

Opinion

Giving Wings to Sustainability: Brazil Needs to Consider Bats as Suppressors of Agricultural Pests and Tropical Disease Vectors

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Abstract: Insect-eating bats play a crucial role in agriculture and public health by suppressing populations of agricultural pests and disease vectors. These ecosystem services promoted by insect-eating bats are essential in a world that seeks sustainability in agricultural production and the management of urban areas. Despite Brazil's status as one of the largest agricultural producers globally, research using insect-eating bats for pest control is lacking. This review underscores the importance of filling this knowledge gap and provides guidelines for future research. Bats exhibit diverse feeding habits and consume significant quantities of insects, including agricultural pests. While studies in the USA and Europe have highlighted insect-eating bats' role in reducing agricultural losses, research in Brazil is limited. Challenges include the need for more advanced diet analysis techniques, such as DNA metabarcoding, and understanding bat habitat use in agricultural and urban landscapes. Research on natural and artificial roosts' effectiveness and population dynamics is also essential. Integrating bat conservation into agricultural sustainability requires investment in technological methods, valuation of ecosystem services, population monitoring, habitat use studies and environmental education. Financial incentives and collaboration between sectors are crucial for advancing research and implementing bat-friendly practices in agriculture, ultimately enhancing biodiversity conservation and production sustainability in Brazil.

Keywords: artificial roosts; bioacoustics; Chiroptera; habitat use; insectivorous bat; sustainable agriculture; urban sustainability



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1. Introduction

Globally, there is increasing pressure on different ecosystems due to increasing human food demand [1,2]. However, this increase and the constant replacement of natural landscapes by agricultural systems have yet to be carried out sustainably. Countries economically dependent on the export of commodities are large consumers of agricultural pesticides and have high deforestation rates [3,4]. Tropical countries that lead agricultural production in the world, such as Brazil, use more pesticides due to the different types of pests in this region, which can cause significant losses in various croplands [5,6]. For example, according to data from the Food and Agriculture Organization (FAO), Brazil

produced between 2020 and 2021 more than 700 million tons of sugar cane and more than 100 million tons of soybeans and maize [7]. In this same period, it is estimated that Brazil consumed 377,176 tons of pesticides [8]. In turn, the Brazilian government sought to relax the rules for the inspection and application of pesticides (see PL 6299/02—<https://www.camara.leg.br/propostas-legislativas/46249>, accessed on 14 February 2024) and release the largest number of pesticides in the history of this country, totalling almost 1000 substances between 2019 and 2021 [9].

On the other hand, other countries are advanced in the knowledge and application of biological control techniques, as there is a scientific consensus that these substances used, mainly in food products, are harmful to human and environmental health [10]. Sustainable production systems bring more benefits to the environment, with less loss of natural landscapes and/or better use of already altered and degraded landscapes [11–13]. For example, Brazil already has agricultural technology (e.g., soil recovery) to double current soybean production in areas already producing or recovering degraded areas without opening new areas for planting [14–16]. Within this dynamic of the Brazilian production system, the main commodity purchasing markets have demanded greater transparency in this system and the commercialization of products free from pesticides and deforestation [17,18].

Sustainability within different agricultural production systems can benefit the human population and the environment, providing healthier food with a smaller environmental footprint [19]. Among the techniques that can be used to reduce the use of pesticides is biological control [20]. Brazil has used this tool in agriculture, such as in the production of sugar cane through the use of insects from the order Hymenoptera [21], but has left aside some species, such as insect-eating bats, which have been considered in different initiatives for biological control in Europe and the United States (see [22,23]). For example, in Brazil, there are estimates that insect-eating bats would bring savings of USD 94 per hectare per harvest in maize production [24]. However, a recent review (see [25]) has shown that in Brazil, only one study has been published evaluating the role of insect-eating bats in the consumption of agricultural pests (see [26]). Therefore, there needs to be more knowledge about how bats can help suppress agricultural pests in Brazil.

In addition to the demand for commodities, another factor that has driven the loss and degradation of habitats worldwide has been the disorderly advance of urbanisation over natural areas [27]. Consequently, large urban centres in tropical regions have been epicentres of epidemics of tropical diseases, such as malaria, dengue, Zika and Chikungunya [28]. Although we know different techniques for biological control of the vectors of these diseases, more needs to be done to implement these more sustainable tools for population control [29]. In Brazil, there are some initiatives, such as studies focused on controlling *Aedes aegypti* (see [30]). However, to our knowledge, no studies have verified the potential of insect-eating bats in controlling tropical disease vectors in Brazil. Worldwide, there are few studies on the consumption of disease-causing arthropods by insect-eating bats, and most are concentrated in Europe (e.g., [31,32]); there are still many gaps, especially in the tropical region.

Here, we will discuss the importance of insect-eating bats for agriculture and public health, focusing on their potential to suppress populations of insects that are agricultural pests and disease vectors (e.g., [32–34]). Furthermore, based on a review of studies of insectivorous bats in Brazil, we will highlight that this country, one of the largest agricultural producers in the world [7,8,35], has not yet invested enough basic research to increase the occurrence and abundance of insect-eating bats locally, as in the case of the use of bat houses, improving the quality of rural and urban habitats, as well as enhancing the use of urban structures such as walls and roofs. In this way, the role of insect-eating bats as suppressors of agricultural pests or vectors of tropical diseases would be strengthened, even helping to demystify them. Finally, we will suggest guidelines that researchers and managers can follow to fill this gap in knowledge to advance with biological control using insect-eating bats in the Neotropics.

2. Relevance of Bats for Agriculture, Public Health and Their Susceptibility to Pesticides

Chiroptera is a highly diverse order within Mammalia in species richness and ecosystem functions [33,36]. To date, we know of 181 species of bats in Brazil, distributed in nine families, with eight families considered insectivorous (Emballonuridae, Mormoopidae, Noctilionidae, Furippteridae, Thyropteridae, Natalidae, Molossidae, Vespertilionidae), which encompass 48% of species ($n = 88$ species; [37,38]). As Chiroptera presents a large diversity of feeding guilds, bats are responsible for seed dispersal, pollination and the population suppression of small vertebrates and arthropods [33,36]. For example, insect-eating bats are responsible for consuming tons of insects throughout the year in a single location (e.g., Madagascar, see [39]).

The consumption of insects by insect-eating bats has led to considering these flying mammals as biological control agents, whether for agricultural pests or insects in urban areas (e.g., [22,32,34,39–41]). For example, insects consumed by insect-eating bats, such as Lepidoptera and Coleoptera, are leaf-chewing insects, and Hemiptera are plant-sucking insects [26,42], being important agricultural pests [43]. In the USA and Europe, several studies have highlighted the importance of insect-eating bats as crop pest suppressors that help reduce the use of pesticides [22,44–46]. In these locations, insect-eating bats help suppress insects in human-modified habitats and are estimated to save more than USD 3.7 billion annually in agricultural losses [22,39,40]. For example, in an experiment, Rodríguez-San Pedro et al. [47] evidenced that insect-eating bats reduce 7% of grapevine pest insect infections, thus increasing harvest yield from organic vineyards and winegrowers' income (USD 188–USD 248/ha/year). Therefore, using insect-eating bats increases productivity per area and decreases production costs [22,48].

For public health, studies have also highlighted the potential of bats to consume disease vectors (e.g., [49,50]). For example, in an experimental assessment, Reiskind et al. [51] verified the impacts of insect-eating bats on mosquito ovipositing. They suggested the impact of aerial predators on pathogen transmission may be large due to the reduction in egg-laying activity associated with bat predation and the decrease in the number of larval mosquitoes in enclosures exposed to bat predation [51]. Gonsalves et al. [49] also related positive correlations between the mosquito *Aedes vigilax* abundance, an important vector of mosquito-borne viruses, and insect-eating bat activity. Furthermore, Diptera is found widely in the diet of several species of insectivorous bats [24,36,47,52–55]. This order of Insecta presents several vectors of zoonotic infections among humans and domestic and wild animals [56,57]. For example, insect-eating bats feeding on several mosquitoes (suborder Nematocera) of interest in public health have already been reported in the literature, such as *Aedes* spp., *Anopheles* spp. and *Culex* spp. [24,58,59]. Many of these mosquitoes are abundant in urban areas, serving as a food resource for insect-eating bats.

Despite the ecological and economic importance of insect-eating bats for agriculture and public health, these flying mammals are susceptible to pesticides because they are at the top of the food chain [60,61]. Exposure to contaminants has been implicated as a major factor contributing to decreases in bat populations [62], and it can occur through food, contaminated water, direct skin contact or from contaminated mothers to offspring during lactation [63,64]. Residues can bioaccumulate in their tissues and compromise their health, affecting organs such as the liver and brain [65]. In addition, it has been shown that pesticide toxicity can decrease the expressions of genes related to the functioning of bats' vocal, auditory, orientation and spatial memory systems [66]. Although there are advances in analytical techniques for the detection of contaminants, there is a scarcity of data to assess the risks to bats [67], and the number of studies is still insufficient compared to the variety of pesticides used [68]. Many studies remain to be conducted to understand the degree and exactly how pesticides act on the physiology of bats since the impacts are high for these animals [65].

3. Gaps and Challenges in the Use of Insect-Eating Bats in Biological Pest Control in Brazil

3.1. Insect-Eating Bat Diet

Our review of studies on insect-eating bats in Brazil showed that approximately 5% of 236 studies analysed diet (see Supplementary Materials). These studies analysed the diet of 16 different species (Table 1), corresponding to around 18% of the 88 insectivorous species in Brazil [38]. *Molossus molossus* (n = 3) was the species with the largest number of studies, followed by *Molossus rufus*, *Eptesicus furinalis* and *Myotis nigricans* (n = 2 for each—Table 1). Therefore, our data highlight that there is a massive gap in the diet of insect-eating bats in Brazil, especially for species that have large populations, as in the case of *M. molossus* in the southeast (e.g., [69]) and *Tadarida brasiliensis* in southern Brazil (e.g., [70]).

Table 1. Studies on diet or use of roosts by species of insect-eating Brazilian bats.

Species	Number of Studies
Diet	
<i>Molossus molossus</i>	3
<i>Molossus rufus</i>	2
<i>Myotis nigricans</i>	2
<i>Eptesicus furinalis</i>	2
<i>Histiotus diaphanopterus</i>	1
<i>Eumops perotis</i>	1
<i>Nyctinomops laticaudatus</i>	1
<i>Molossus molossus</i>	1
<i>Cynomops planirostris</i>	1
<i>Tadarida brasiliensis</i>	1
<i>Saccopteryx bilineata</i>	1
<i>Saccopteryx leptura</i>	1
<i>Thyroptera wynnneae</i>	1
<i>Eptesicus diminutus</i>	1
<i>Myotis albescens</i>	1
<i>Rhynchonycteris naso</i>	1
Artificial roosts	
<i>Molossus rufus</i>	4
<i>Molossus molossus</i>	2
<i>Saccopteryx leptura</i>	2
<i>Peropteryx kappleri</i>	1
<i>Peropteryx macrotis</i>	1
<i>Pteronotus parnellii</i>	1
<i>Furipterus horrens</i>	1
<i>Natalus macrourus</i>	1
<i>Molossops temminckii</i>	1
<i>Nyctinomops laticaudatus</i>	1
<i>Rhogeessa hussoni</i>	1
<i>Myotis lavalii</i>	1
<i>Peropteryx leucoptera</i>	1
<i>Eumops perotis</i>	1
<i>Myotis nigricans</i>	1
<i>Eptesicus furinalis</i>	1
<i>Myotis levis</i>	1

To date, only one study has analysed the diet of insect-eating bats in Brazil and highlighted the consumption of agricultural pests (e.g., *Batachedra* sp.) and disease-carrying insects (e.g., *Culex* sp.—see [24]). This same study analysed the diet of bats based on DNA sequencing, with a predominance of insects considered agricultural pests from the orders Lepidoptera and Hemiptera that were consumed by at least five different species of bats (*Eumops perotis*, *Nyctinomops laticaudatus*, *Histiotus diaphanopterus*, *Molossus molossus* and

Cynomops planirostris—see [24]). Based on these data, the consumption of agricultural pests by bats in Brazil could save USD 390.6 million annually per harvest in maize fields [24]. Other studies have sought to quantify the mass of insects consumed by bats in artificial roosts, with an estimate of 0.8 g/bat for *M. molossus* [71] and with *M. rufus* consuming from 10.67 to 19.00 mg/min of insects [72]. Moreover, cave-dwelling species consume from 0.6 to 2.5 g/bat (*Pteronotus gymnonotus*) and from 0.8 to 2.0 g/bat (*Pteronotus personatus*—see [73]). Therefore, even with these few studies of a few species, the importance of these flying mammals in insect consumption in this country, one of the world's largest agricultural producers, is evident.

The main challenge for us in filling this gap in knowledge regarding bat diets is the type of diet analysis used in the studies. While most studies have used the morphological comparison of items found in the faeces of Brazilian insect-eating bats (e.g., [74–76]), recently, studies have begun to use DNA analysis to identify food items [24,73]. This last technique is more effective and faster but is more expensive [77]. Considering the budget cuts that education, science and technology have suffered in recent years [78,79], there is not much prospect for this analysis to be more accessible to researchers working in Brazil. One solution would be to participate in international research groups and seek external funding for basic science. Another important aspect is that higher-impact journals tend not to accept more specific and regional studies, as in the case of monitoring a colony and using more traditional diet assessment techniques. One solution to this would be creating article types (e.g., natural history notes) that encompass more specific studies or studies on species' natural history in higher-impact journals. Studies on natural history are very important for advancing science in general and especially for ecology, zoology and conservation (e.g., [80]).

3.2. Bioacoustics and Habitat Use

Bats are abundant and diverse and have a high trophic diversity, especially in the neotropical forest [81]. In addition, these flying mammals are less expensive to sample, have a higher capture rate than other groups of mammals and are locally abundant (even in degraded areas) [82]. However, the main method used to sample bats is the mist net, which has a low efficiency for sampling insect-eating bats [83,84]. In the case of this bat trophic guild, most species have a greater chance of being detected and identified through acoustic recording [84]. Currently, acoustic recordings have been used in approximately 33 or 14% of studies on insect-eating bats in Brazil (total number of studies = 236), and most studies were carried out to evaluate habitat use by a species or an assemblage (e.g., [85–89], Supplementary Materials). None of these studies evaluated habitat use in an agricultural landscape, focusing on determining species that use more or fewer plantations to forage, for example. However, two studies analysed urban insect-eating bats, highlighting the importance of urban green areas for this bat trophic guild (see [89,90]). Studies evaluating habitat use in agricultural systems or urban areas would give us an idea of which species would be more or less likely to be considered for agricultural pest and disease vector insect suppression, for example. Furthermore, due to a lack of basic knowledge of different species, other tools for promoting and increasing the richness and activity of bats in agricultural and urban areas are no longer considered, such as: the implementation, recovery and maintenance of water bodies; revegetation around rivers and watercourses; maintenance of native vegetation in agricultural landscapes, mainly ensuring the maintenance of connectivity between natural areas and greater availability of shelter and food; and the best agricultural management practices, such as crop diversification and transition to organic agriculture (e.g., [91–93]).

Despite the difficulty we have in distinguishing the different neotropical insectivorous bats [94], it is essential to increase studies using bioacoustics to inventory and monitor them since today we have more accessible and cheaper recorders (e.g., [95]). Most studies carried out in Brazil were developed in the Amazon (see [83,84,88]), with few studies in Cerrado (e.g., [96]), Caatinga (e.g., [97]), Atlantic Forest (e.g., [98]), Pantanal (e.g., [87]) or Pampa (e.g., [85]). Furthermore, few studies have been carried out in urbanised areas [89,90],

which would help to understand how bats use urbanised landscapes to move and forage. Therefore, a large part of Brazil, as well as insectivorous species, lack acoustic sampling, which identifies the main characteristics of the sonograms and verifies the different types of habitats that are most foraged. For example, through knowledge about the species that most use agricultural fields, forest plantations and urbanised areas, we can direct resources and research to enhance artificial roosts, such as bat houses.

Most of the studies we analysed that used bioacoustics as a sampling method were conducted in experimental areas seeking to understand the effects of forest fragmentation (see [99]). As well as recent reviews on the impact of agricultural ecosystems on bats, no studies have investigated, for example, the effect of croplands (e.g., soybeans or maize) on insectivorous bats in Brazil (see [25]). This result is alarming because, as mentioned previously, Brazil is one of the largest agricultural producers in the world, with record production of soybeans and maize [7]. Not knowing the effect of these plantations on bats and which insectivorous species most use these cultivated areas makes it extremely difficult to try to find solutions that consider bats as suppressors of agricultural pests in Brazil. In this sense, researchers should seek to understand how Brazilian insect-eating bats use agricultural landscapes so that we can enhance the use of these areas by species with higher occupation and abundance.

3.3. Use of Artificial Roosts

Different studies have highlighted the importance of bat boxes placed in forests close to urban areas or in plantations and agricultural fields to help in the conservation of bats and in the consumption of agricultural pests and insects that can cause diseases (e.g., [100]). Although bat boxes are widely used in several countries, there is still much to be understood about using this artificial roost for bats [101,102]. Some studies denote that bat boxes need to be used carefully, and are usually used by common, abundant species with minimal conservation concerns [103]. Specifically for Brazil, this issue is even more problematic as we found that around 5% of studies ($n = 13$) are focused on population ecology in roosts or on how bats use these roosts for ~20% of the Brazilian insectivorous bat species ($n = 88$ species, [38]; Table 1, Supplementary Materials). The most studied species are *M. molossus* ($n = 2$) and *M. fluminensis* (previously described as *M. rufus* in the state of Rio de Janeiro) ($n = 4$), mainly in the state of Rio de Janeiro (e.g., [69,104]). This issue regarding the interaction of insect-eating bat species with their roosts is even more problematic if we consider that the last study evaluating artificial roosts was conducted in 2018 (see [105]). Therefore, we do not know how bats interact with their roosts in Brazil, which greatly limits the implementation of any initiative aimed at building artificial roosts, such as bat houses, as these need to be able to be occupied and to guarantee the permanence of the bats.

Studies using artificial roosts, such as bat boxes, have predominantly been conducted in Europe and North America, with few examples in tropical regions (e.g., [101]). Some initiatives in Brazil, such as the Pampa biome, are being carried out to house mainly *Tadarida brasiliensis* (see [106]). Other initiatives in Brazil have attempted to compare bat hotel (type of bat house with larger dimensions and occupied by large populations of bats) models used in Spain with models based on roof linings made in most houses in the northern region of Brazil (a project under development in Amapá, Brazil). In another initiative in the state of Rio de Janeiro, bat houses similar to those used in Europe and the United States are being implemented (see <https://piper3d.com.br/bat-houses>, accessed on 14 February 2024). Marques and Ramos [107] also report the use of bat houses for Molossidae and Vespertilionidae species in the Auracária forest in southern Brazil. However, these initiatives in Brazil are based on a few published studies on the life history of insectivorous bats, their population structure and the interaction between species and their shelters, as we see in our review.

It is urgent to provide funding and incentives for different research groups to once again study the population structure of bats that live in artificial or natural roosts. In addition to helping to improve the knowledge about how these bats interact with their

roosts, studies can also help enhance the interaction between humans and bats, especially in places with this type of conflict. For example, in different locations, there are conflicts related to bat faeces that fall into homes [108]. By learning better what population dynamics are like and what types of roofs and ceilings bats prefer, it is possible to house bats in the best way so as to prevent this type of negative interaction and the dropping of faeces inside homes. Furthermore, it would be possible to develop artificial roosts such as bat houses, tiles and bricks that serve as roosts, among other materials exclusive to neotropical bats.

4. Where to Start and How to Move Forward

To move forward with an agenda integrating bat conservation and improved sustainability in agricultural production, more is needed to reduce deforestation rates or restore degraded areas. To do this, we must consider our impact when changing land use and adapting our production systems to be more animal-friendly. For example, studies carried out in different parts of the world have shown that farmers want to participate in collaborative initiatives to benefit biodiversity and ecosystem services, including those provided by bats (see [109,110]). In this case, considering bats as agents for suppressing agricultural pests and disease-carrying insects is extremely important for maintaining this ecosystem service, improving the quality of our food and reducing the impact of tropical diseases. However, there are still different gaps on these issues, and for Brazil to make progress with this, it would be necessary to invest in studies that investigate the following areas:

- The use of more technological methods (e.g., DNA metabarcoding) to analyse faeces from insectivorous bats captured or guano from roosts. This will allow taxonomic identification of food items with greater precision and breadth;
- The valuation of ecosystem services is essential for nature, translating the results into a more accessible language for public managers and businesspeople. In this way, knowledge becomes more accessible for the implementation of public policies and private sector actions;
- Estimate the size and population dynamics of insectivorous bat species in Brazil, trying to understand the main characteristics of the roosts that allow bat species to remain occupied. For this type of study, carry out population monitoring in roosts using the mark–recapture technique;
- Verify habitat use, mainly considering the effect of changing land use from natural habitats to agricultural systems and urban areas for Brazilian insectivorous bats. Furthermore, studies must verify the minimum amount of natural, regenerated or planted area to have maximum bat richness and activity, which facilitates the implementation of more bat-friendly urban green areas and improves the occupation and permanence of these species in agricultural ecosystems. For these studies, consider using more modern and accessible technologies such as ultrasound recorders, radio collars, GPS tags or radar systems;
- Greater incentives for researchers to further study how artificial roosts can be used in agricultural areas and urban areas without increasing conflicts between bats and humans;
- Carry out a diagnosis of the problems faced by agricultural producers, including key people from agribusiness and organic agriculture, seeking collaborative solutions that include the sustainable use of insectivorous bats;
- Incentives for using environmental education and outreach to demystify bats, resolve conflict problems and improve the general population's knowledge of how bats are essential for maintaining biodiversity.

Through incentives, public policies and private sector actions that consider these suggestions, we will improve our knowledge to enhance bat conservation and production sustainability in one of the largest agricultural producers in the world. Specifically, regarding financial incentives for researchers to advance these themes, there must be strong integration between the different actors in the productive sector, mainly the private sector. Moreover, producers must bear in mind that they only gain from this, as this is an invest-

ment and not a loss of financial resources, as it will produce more sustainable food and may even add more value to their product.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su16145858/s1>, Bibliographic review method; bibliography list: (1) studies on diet; (2) studies that describe bioacoustic parameters; (3) habitat use; and (4) use of roosts. The remaining studies were classified as “other”.

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