



SPECIAL ISSUE: BEES AND POLLINATORS IN THE FACE OF CLIMATE CHANGE

OPINION

Solitary Bees Facing Climate Change

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Abstract

Solitary bees comprise over 15,000 species. They represent the vast majority of bees on earth (>77%), but they are less studied than the social species. Several threats from the modern world, like agricultural intensification, excessive use of pesticides, urbanization, different types of pollution, and invasive species, are leading the fragile populations of solitary bees to decline. Climate change has become a new stressor for bees, potentially amplifying these previously known threats. Warming temperatures are already causing shifts in some species' geographical distribution and interrupting the temporal synchrony between the flowering period and the bee developmental cycle, leading to a "phenological mismatch". As a result, bees starve, and plants fail to reproduce. Pollination of many native and cultivated plants is impaired.

The solitary bees

Bees have diversified into seven families, 28 subfamilies, and over 20,000 described species (Ascher & Pickering, 2018). In contrast to the well-known highly social and complex lifestyle of eusocial bees, commonly found among species of *Apis* and Meliponini (Michener, 1974; Engels, 1990), in 24 subfamilies, all species (100%) are solitary; in two other subfamilies, 80% are solitary. In other words, solitary species comprise most bees on earth (>77%). Thus, over 15,000 bee species are solitary (Danforth et al., 2019). In this case, only one female is responsible for all tasks in the nest, from its foundation, defense, provisioning, and oviposition (Batra, 1984; Alves-dos-Santos, 2002). The foundation includes the location of a suitable site for building the nest, which can be on the ground, in ravines,

walls of different sediments, in tree trunks, termite mounds, and preexisting cavities, among others (Stephen et al., 1969). Upon finding the site, the female begins to excavate a tunnel, which is linear or branched. She then builds the brood cells, reinforcing the tunnel wall with sand, resin, oil, and pieces of leaves or petals (Camillo et al., 1995). The female makes several trips to collect food from flowers and provide brood cells (Neff, 2008). In each cell, she lays an egg on or in the middle of the food and closes it, leaving the immature protected during its development. This is repeated several times throughout the female's reproductive period. Generally, after some weeks, she dies and has no contact with her offspring (Michener, 2007). A good description of solitary bee life cycles is given in Chapter 3 by Danforth et al. (2019), containing many examples of species with one (univoltine), two (bivoltine), or many (multivoltine) generations per year.



Due to their sparse populations (valid for the majority) and the enormous difficulty in locating their nesting sites, solitary species have been less studied (Danks, 1971; Jayasingh & Freeman, 1980) than social bees. Knowledge has been accumulated about species that nest in preexisting cavities since they can be captured in traps (Krombein, 1967; Garófalo et al., 2004) and species that form large aggregations with a high density of nests arranged in the same place (Rozen, 1984; Cane, 2024a). Such aggregations tend to remain in the same area for several years, making them easier to locate, as is the case of *Andrena fenningeri* Viereck, followed for more than 10 years by Suzanne Batra (Batra, 1999).

Maternal care, a distinctive and extraordinary feature of many Hymenoptera, ensures a higher reproductive success rate than other insects (Clutton-Brock, 1991). As mentioned above, bees build nests to shelter and protect their immature during growth. The brood cells are supplied with food (usually pollen and nectar), which forces the female to perform an intense task of foraging in flowers to collect the resources their larvae need to complete the development (Neff, 2008). The obligatory collection of resources in flowers has named the bees Anthophila insects, which means “lover of flowers”, and does justice to the strong dependence of bees on floral resources (Engel, 2005).

In the interaction with plants, polylectic and oligolectic bee species are used for pollen collection (Cane & Sipes, 2006), which concerns the degree of specialization regarding the plant used in the diet of the immatures. A generalist species tends to collect pollen from various unrelated plant groups, while a specialist species restricts its pollen sampling to just a few related genera, showing host plant preferences (Robertson, 1925). For a complete terminology to describe the range of host-plant preferences in bees, see Cane and Sipes (2006).

The relationship between bees and plants directly impacts the global economy as they are often essential for agricultural production (Klein et al., 2007). Global agriculture has become increasingly dependent on bees (Aizen et al., 2008), with a considerable portion due to solitary bees, which are more specific to certain groups of plants (Peterson & Artz, 2014). Solitary bees have been identified as the primary pollinators of important crops in Brazil, such as acerola (Vilhena & Augusto, 2007; Magalhães & Freitas, 2013), passion fruit (Yamamoto et al., 2012), Brazil nuts (Maués, 2002), cambuci (Cordeiro et al., 2017), among others. However, there is a significant knowledge gap about the role of solitary bees in food production worldwide, especially concerning pollination dependence values.

Bees suffering from multiple threats

All the bees, as well as insects in general, are facing several threats from the modern world. Severe ecosystem changes caused by agricultural expansion and intensification,

indiscriminate and excessive use of pesticides and herbicides, intensive arable farming, mining and quarrying, fire and fire susceptibility, urbanization, different types of pollution, and invasive species are leading declines in bee populations and driving species to extinction (Vulliamy et al., 2006; Martins & Melo, 2009; Hagen et al., 2012; Arbetman et al., 2013; Sydenham et al., 2014; Gill & Raine, 2014; Pisa et al., 2015; Rafferty, 2017; Albacete et al., 2023; Cane, 2024b). On a global scale, climate change is a multiplier endangering all living organisms.

Regarding solitary bees, the first threat is that they are poorly known and less studied. Many species have not yet been described. For the vast majority, nothing is known about their lives. For example, in the Eucerini tribe, which is cosmopolitan and includes 780 species, there are studies on the biology of only 32 species, which is around 4% (Alves-dos-Santos, 2023). Thus, when we do not know where they nest, the plants they use, and their natural enemies, we cannot protect them or assess their survival requirements. Even in Europe, which may have the best-known bee fauna in the world (consisting of nearly 2,000 described species), data are deficient for most species. The IUCN European Red List of Bees has nearly 60% of the species that were deemed data deficient, meaning that there was insufficient information to make a conclusive statement about the conservation status of the species (Nieto et al., 2014).

Furthermore, many taxa of solitary bees still require basic taxonomic research before their population trends can be evaluated. The aggravating aspect of the taxonomic impediment is the lack of taxonomic expertise, a worldwide problem (Engel et al., 2021). Unfortunately, the community of bee taxonomists has been markedly reduced during the second part of the last century.

Among the many drivers of biodiversity loss, climate change is the most worrying driver since synergistic effects with other stresses (mentioned above in the previous paragraph) enhance the mechanisms of action. For example, wildfires and floods, extreme events recently occurring in Brazil (in 2024) on excessive scales due to deforestation and extreme warmth, are likely to destroy bee habitats, food sources, and nests in enormous numbers, impair subsequent generations, or even cause local extinctions. In Europe, many bee species are considered threatened by climate change due to the conversion of habitats: in the steppe regions of eastern Europe, an increase in summer rainfall (Shahgedanova, 2002) has led to habitat conversion from dry xeric grasslands to meadow and scrub (Penksza, 2003) to the detriment of bee species that are restricted to these dry habitats (Radchenko, 2009). Widespread and prolonged heat waves and summer droughts increase the temperature across the Boreal, Arctic, and Alpine regions will severely impact the vegetation composition, affecting the bee species associated with these habitats (Olesen & Bindi, 2002; Callaghan et al., 2004; Maracchi et al., 2005; Odegaard et al., 2009, Rasmont et al., 2015).

Also, solitary bees may be more sensitive to urban warming. Those bees are physiologically more impacted by rising temperatures than social groups and may face population declines (Hamblin et al., 2017).

Some studies are showing that the warming of the planet and changes in weather patterns are disrupting native ranges for bees, making ecosystems unsuitable for their reproduction, and altering the synchrony between their host plants (Memmott et al., 2007; Kuhlmann et al., 2012; Forrest, 2015; Hamblin et al., 2017; Vázquez et al., 2023; Kazenel et al., 2024). Pereira et al. (2024) projected shifts in the range of several wild bee species in southeastern South America due to a decline in richness in the northernmost regions. In fact, the effects of climate change may reach even greater proportions, escalating into unexpected and not-so-obvious consequences such as these.

Predictions to some specific Brazilian biomes

Climate change and impact on solitary bees in the Amazon

The Amazon faces an increased susceptibility to extreme weather events, such as prolonged droughts, which affect ecosystem dynamics and precipitation recycling in the region (Bottino et al., 2024). In addition, the Amazon rainforest, when deforested and degraded, contributes significantly to global warming, exacerbating the feedback cycle between climate change and changes in land use (Shukla et al., 1990; Gatti et al., 2021; Lapola et al., 2023).

Studies that evaluated the potential response of bees that occur in the Eastern Amazon region (more specifically in the state of Pará) to climate change indicated that 95% of the 216 bee species evaluated would face a decline in their total area of occurrence (Giannini et al., 2020). Among the analyzed species, most solitary, the genus *Centris* stands out since many species are important pollinators of crops such as tomato (*Lycopersicon esculentum* Mill.), acerola (*Malpighia emarginata* DC.), murici (*Byrsonima crassifolia* L.), among others.

One specific study case for the Amazon region projects a 50% reduction in the area of occurrence of Brazil nut (*Bertholletia excelsa* Bonpl.) (Figure 1A) pollinators, leading to a reduction of almost 80% in the potential for co-occurrence (Sales et al., 2021). This divergence occurs because, in scenarios where some environmental parameters change (e.g., temperature, precipitation), even areas suitable for the plant species may not be ideal for pollinators and vice versa. Although several species visit Brazil nut flowers, only large solitary bees, such as those of the genera *Centris*, *Xylocopa*, *Eulaema*, and *Epicharis*, are considered effective pollinators (Maués, 2002; Cavalcante et al., 2012). In this case, the mismatch between the plant and pollinators might lead to a cascade effect that will also affect human communities. Brazil nuts play a crucial role in the sustainability of Amazon forests, contributing to the preservation of ecosystems and ensuring

the livelihood of traditional populations (Scoles & Gribel, 2012), and are essential for the economic development of this region with a low human development index (Rodrigues et al., 2009).

The impacts of climate change on the solitary bee communities still need to be studied further, mainly due to the lack of data on species distribution on the Amazon. Many species have unique functional traits, which make them irreplaceable in various interactions. However, studies show that the northeast region of Pará appears to be a refuge area for several groups of bees (see Giannini et al., 2020), mainly due to its high rainfall levels.

Climate change and impact on solitary bees in the Caatinga

In contrast to the Amazon biome, the Caatinga has a semiarid climate with a long dry season lasting more than eight months. This biome occupies an area equivalent to approximately 10% of the Brazilian territory. Due to the unsustainable use of its soils and natural resources over hundreds of years of occupation, the Caatinga is one of the most fragile Brazilian biomes. Current forecasts indicate a gradual increase in temperature and a decrease in rainfall patterns, further aggravating the regional water deficit (Marengo et al., 2011). The biome is already experiencing the consequences of climate change, as evidenced by the growth of arid or desert areas where the original forest has been removed (IPCC, 2013; Tomasella et al., 2023).

Living in a semiarid region requires the bees' adaptations to extreme weather conditions, such as high solar radiation, high average annual temperatures, low relative humidity, and low precipitation rates (Sampaio, 1995). Given the low species richness and high concentration of rare and endemic taxa (Zanella & Martins, 2003), the Caatinga's solitary bee fauna may be particularly vulnerable to the consequences of climate change. Giannini et al. (2012) projected a reduction of up to 35% in the distribution ranges of species like *Centris hyptidis* and *Centris trigonoides* (Figure 1C). Both species are widely spread in northeastern Brazil and have a strong relationship with wild plant species such as the *Angelonia* genus (Vogel & Machado, 1991; Machado et al., 2002) and cultivated plants such as the West Indian cherry (*Malpighia emarginata* DC) (Kiill et al., 2023). The diversity of shrubby and herbaceous vegetation also declines with the expansion of arid regions (Oliveira et al., 2024), consequently reducing the food sources for the bees. Among these plant categories are many species such *Rhaphiodon echinus* (Lamiaceae), *Cenostigma microphyllum*, and *Chamaecrista* species (Fabaceae) abundant in the provision of the brood cells of Caatinga's solitary bees (Aguiar et al., 2003; Dórea et al., 2010; Martins et al., 2024).

Since most solitary bees are ground-nesting species (Cane, 1991; Antoine & Forrest, 2021) (Figure 1F), the availability of suitable nesting habits might be as limiting as the plants. The desertification process associated with grazing

degrades the functionality of soils in the Caatinga, increasing compaction, decreasing porosity, and possibly altering the composition (Lima et al., 2024).

Habitat loss combined with the expansion of arid regions represents one of the main threats to bees living in the caatinga, crashing into especially endemic species and plants with specialist reproductive attributes (Silva et al., 2019). Some narrow mutual associations at risk comprise

the bee species *Ceblurgus longipalpis* Urban & Moure and its host plant *Cordia leucocephala* Moric. (Cordiaceae), *Perditomorpha* aff. *leaena* (Vachal) and its pollen source, *Sida galheirensis* Ulbr. (Malvaceae) (Figure 1E), as well as *Protomeliturga turnerae* (Ducke) specialized in flowers of *Turnera subulata* Sm. (Turneraceae) (Figure 1D). All these bees are endemic to the Caatinga (Medeiros & Schlindwein, 2003; Milet-Pinheiro & Schlindwein, 2010). Solitary bee

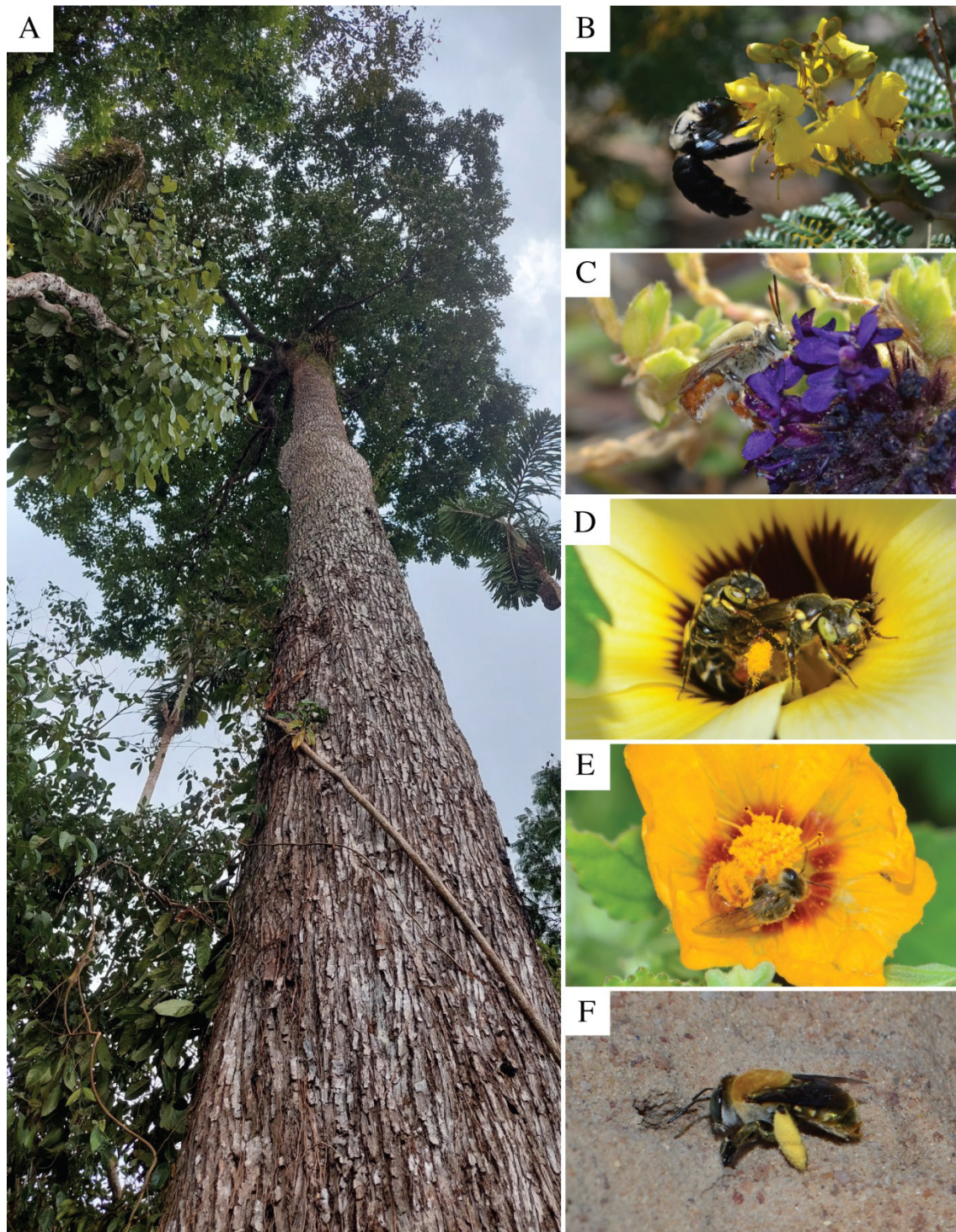


Fig 1. Plant and bee species mentioned in the text. a. Brazilian nut tree *Bertholletia excelsa*. b. Female of *Xylocopa griseescens* on flower of *Cenostigma microphyllum*. c. Male of *Centris trigonoides* visiting *Rhaphiodon echinus* d. Copulation of *Protomeliturga turnerae* on flowers of *Turnera subulata*. e. Oligolectic bee *Perditomorpha* aff. *leaena* collecting pollen from its host plant *Sida galheirensis*. f. Ground-nesting bee *Centris caxienseis*.

species of the genera *Melitoma*, *Melitomella*, *Ancyloscelis*, and *Diadasina* collect pollen exclusively from herbaceous plants of the families Convolvulaceae and Malvaceae (Pick & Schlindwein, 2011). The adults of these species have a relatively short active period because they usually coincide with the flowering period of the host plants (Schlindwein, 2000). The irregularity of the Caatinga's rain cycles and the shortening of the rainy season raise the alert to the possible disturbances in the reproductive cycles of these species.

As mentioned above, the Caatinga is notably seasonal, with a period of abundant food supply followed by a period of resource shortage (Sampaio, 1995). Thus, changes in climate cycles will undoubtedly be felt by solitary species with prolonged diapause, disrupting the synchronicity of their emergence and their host plant's bloom period.

Final remarks

In the media, in general, the prominent role of bees in ecosystem services is well publicized, and there is concern about their conservation. However, the images always focus on the most common species, popularly known as honey bees and bumble bees. Solitary bees, although often overlooked compared to social bee species, play a vital role in pollination and biodiversity. Their vulnerability to climate change, exacerbated by habitat loss, deforestation, and environmental degradation, presents a major conservation challenge. Indeed, the many stresses causing the well-quantified decline of honeybee colonies might also affect the solitary bees. Survey data are lacking for them.

A good synopsis of the many threats is presented in the last chapter of the book "The Solitary Bees" by Bryan Danforth and collaborators (2019). Warming temperatures are already causing shifts in the geographical distribution (altitudinal or latitudinal) of the species (Kuhlmann et al., 2012) and interrupting the temporal synchrony between the flowering period and the bee activity cycle (Memmott et al., 2007), leading to a phenomenon known as "phenological mismatch". This phenomenon can reduce biodiversity, compromise ecosystems that depend on these interactions (Hegland et al., 2009; Kudo & Ida, 2013), and ultimately lead the bees to nutritional stress.

The synergy between climate change and other threats, such as agricultural expansion and pesticide use, can potentially reduce the populations of solitary bees. A major challenge would be to convince farmers that bees are partners in their productivity and that more friendly and sustainable agricultural practices would be beneficial to everyone (Garibaldi et al., 2013; Dicks et al., 2013). Addressing the knowledge gaps, particularly regarding species distribution and ecological interactions, is critical for developing effective conservation strategies. Urgent action is required to mitigate these impacts and ensure the survival of solitary bees, whose decline could have cascading effects on biodiversity, food security, and ecosystems.

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Authors' Contributions

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HOJM: Conceptualization, writing-original draft, writing-review & editing

WOS: Conceptualization, writing-original draft, writing-review & editing.

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