees (Hymenoptera, Apoidea) in the Neotropical Region. https://www.moure.cria.org.br/catalogue (accessed date: 27 June 2024).

Muschett, G. & Fontúrbel, F.E. (2022). A comprehensive catalogue of plant-pollinator interactions for Chile. Scientific Data, 9: 78. https://doi.org/10.1038/s41597-022-01195-8

Nemésio, A., Santos, L.M. & Vasconcelos, H.L. (2015). Long-term ecology of orchid bees in an urban forest remnant. Apidologie, 46: 359-368. https://doi.org/10.1007/s13592-014-0328-8

Nieto, A., (2014). European Red List of Bees, IUCN: International Union for Conservation of Nature. European Commission, IUCN European Union Representative Office, IUCN Species Survival Commission (SSC), IUCN Species Survival Commission (SSC), Bumblebee Specialist Group.

Nogueira, D.S., Oliveira, F.F. & Oliveira, M.L. (2022a). Revision of the *Tetragona clavipes* (Fabricius, 1804) species-group (Hymenoptera: Apidae: Meliponini). Zootaxa, 5119: 1-64. https://doi.org/10.11646/zootaxa.5119.1.1

Nogueira, D. S., Santos-Silva, J.A., Carvalho, M.M., Carvalho-Zilse, G.A., Alves, R.M.O. & Oliveira, M.L. (2022b). Two new species of *Scaptotrigona* Moure,1942 from the Amazon Forest (Hymenoptera: Apidae: Meliponini). EntomoBrasilis, 15: (e985). https://doi.org/10.12741/ebrasilis.v15.e985

Oliveira, F.L., Dias, V.H.P., Costa, E.M., Filgueira, M.A., Sobrinho, J.E. (2012). Influência das variações climáticas na atividade de vôo das abelhas jandairas *Melipona subnitida* Ducke (Meliponinae). Revista Ciência Agronômica, 43: 598-603. https://doi.org/10.1590/S1806-66902012000300024

Oliveira, R.C., Menezes, C., Soares, A.E.E. & Fonseca, V.L.I. (2013). Trap-nests for stingless bees (Hymenoptera, Meliponini).

Apidologie, 44: 29-37. https://doi.org/10.1007/s13592-012-0152-y

Ollerton, J., Winfree, R. & Tarrant, S. (2011). How many flowering plants are pollinated by animals? Oikos, 120: 321-326. https://doi.org/10.1111/j.1600-0706.2010.18644.x

Ostwald, M.M., Fox, T.P., Hillery, W.S., Shaffer, Z., Harrison, J.F. & Fewell, J.H. (2022). Group-living carpenter bees conserve heat and body mass better than solitary individuals in winter. Animal Behaviour, 189: 59-67. https://doi.org/10.1016/j.anbehav.2022.04.012

Pereira, F.W., Goncalves, R.B. & Ramos, K.D.S. (2021). Bee surveys in Brazil in the last six decades: a review and scientometrics. Apidologie, 52: 1152-1168. https://doi.org/10.1007/s13592-021-00894-2

Peruquetti, R.C., Costa, L.D.S.M.D., Silva, V.S.D. & Drumond, P.M. (2010). Frugivory by a stingless bee (Hymenoptera: Apidae). Neotropical Entomology, 39: 1051-1052. https://doi.org/10.1590/S1519-566X2010000600033

Powell, A.H. & Powell, G.V.N. (1987). Population dynamics of male Euglossine bees in Amazonian forest fragments. Biotropica, 19: 176-179. https://doi.org/10.2307/2388742

Prado, I., Rocha, A., Silva, L. & Gonzalez, V. (2023) Glyphosate-based formulation affects *Tetragonisca angustula* worker's locomotion, behavior and biology. Ecotoxicology, 32: 1-12. https://doi.org/10.1007/s10646-023-02658-3

Ratnasingham, S. & Hebert, P.D.N. (2007). Bold: The barcode of life data system (http://www.barcodinglife.org). Molecular Ecology Notes, 7: 355-364. https://doi.org/10.1111/j.1471-8286.2007.01678.x

REBIPP (Rede Brasileira De Pesquisas Em Biodiversidade E Ecologia De Interações Plantas-Polinizadores). (2024). Available at: http://db.rebipp.org.br/. (accessed date: 22 July 2024).

Ribeiro, T.M.A., Martins, A.C., Silva, D.P. & Aguiar, A.J.C. (2021). Systematics of the oil bee genus *Lanthanomelissa* (Apidae: Tapinotaspidini) and its implications for the biogeography of South American grasslands. Journal of Zoological Systematics and Evolutionary Research, 59: 1013-1027. https://doi.org/10.1111/jzs.12472

Ribeiro, C.F., Nogueira, D.S., de Oliveira, F.F. & de Oliveira, M.L. (2023). Review of *Trigona* (Nostotrigona) Engel, 2021 from Brazil with description of three new species (Hymenoptera: Apidae: Meliponini). Zootaxa, 5306: 349-366. https://doi.org/10.11646/zootaxa.5306.3.3

Ribeiro, C.F., Nogueira, D.S., De Oliveira, F.F. & De Oliveira, M.L. (2024). Two new species of *Trigona* Jurine, 1807 with an illustrated key for the species occurring in Brazil (Hymenoptera: Apidae: Meliponini). Zootaxa, 5458: 524-546. https://doi.org/10.11646/zootaxa.5458.4.3

Romanelli, J.P., Meli, P., Santos, J.P.B., Jacob, I.N., Souza, L.R., Rodrigues. A.V., Trevisan, D.P., Huang, C., Almeida, D.R.A., Silva, L.G.M., Assad, M.L.R.C.L., Cadotte, M.W., & Rodrigues, R.R. (2022). Biodiversity responses to restoration across the Brazilian Atlantic Forest. Science of the Total Environment, 821: 153403. https://doi.org/10.1016/j.scitotenv.2022.153403

Santos, C.F., Menezes, C., Vollet-Neto, A. & Imperatriz-Fonseca, V.L. (2014). Congregation sites and sleeping roost of male stingless bees (Hymenoptera: Apidae: Meliponini). Sociobiology, 61: 115-118. https://doi.org/10.13102/sociobiology.v61i1.115-118

Santos, R.M. (2021). A new species of the genus *Augochloropsis* Cockerell 1897 (Halictidae, Augochlorini) from northeast Brazil, and a key to species from the Bahia state. Holotipus, 2 (2). https://doi.org/10.53561/IRGI9543

Schlindwein, C. (1998). Frequent oligolecty characterizing a diverse bee-plant community in a xerophytic bushland of subtropical Brazil. Studies on Neotropical Fauna and Environment, 33: 46-59. https://doi.org/10.1076/snfe.33.1.46.2168

Sexton, A.N., Emery, S.M. (2020). Grassland restorations improve pollinator communities: a meta-analysis. Journal of Insect Conservation, 24: 719-726. https://doi.org/10.1007/s10841-020-00247-x

Silva, F.S. & Rebêlo, J.M.M. (2002). Population dynamics of Euglossinae bees (Hymenoptera, Apidae) in an early second-growth forest of Cajual Island, in the State of Maranhão, Brazil. Brazilian Journal of Biology, 62: 15-23. https://doi.org/10.1590/S1519-69842002000100003

Silva, D. P., Gonzalez, V. H., Melo, G. A., Lucia, M., Alvarez, L. J. & De Marco Jr, P. (2014). Seeking the flowers for the bees: integrating biotic interactions into niche models to assess the distribution of the exotic bee species *Lithurgus huberi* in South America. Ecological Modelling, 273: 200-209. https://doi.org/10.1016/j.ecolmodel.2013.11.016

Silva, E., Naji, W., Salvaneschi, P., et al (2023). Prioritizing areas for ecological restoration: A participatory approach based on cost-effectiveness. Journal of Applied Ecology, 60: 1194-1205. https://doi.org/10.1111/1365-2664.14395

Silveira, F.A., Melo, G.A.R. & Almeida, E.A.B. (2002). Abelhas brasileiras: sistemática e identificação, 1. ed. Silveira, Belo Horizonte.

Siopa, C., Carvalheiro, L.G., Castro, H., Loureiro, J. & Castro, S. (2024). Animal-pollinated crops and cultivars - A quantitative assessment of pollinator dependence values and evaluation of methodological approaches. Journal of Applied Ecology, 61: 1279-1288. https://doi.org/10.1111/1365-2664.14634

Strassburg, B.B.N., Brooks, T., Feltran-Barbieri. R., Iribarrem, A., Crouzeilles, R., Loyola, R., Latawiec, A.E., Filho, F.J.B.O., Scaramuzza, C.A.M., Scarano, F.R., Soares-Filho, B. & Balmford, A. (2017). Moment of truth for the Cerrado hotspot. Nature Ecology and Evolution, 1: 1-3. https://doi.org/10.1038/s41559-017-0099

Suding, K.N., Lavorel, S., Chapin III, F.S., Cornelissen, J.H.C., Díaz, S., Garnier, E., Goldberg, D., Hooper, D.U., Jackson, S.T. & Navas, M-L. (2008) Scaling environmental change through the community-level: a trait-based response-and-effect framework for plants. Global Change Biology, 14: 1125-1140. https://doi.org/10.1111/j.1365-2486.2008.01557.x

Tavares, M.G., Almeida, B.S., Passamani, P.Z., Paiva, S.R., Resende, H.C., Campos, L.A.O., Alves, R.M.O & Waldschmidt, A.M. (2013). Genetic variability and population structure in *Melipona scutellaris* (Hymenoptera: Apidae) from Bahia, Brazil, based on molecular markers. Apidologie, 44: 720-728. https://doi.org/10.1007/s13592-013-0220-y

Tosta, T.H.A., Silveira, G.C., Schiavini, I., Sofia, S.H. & Augusto, S.C. (2017). Using short-term surveys and mark-recapture to estimate diversity and population size of orchid bees in forest formations of the Brazilian savanna. Journal of Natural History, 51: 391-403. https://doi.org/10.1080/00222933.2016.1274441

Urban, D. & Melo, G.A.R. (2024). Antonapis gen. nov., espécies novas e notas sobre Eucerini neotropicais (Hymenoptera, Apidae) Antonapis gen. nov., new species and notes on neotropical Eucerini. Acta Biológica Paranaense, 53: e97250.

Vanderplanck. M., Martinet, B., Carvalheiro, L.G., Rasmont, P., Barraud, A., Renaudeau, C. & Michez, D. (2019). Ensuring access to high-quality resources reduces the impacts of heat stress on bees. Scientific Reports, 9: 12596. https://doi.org/10.1038/s41598-019-49025-z

Vaudo, A.D., Tooker, J.F., Grozinger, C.M. & Patch, H.M. (2015). Bee nutrition and floral resource restoration. Current Opinion in Insect Science, 10: 133-141. https://doi.org/10.1016/j.cois.2015.05.008

Vereecken, N.J., Weekers, T., Leclercq, N., Greef, S.D., Hainaut, H., Molenberg, J-M., Martin, Y., Janssens, X., Noël, G., Pauly, A., Roberts, S.P.M. & Marshall, L. (2021a). Insect biomass is not a consistent proxy for biodiversity metrics in wild bees. Ecological Indicators, 121: 107132. https://doi.org/10.1016/j.ecolind.2020.107132

Vereecken, N.J., Weekers, T., Marshall, L., D'Haeseleer, J., Cuypers, M., Pauly, A., Pasau, B., Leclercq, N., Tshibungu, A., Molenberg, J-M. & Greef, S.D. (2021b). Five years of citizen science and standardised field surveys in an informal urban green space reveal a threatened Eden for wild bees in Brussels, Belgium. Insect Conservation and Diversity, 14: 868-876. https://doi.org/10.1111/icad.12514

Viana, B.F., Kleinert, A.M.P., & Imperatriz-Fonseca V.L. (1997). Abundance and Flower Visits of Bees in a Cerrado of Bahia, Tropical Brazil. Studies on Neotropical Fauna and Environment, 32: 212-219. https://doi.org/10.1080/01650521.1997.11432424

Vivallo, F. (2022a) The oil-collecting bees of *Centris* (Aphemisia)/(Schisthemisia) (Hymenoptera: Apidae). Rio de Janeiro: Author's edition, xiii+ 281 p. ISBN: 978-65-00-51221-2

Vivallo, F. (2022b). The oil-collecting bees of *Centris* (Melanocentris) (Hymenoptera: Apidae). Rio de Janeiro: Author's Editions, xix+ 514p. ISBN: 978-65-00-43381-4

Werneck, H.A. (2023). "Descrição de uma nova espécie do genêro *Plebeia* Schwarz, 1938 do Acre-Brasil (Apidae-Meliponini)". In Estudos Sobre Abelhas e Vespas Brasileiras: uma homenagem ao Professor Lucio Campos edited by Helder Canto Resende, and Hugo de Azevedo Werneck, 257-260. Viçosa: Universidade Federal de Viçosa.