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REVIEW

Predicting Climate Change Impacts on Crop Pollinators in Brazil

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Abstract
Pollinators are critical elements of biodiversity as they participate in the reproduction of plant species. Due to their importance in food production, they are one of the most studied groups of ecosystem service providers globally. However, climate change poses a significant threat to this important service delivered to agriculture. We aim to summarize the main advances in Brazilian research on crop pollinators under climate change in the last years, emphasizing future impact predictions. To analyze the effects of climate change on agricultural pollinators, structured data on pollinators and crop species were organized, which also allowed advances in the structuring of data related to the dependence of Brazilian crops on pollinators, as well as determining the value of the pollination service for agriculture. Studies analyzed here cover the following issues: [1] interaction networks; [2] crop pollinators, crop dependence, and pollination service valuation; and [3] climate change impacts. We also present ten recommendations to foster further initiatives related to crop pollinators under climate change.

Introduction

Pollinators play a crucial role in plant reproduction and food production, establishing a clear link between biodiversity and human well-being. Protecting pollinators is an essential activity that paves the way for sustainable development, helping to safeguard nature, economy, and society. Pollination is key to food production worldwide, as 75% of crops depend to some degree on pollinators (Klein et al., 2007). The value of global crop pollination services was estimated to range from US$ 195 to ~ US$ 387 billion annually, depending on the estimation methods (Porto et al., 2020). Additionally, animal-pollinated crops are crucial to nutrition quality since they provide a considerable variety of nutrients (e.g., lipids, vitamins, folic acid, and minerals) (Eilers et al., 2011). Moreover, the quality of fruits is also enhanced with pollination since fruits present a better shape, color, and flavor (Bashir et al., 2018; Wietzke et al., 2018), nutritional value (Porto et al., 2021; Semba et al., 2022), and shelf life (Klatt et al., 2014), contributing to their market value and enhancing the profit of farmers. The production of seeds for non-permanent crops, such as vegetables, is also an essential asset to farmers, delivered by effective pollination services (Feuerbacher et al., 2024). However, the pollination deficit

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hinders pollinator-dependent crop yield growth, reducing the temporal stability of global agricultural production (Garibaldi et al., 2011; Reilly et al., 2020). Further, climate change has a decisive role in pollination, and pollinators decline since pollinators and flowers depend on climate on large extension (IPBES, 2016; Potts et al., 2016; Dicks et al., 2021; Cordeiro & Dötterl, 2023a and b).

Climate change causes globally unequal impacts, affecting more heavily low-income countries, with reduced or slow capabilities to adapt, hindering their economic development (Taconet et al., 2020; IPCC, 2022), and jeopardizing food security mainly in areas currently facing hunger and undernutrition (Wheeler & Von Braun, 2013). Tropical developing countries like Brazil, with different biomes, mega-diverse regions, and widespread knowledge gaps (Carvalho et al., 2023), need robust basic research initiatives to anticipate the impact of climate change on pollinators and food production. We summarize here the main advances in Brazilian research related to crop pollinators under climate change, emphasizing future forecasting since the first Brazilian publications on this issue. In the first section, we address studies related to interaction networks, emphasizing crop-pollinator interactions. Secondly, we summarize the main Brazilian studies about crop pollinators, crop dependence, and pollination services valuation. In the third section, we present the leading publications about climate change impact, emphasizing the predictions of future impact using species distribution modeling. Finally, we present ten recommendations to foster further initiatives related to crop pollinators under climate change.

Interaction networks

Interactions between plants and their pollinators form complex networks with well-documented standard features (Bascompte & Jordano, 2007). One of them is the presence of a core of generalist species, which dominates most of the interacting links, connecting otherwise unconnected subnetworks and helping to maintain the network (Gonzalez et al., 2010). The other feature is that some species act as specialists, usually interacting with generalists; they are potentially less able to adapt to global changes as they depend on few partners (Bogusch et al., 2020). It is important to emphasize that not all insect-flower interactions result in pollination and may consist only of visits to collect resources, such as pollen, nectar, or resin. Thus, pollination effectiveness is determined by specific experiments that usually investigate the pollinator behavior on the flower, demonstrating the effective pollen deposition on the floral reproductive organs. Considering crop pollination globally, previous studies showed that *Apis mellifera* L., a well-known generalist pollinator, introduced in many countries (Moritz et al., 2005), and wild insects contribute similarly to crop yields, emphasizing the importance of pollinator diversity (Garibaldi et al., 2013; Reilly et al., 2024). However, they can also negatively impact native bee species, as already demonstrated for *Apis mellifera* in interaction networks of natural areas (Valido et al., 2019; Ropars et al., 2022). Generalist species usually exhibit strong dominance within bee communities, with implications for overall abundance and species richness (Garibaldi et al., 2021). Thus, understanding the role of each species in interaction networks is an important step in designing effective decision-making for species protection, conservation, and habitat restoration programs.

For Brazilian bee-plant interaction networks, the role of *Apis mellifera* and *Trigona spinipes* Fabricius as super-generalists was demonstrated based on 21 interaction networks from different habitats, including natural and urban (Kleinert & Giannini, 2012; Santos et al., 2012; Giannini et al., 2015a). *Apis mellifera* is an exotic species in Brazil, whereas *Trigona spinipes* is a native stingless bee (Pedro, 2014). Both are well adapted to modified environments, prevalent in many areas (Giannini et al., 2015a; Jaffe et al., 2016). Furthermore, they are important pollinators for Brazilian crops that are highly dependent on pollinators and have a high annual production rate (Giannini et al., 2020a). Another study analyzing 15 Brazilian networks highlighted some specialist bees, such as oil bees (*Centris)* and bumblebees (*Bombus)* (Apidae) (Raiol et al., 2021). Both genera are important crop pollinator bees in Brazil (Giannini et al., 2020a). Nevertheless, other studies are still necessary to encompass the rich biodiversity of bees in the country (Schlindwein, 2004).

Regarding plants, a study examined the role of foraging plants in the Brazilian interaction networks and showed the importance of certain families of plants that support the interaction networks (Campbell et al., 2019). The most generalist ones, i.e., those that interact with many species of bees as food resources, are species of Malpighiaceae and Euphorbiaceae. Such information is important for restoration programs, which can prioritize key plant species to foster the recovery of interaction networks.

Other studies in Brazil also showed the use of pollen to analyze networks, highlighting the foraging bee species that visit plant species specifically for Eastern Amazon restoration, emphasizing trees whose importance for bees is not easily recognized using traditional sampling methods, such as entomological nets, due to the canopy height (Romeiro et al., 2023). Additionally, the foraging plants that provide food for passion fruit pollinators were also reported, a piece of important information for crop management, as passion fruit essentially depends on pollinators for fruit production (Silva et al., 2010; Giannini et al., 2013a). The first article quoted here (Romeiro et al., 2023) also highlighted the importance of biological collections as a data source on interactions since the data were retrieved from pollen adhered to the specimens' bodies during pollen transportation. Another article using data located at the biological collections analyzed the floral preferences of *Xylocopa* species, using the information presented on the specimens' labels about the plants where the bee species were collected (Ferreira et al., 2023).

Crop pollinators, crop dependence, and pollination services valuation

Brazil's first structured database on crop pollinators was published in 2015 (Giannini et al., 2015b). This study identified the reported pollinators for 85 crop species, including bees (Apidae), the most quoted pollinators. A second study, published in the same year, evaluated the dependence of 141 crops on pollinators, showing that 60% of them have some degree of pollinator dependence (Giannini et al., 2015c). This last article also showed that more than 40 plant species had not yet been assessed regarding their pollinator dependence. Brazil's central-western and northern regions presented the highest lack of information on the subject.

Despite the effort, both quoted studies likely underrepresent the diversity of plants and pollinators. Evidence of this is that recently, an assessment carried out exclusively for the Brazilian Amazon forest listed more than 180 plant species used by local communities as food (among other uses) (Paz et al., 2021). This assessment emphasizes that Brazil has a great diversity of plants used by the population, which are not included in the public database provided by the Brazilian Institute of Geography and Statistics (IBGE), the national public repository of agriculture data.

The importance of more than 250 pollinator species for Brazilian crops was highlighted in 2015 (Giannini et al., 2015b), and more recently, a second study drew attention to the fourteen bee species that have the highest number of interactions, which pollinate crops that are highly dependent on pollinators and that have significant production value (Giannini et al., 2020a). This latter study shows the important role of solitary species (especially oil and carpenter bees), social stingless bees, and bumblebees, as well as the current scarce knowledge about the management of species with potential for crop pollination. For example, a few Brazilian native solitary bees have been tested for management, such as oil bees (*Centris analis* Lepeletier, A. L. M. 1841), carpenter bees (*Xylocopa frontalis* Olivier, 1789), and orchid bees (*Eulaema nigrita* Lepeletier, 1841). A low number of social stingless bees are managed at a large scale (e.g., *Melipona quadrifasciata* Lepeletier, 1836 and *Tetragonisca angustula* Latreille, 1811). A new study in Brazil discussed bees management practices of eleven crop-pollinator bee species, including one species of *Centris* (*Centris analis*), two *Xylocopa* species (*Xylocopa frontalis* e *Xylocopa grisescens* Lepeletier, 1841), and three stingless bees (*Melipona subnitida* Ducke, 1910, *Scaptotrigona* aff. *depilis* Moure, 1942, and *Plebeia flavocincta* Cockerell, 1912) (Freitas & Bezerra, 2024). Another study provided the interacting crop pollinator species list related to 191 crops (Wolowsky et al., 2019).

The first Brazilian assessment that analyzed the value of crop pollination service resulted in a figure of around 12 billion dollars per year based on 141 crops (the year 2013; nearly 42 billion reais considering the currency value at the time) (Giannini et al., 2015c), which corresponded to approximately one-third of the total agricultural production for that year. Almost half of this value was due to soybean (nearly US$ 5.7 bi; 47%), followed by coffee. An impressive higher value of pollination service was obtained recently based on 199 Brazilian crops (around US$ 41 billion for the year 2021), where soybean accounts for nearly US$ 31 billion (71%), followed by coffee (Oliveira et al., 2024). When comparing this latest article with the first published one (Giannini et al., 2015c), the increase in the pollination service value for soybean in Brazil over the eight years analyzed (2013-2021) stands out since it has almost quintupled, following the same increase of production value of soybeans produced in the country in the same period (from approximately R$ 68 bi on 2013 to R$ 340 bi on 2021) (IBGE, 2024).

Explicitly considering the Brazilian Amazon rainforest, three recent assessments analyzed the value of pollination services. The first one analyzed the data for the state of Pará, in the eastern Amazon, demonstrating that 983.2 million dollars per year correspond to the pollinators' contribution to agriculture, considering the annual production of 2016, most of it due to açai (64%) followed by cocoa (Borges et al., 2020a). The second, analyzing specifically crop production associated with agroforests, showed that the value of pollination service was US$ 156 million (year 2017), most of it due to açai (82%) followed by Brazilian nut (Sabino et al., 2022). Finally, analyzing only the crop production related to Brazilian Amazon native palm trees, the value of pollination service obtained was US$144.2 million (year 2017), most of it due to açai (92%) followed by babassu (Ferreira et al., 2024).

We also noticed that in the state of Pará, few crops are cultivated on a relatively larger scale (mainly açai and cocoa) (Borges et al., 2020) and are highly dependent on pollinators (Campbell et al., 2018, 2022; Toledo-Hernandez et al., 2017, 2023). On the other hand, there is a wide variety of plants used by traditional communities in the Amazon (Paz et al., 2021; Coradin et al., 2022) that are not being monitored (i.e., not included in the official agricultural database), which may represent a significant opportunity for food diversification and security, especially in the face of adverse climate change scenarios for bees in the eastern Amazon (Giannini et al., 2020b). We reinforce that all the above-mentioned studies relied on data from annual agricultural production retrieved from IBGE. However, this database does not contain some crops (especially the regional ones), which hinders a more realistic evaluation. Moreover, the dependence rate of some cultivars needs to be determined to evaluate crop pollination service more accurately (Siopa et al., 2024). Concerning other Brazilian biomes, there is still no specific assessment of the value of pollination services and the dependence of regional crops on pollinators.

Another aspect that deserves to be mentioned is that besides the well-known importance of bees as crop pollinators globally (Potts et al., 2016), other animals also play a significant role. A global study showed that non-bee insects, such as flies, wasps, beetles, and butterflies, are efficient pollinators, providing 39% of visits to crop flowers and playing a significant role in global crop production (Rader et al., 2016). For example, flies (Diptera) are likely the primary pollinators of cocoa in tropical regions (Toledo-Hernandez et al., 2017, 2023). Beetles are key pollinators of Amazonian native palm trees (Ferreira et al., 2024). Other insects, such as moths and vertebrate species (bats), are likely important pollinators of Amazonian plant species used by local people (Paz et al., 2021). Recent evaluations that examined the potential pollinator species that have not yet been reported showed that the neglected diversity of crop pollinators in Brazil includes insects and vertebrates, indicating that many plant-pollinator interactions are still entirely unknown (Lopes et al., 2021; Carvalheiro et al., 2024).

Climate change impact

One of the biggest current challenges for biodiversity is the ongoing climate change. In particular, the impact of pollinators deserves to be highlighted due to their essential role in plant reproduction and, consequentially, in habitat maintenance and food production. Physiological and phenological differences among different bee and plant species and their trophic and geographic niche breadth could be differentially affected by climate change, potentially resulting in behavioral changes and mismatches (Cariveau & Winfree, 2015). Hence, long-term monitoring of pollinators and their interactive partners is paramount. Moreover, experiments related to thermal tolerance are also important, and some Brazilian bees, such as *Melipona subnitida*, have already been examined, showing that critical thermal maxima are 40 °C when individuals have access to water and 38.6 °C without water supply (Silva et al., 2017; Hrncir et al., 2019). However, at external temperatures above 30 °C, bees cannot compensate for the high heat gain in some areas of the body, causing an excessive increase in temperature in these areas (Souza-Junior et al., 2020). A decrease in the duration of pollen foraging with increasing external temperature was also demonstrated for *M. subnitida* (Maia-Silva et al., 2021). In addition, pioneering articles have already analyzed the influence of temperature on the external activity of stingless bee species. High temperatures negatively influenced the number of pollen loads collected by *Melipona rufiventris* Lepeletier, 1836 (Fidalgo & Kleinert, 2010). Months with higher temperatures and lower relative humidity also presented the lowest number of Apoidea specimens collected in a field experiment (Oliveira et al., 2010). The intranidal behavior is also affected by temperature, impacting positively the bees' activity and involucrum production of *Friesella schrottkyi* (Friese, 1900) (Lima et al., 2010), as well the rate of brood cell production of *Nannotrigona testaceicornis* (Lepeletier, 1836) (Vollet-Neto et al., 2011).

The computational tool called Species Distribution Modeling (SDM) can be used to forecast the impact of climate change on species range area. By employing various algorithms, this tool utilizes data on the species records and environmental variables (as predictors) to project/extrapolate areas suitable for species occurrence. SDM requires the definition of the species list that will be evaluated and the availability of multiple spatially unique and well-curated occurrence points. There is still a major challenge ahead, especially when considering sampling sites such as the tropical regions since the lack of knowledge on bee occurrences can sometimes hinder the application of SDMs. However, significant efforts are being made to share data on bees using international protocols for data standardization (e.g., Darwin Core; Wieczorek et al., 2012), including data on occurrence points (e.g., GBIF), functional traits (e.g., Borges et al., 2020b) and interactions (Salim et al., 2022). Many examples of publicly shared data are growing on the subject, such as WorldFAIR Agricultural Biodiversity (https://worldfair-project.eu/agricultural-biodiversity/). Citizen science for interaction data also offers an important alternative, such as the Brazilian 'Guardiões da Chapada' (https://sibbr.gov.br/cienciacidada/guardioesdachapada.html). Including Indigenous and local knowledge related to applied ecosystem research is paramount (McElwee et al., 2020), especially considering the robust knowledge of traditional communities about bees from Brazil (Posey, 1982; Santos & Antonini, 2008; Imperatriz-Fonseca, 2020). Considering the predictors, data on environmental variables may include land use – land cover through satellite images, such as those from the Mapbiomas project, or vegetation structure, soil, or even the most commonly used bioclimatic data derived from the monthly values of temperature and precipitation (WorldClim version 2.1, Fick and Hijmans 2017). Global Circulation Models (GCM) and the future period must be determined to perform future predictions. Currently, several GCMs are available, based on the Coupled Model Inter-comparison Project Phase 6 (CMIP 6), which considers a set of different Shared Socioeconomic Pathways and different future periods (available at https://worldclim.org/). Data must consider the FAIR (Findable, Accessible, Interoperable, Reusable; Wilkinson et al., 2016) and CARE (Collective Benefit, Authority to Control, Responsibility, Ethics; Gupta et al., 2023) principles. Enhancements to the methodological approaches of SDM were developed in Brazil, including data on interactive plants to model pollinators (or biotic data) (Giannini et al., 2013a, 2013b, 2017b) and developing new strategies to identify priority zones for conservation under climate change (Acosta et al., 2024).

Once the database about crop pollinators was structured, as described in the previous sections, it was possible to develop studies related to the impact of climate change on Brazilian crop pollinators; thus, some progress has been made in the last few years (Figure 1). In 2012, the two first studies analyzed species of bees quoted as crop pollinators, showing that in addition to the potential reduction of suitable habitats, climate change could cause habitat fragmentation, with deleterious consequences for pollinator populations (Giannini et al., 2012a, b). Crops highly dependent on pollinators deserve even greater attention, such as passion fruit, whose flowers are

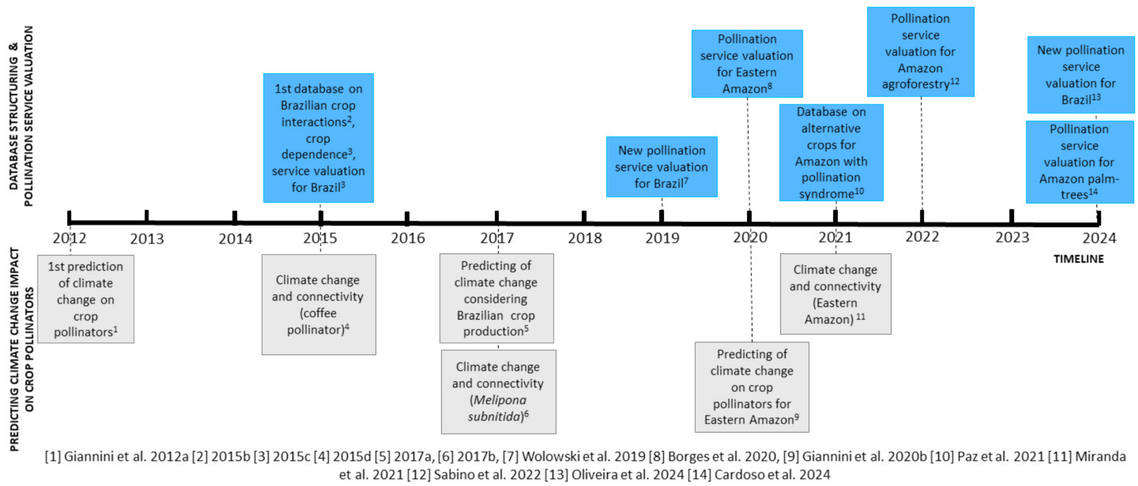

Fig 1. Main Brazilian crop pollinator studies, with emphasis on climate change impact predictions. [1] Giannini et al., 2012a, [2] 2015b [3] 2015c [4] 2015d [5] 2017a [6] 2017b, [7] Wolowski et al., 2019, [8] Borges et al., 2020, [9] Giannini et al., 2020b, [10] Paz et al., 2021, [11] Miranda et al., 2021, [12] Sabino et al., 2022, [13] Oliveira et al., 2024, and [14] Cardoso et al., 2024.

pollinated mainly by species of carpenter bees (*Xylocopa*), which in turn depend on other plant species for pollen (i.e., female bees of this genus only collect nectar and only in the passion fruit flowering season). Thus, the impact of climate change was projected, considering the species of *Xylocopa* and the plants that these species visit in areas of the Cerrado biome. It pointed out the negative changes in the suitability of bee occurrence areas in future scenarios (Giannini et al., 2013a), directly affecting decision-making regarding passion fruit production. Another study also analyzed the impact of climate change on passion fruit and *Xylocopa* species in Brazil, predicting a potential reduction of area suitability and in the overlapping area of bees and passion fruit (Bezerra et al., 2019). More recently, other *Xylocopa* species occurring in Maranhão state (northeast Brazil) were also analyzed using SDM (Ferreira et al., 2024). Stingless bees, another important group for crop pollination in Brazil, will also potentially face severe impacts related to climate change (Marchioro et al., 2020; Lima & Marchioro, 2021). Species of bumblebees (*Bombus*), another important group of crop pollinators, were also predicted to be threatened by climate change in Brazil (Martins & Melo, 2010; Martins et al., 2015; Françoso et al., 2018; Krechemer & Marchioro, 2020).

The impacts of climate change on pollinators of thirteen Brazilian crops showed that many municipalities that currently produce these crops may face pollinator deficits in the future, potentially leading to declines in production and a reduction in the national Gross Domestic Product (GDP) (Giannini et al., 2017a). Especially for the eastern Amazon Forest, bees that pollinate crops and species with a more restricted geographical distribution will potentially be the most affected (Giannini et al., 2020b). The loss of species with small distribution areas is particularly worrying because they are potentially the primary pollinators of plants with more regional interest, which local indigenous peoples and other local communities often use. However, other studies showed that bees in the hottest areas of the Brazilian dry forest (caatinga biome) could potentially face a smaller loss of suitable areas in the future (Giannini et al., 2017b; Maia et al., 2020). For the eastern Amazon Forest, previous studies addressed the impact of climate change on bats (Costa et al., 2018) and birds (Miranda et al., 2019), considering their role as pollinators and also as seed dispersals, and pest control, showing a significant reduction of climate suitability on most of the study area for the analyzed species. However, a significant knowledge gap about species occurrence remains a major challenge in predicting climate change effects on them. For example, ten of the above-mentioned articles (Acosta et al., 2024; Maia et al., 2020; Giannini et al., 2012a,b, 2013a,b, 2015d, 2017a,b, 2020b) used SDM to forecast Brazilian climate change impact on 271 bee species (Supplementary Material A). However, the available occurrence points of these species do not equally cover all biomes and show evident geographical bias (i.e., concentrating points in some specific locations and other regions with sampling gaps) (Figure 2, Supplementary Material A).

Other Brazilian crops have been studied during these last twelve years about the impacts of climate change. Evidence related to the vulnerability of cocoa trees showed high cocoa tree mortality, a decrease in cocoa yield, and an increased infection rate by chronic fungal disease under severe drought (Gateau-Rey et al., 2018). Modeling climate change impact on cocoa distribution showed a likely reduction in the suitability of cocoa production in the Brazilian Amazon biome, potentially resulting in a decrease in the suitable areas for this crop (Igawa et al., 2022). The local perception of açai farmers was also evaluated concerning climate change impacts, showing that they have reported a decrease in production in hot years, associating this climatic event with failures in fruit development (Tregidgo et al., 2020). As for

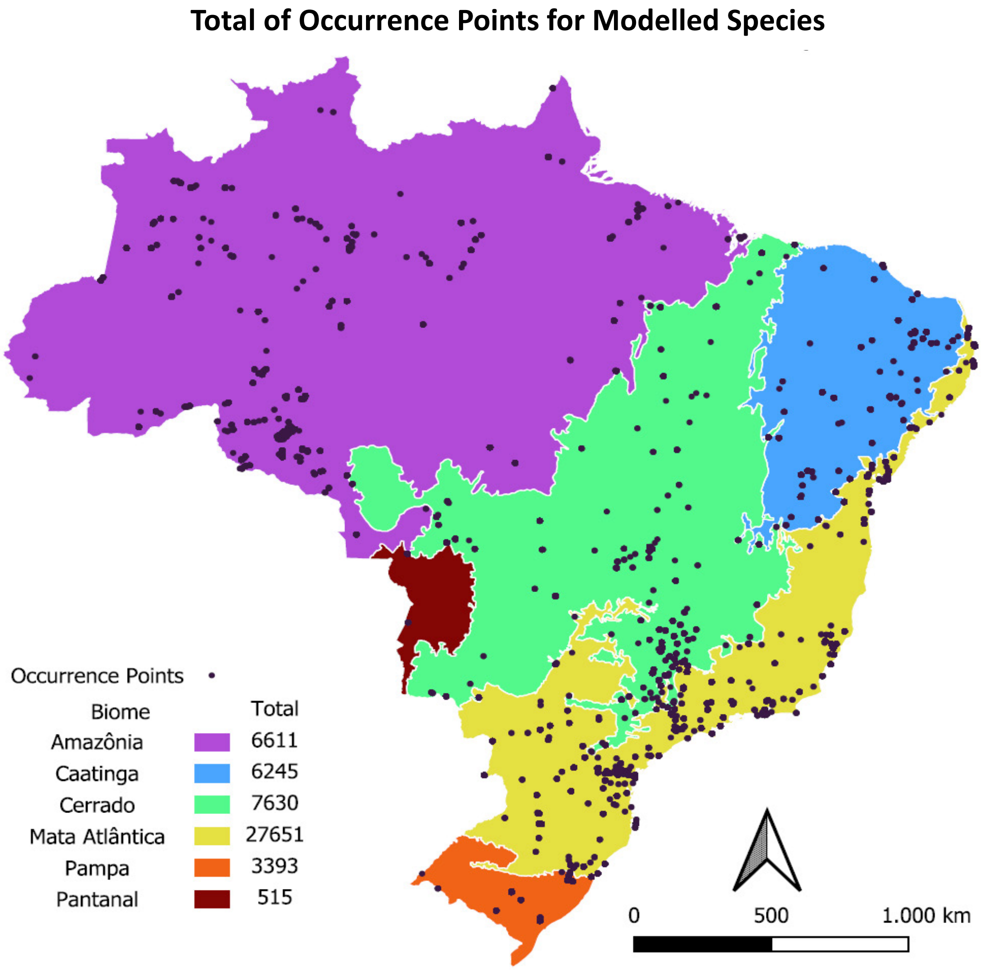

Fig 2. Occurrence points of Brazilian crop pollinators used to analyze climate change impact with species distribution modeling, considering ten articles (Acosta et al., 2024; Giannini et al., 2012a,b, 2013a,b, 2015d, 2017a,b, 2020; Maia et al., 2020) and 271 bee species (Supplementary Material A).

crop pollinators, a study showed that tomato pollinators can be severely affected by climate change, with potential mismatches between crops and bees in suitable areas in the future (Elias et al., 2017). The pollinators of Brazilian nuts could lose up to 50% of their suitable distribution areas in the future, reducing their co-occurrence with the plant and likely affecting local pollinators' richness (Sales et al., 2021).

Two other important issues associated with the effects of climate change are related to the asynchrony between plants, pollinators, and invasive species. Climate change affects the phenology of many species by altering the response of interacting organisms, potentially disrupting their interactions (Freimuth et al., 2022). In addition to temporal (phenological) changes, spatial changes with consequences on species occurrence and demography are also expected (Reddy et al., 2013). Such mismatches may affect plants by reducing insect visitation and pollen deposition, while pollinators experience reduced food availability. Future spatial projections on Brazil indicated that climate change may have a potential effect on the flowering phenology of plants pollinated by hummingbirds (Correa-Lima et al., 2019) and on the distribution of Brazil nut pollinators since local pollinator richness would decrease by 20%, affecting their interactions (Sales et al., 2021). Threats associated with invasive species continue to increase and interact with climate change, exacerbating negative impacts. Interactions between climate change and invasive species include changes in the distribution of invasive species, altered effectiveness of invasive species treatments, new direct pathways for species introduction, and decreasing the effective adaptation to climate change in the face of increased ecosystem stress, further exacerbating biodiversity declines (Bradley et al., 2023). In South America, in addition to the well-documented spread of *Apis mellifera* (Moritz, 2015), the invasion and introduction of *Bombus terrestris* (Linnaeus, 1758) and *Bombus ruderatus* (Fabricius, 1775) has gained interest (Montalva et al., 2024). These exotic species have been associated with population declines of *Bombus dahlbomii* Guérin-Méneville, 1835 in Patagonia. Compared with historical records, the current distribution of *B. dahlbomii* is narrowing and is expected to shrink even more under the most pessimistic future climate scenario, while that of *B. terrestris* shows an extensive and still expanding distribution.

The United Nations (UN) has launched a campaign on ecosystem restoration to cope with climate change, considering that this is a crucial mission for mitigating climate change and protecting biodiversity and ecosystem services (https://www.decadeonrestoration.org/). Conserving protected areas is critical to protect species and their ecosystem services. However, especially in the context of global changes, the connectivity of protected areas also needs to be fostered. Species move around their habitats in search of food, sexual partners, or nesting areas, and this movement is fundamental to avoid inbreeding and impoverishment of intraspecific genetic diversity. In this sense, a first study was made to analyze a coffee-pollinator species (*Melipona quadrifasciata* Lepeletier) in the Atlantic Forest biome (Giannini et al., 2015d) to prioritize connectivity under climate change. Another study was presented recently, aiming to increase the connectivity between the Carajás National Forest in Pará state, also considering the impact of climate change on bees, bats, and birds (Miranda et al., 2021; Cavalcante et al., 2022). Priority areas for conservation (which still have forests) and priority areas for restoration (deforested areas) were thus specified, considering those where the climate is currently suitable for the species and will continue to be suitable in the near future. Additionally, plant species prioritization for restoration projects, aiming to provide pollinator resources and foster interaction networks recovery, can be selected using habitat suitability in future climate scenarios, network metrics (Campbell et al., 2019), pollen analysis (Romeiro et al., 2023), and plants' functional traits (Giannini et al., 2017c).

Recommendations to reduce knowledge gaps

Over the past years, studies in Brazil have shown that a rich diversity of pollinators and plants is essential for sustaining traditional communities, family farms, and large-scale agriculture. Rapid changes in land use, such as the deforestation of the Amazon forest, Cerrado, and other biomes in Brazil, as well as the accelerated pace of climate change, can cause irreversible damage to biodiversity and the delivery of ecosystem services. The profound global risk of food production associated with climate change has already been discussed, with the potential to increase other risks such as poverty, the spread of diseases, habitat degradation, societal unrest, and violence (FAO, 2015; Levy et al., 2017; Nguyen et al., 2023). In response, actions toward ecosystem-based adaptation, which address ecosystems and livelihoods, such as sustainable management, conservation, and restoration, are fundamental (Munroe et al., 2012; IPCC, 2022).

The data revised here led to identifying ten key recommendations to reduce knowledge gaps related to climate change threats to crop pollinators (Figure 3). Addressing these challenges is crucial to effectively protect native habitats, pollinators, and their services to crop production grounded on the state of the art of scientific methods and traditional knowledge. By doing so, we hope to mitigate the food vulnerability risk in a world increasingly ravaged by the impacts of global change. The ten recommendations are:

[1] Addressing taxonomic impediments of pollinator species and promoting entomological collections/museums by funding initiatives for taxonomic research and incentivizing collaboration between taxonomists and ecologists.

[2] Developing controlled experiments of pollinators' thermal tolerance to map the effects of temperature increase on their physiology by promoting international collaboration to access specialized equipment and expertise, knowledge exchange, and prioritizing research on the most vulnerable species.

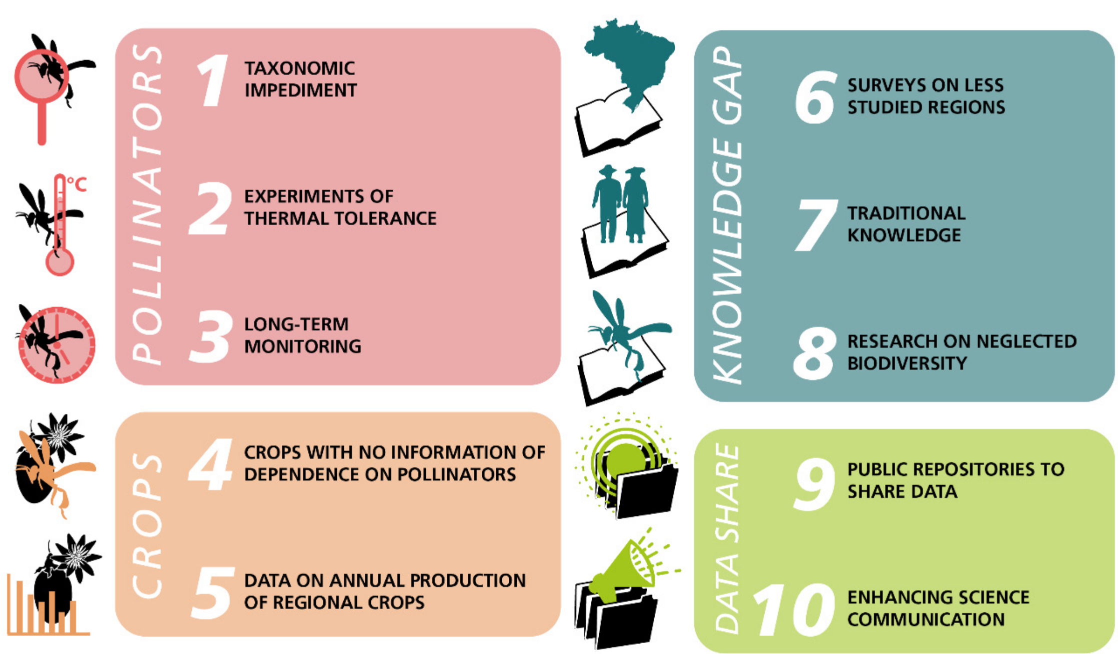

Fig 3. Ten recommendations to reduce knowledge gaps on climate change threats to crop pollinators (designed by Marcelo Kubo).

[3] Developing long-term monitoring of pollinators and pollination to understand the effects of environmental drivers; establishing standardized protocols for pollinator populations and pollination services; collaborating with government agencies and citizen science initiatives to collect data.

[4] Prioritizing research on crops with no information of dependence on pollinators and the determination of effective pollinators by encouraging interdisciplinary collaborations between agronomists, ecologists, and economists to assess the pollination requirements of understudied crops.

[5] Addressing the absence of data on annual production of regional crops on public databases, e.g., improving data collection and sharing mechanisms, including collaboration with agricultural agencies, farmer cooperatives, and non-governmental organizations.

[6] Prioritizing surveys on less studied regions in the country to address the lack of knowledge by implementing targeted research programs in collaboration with local universities and research institutions to address these gaps.

[7] Embracing indigenous and local knowledge, fostering the participation of poorly represented people from traditional/rural communities in science and decision-making, e.g., by developing formal mentoring programs, increasing minority representation within scientific leadership, and stimulating people representativeness via science communication and citizen science.

[8] Fostering incentives for research about neglected biodiversity, mainly insects, and addressing the lack of knowledge about the representativeness of non-bee pollinators, e.g., by opening specific research programs.

[9] Strengthening public repositories to share standardized data on interactions and pollinators to enable more comprehensive analyses. International data standards (e.g., Darwin Core) and principles (e.g., FAIR and CARE) should be followed. Encouraging the acquisition of data from citizen science is also an important initiative.

[10] Enhancing scientific dissemination is also an important step, e.g., by fostering funding programs at universities for training in science communication in clear and accessible language for non-specialists and encouraging researchers to use diverse communication channels, including social media, podcasts, and community workshops, to engage with non-specialist audiences.

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

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