



Universidade Federal de Uberlândia
Instituto de Biologia
Programa de pós-graduação em Ecologia, Conservação e
Biodiversidade



Os beija-flores e as pessoas: desvendando a contribuição da
ciência cidadã e o efeito da urbanização nas interações com as
flores

Camila Ferreira Bosenbecker

2024

Camila Ferreira Bosenbecker

Os beija-flores e as pessoas: desvendando a contribuição da
ciência cidadã e o efeito da urbanização nas interações com as
flores

Tese apresentada à Universidade
Federal de Uberlândia, como parte das
exigências para obtenção do título de
Doutor em Ecologia, Conservação e
Biodiversidade

Orientador: Pietro K. Maruyama
Co-orientador: Paulo E. Oliveira

Uberlândia-MG

Novembro 2024

Dados Internacionais de Catalogação na Publicação (CIP)
Sistema de Bibliotecas da UFU, MG, Brasil.

- B743b
2024
- Bosenbecker, Camila Ferreira, 1993-
Os beija-flores e as pessoas [recurso eletrônico]: desvendando a contribuição da ciência cidadã e o efeito da urbanização nas interações com as flores / Camila Ferreira Bosenbecker. - 2024.
- Orientador: Pietro K. Maruyama.
Coorientador: Paulo E. Oliveira.
Tese (Doutorado) - Universidade Federal de Uberlândia, Programa de Pós-graduação em Ecologia, Conservação e Biodiversidade.
Modo de acesso: Internet.
Disponível em: <http://doi.org/10.14393/ufu.te.2024.5508>
Inclui bibliografia.
Inclui ilustrações.
1. Ecologia. 2. Biodiversidade. 3. Ecologia urbana. I. Maruyama, Pietro K., 1985-, (Orient.). II. Oliveira, Paulo E., 1959-, (Coorient.). III. Universidade Federal de Uberlândia. Programa de Programa de Pós-graduação em Ecologia, Conservação e Biodiversidade. IV. Título.

CDU: 574



ATA DE DEFESA - PÓS-GRADUAÇÃO

Programa de Pós-Graduação em:	Ecologia, Conservação e Biodiversidade				
Defesa de:	Tese, número 97, PPGECEB				
Data:	primeiro de novembro de dois mil e vinte e quatro	Hora de início:	13:30	Hora de encerramento:	17:30
Matrícula do Discente:	12023ECR001				
Nome do Discente:	Camila Ferreira Bosenbecker				
Título do Trabalho:	Os beija-flores e as pessoas: desvendando a contribuição da ciência cidadã e o efeito da urbanização nas interações com as flores				
Área de concentração:	Ecologia				
Linha de pesquisa:	Ecologia aplicada e conservação				
Projeto de Pesquisa de vinculação:	Tornando modelos de distribuição geográfica mais aplicáveis para a conservação de espécies				

Reuniu-se por videoconferência a Banca Examinadora designada pelo Colegiado do Programa de Pós-graduação em Ecologia, Conservação e Biodiversidade assim composta pelos doutores: Jefferson Vizentin Bugoni - UFPel; Vinicius Lourenço Garcia de Brito - UFU; Fernando Augusto de Oliveira e Silveira - UFMG; Renata Trevizan Telles de Souza - UFMG e Pietro Kiyoshi Maruyama Mendonça - UFMG, orientador(a) do(a) candidato(a).

Iniciando os trabalhos o(a) presidente da mesa, Dr(a). Pietro Kiyoshi Maruyama Mendonça, apresentou a Comissão Examinadora e o(a) candidato(a), agradeceu a presença do público e concedeu ao(à) Discente a palavra para a exposição do seu trabalho. A duração da apresentação do(a) Discente e o tempo de arguição e resposta foram conforme as normas do Programa.

A seguir o(a) senhor(a) presidente concedeu a palavra, pela ordem sucessivamente, aos(às) examinadores(as) que passaram a arguir o(a) candidato(a). Ultimada a arguição, que se desenvolveu dentro dos termos regimentais, a Banca, em sessão secreta, atribuiu o resultado final, considerando o(a) candidato(a):

Aprovado(a).

Esta defesa faz parte dos requisitos necessários à obtenção do título de Doutor.

O competente diploma será expedido após cumprimento dos demais requisitos, conforme as normas do Programa, a legislação pertinente e a regulamentação interna da UFU.

Nada mais havendo a tratar foram encerrados os trabalhos. Foi lavrada a presente ata que após lida e achada conforme foi assinada pela Banca Examinadora.



Documento assinado eletronicamente por **Pietro Kiyoshi Maruyama Mendonça, Usuário Externo**, em 06/11/2024, às 10:16, conforme horário oficial de Brasília, com fundamento no art. 6º, § 1º, do [Decreto nº 8.539, de 8 de outubro de 2015](#).



Documento assinado eletronicamente por **Fernando Augusto de Oliveira e Silveira, Usuário Externo**, em 06/11/2024, às 11:01, conforme horário oficial de Brasília, com fundamento no art. 6º, § 1º, do [Decreto nº 8.539, de 8 de outubro de 2015](#).



Documento assinado eletronicamente por **Renata Trevizan Telles de Souza, Usuário Externo**, em 06/11/2024, às 13:44, conforme horário oficial de Brasília, com fundamento no art. 6º, § 1º, do [Decreto nº 8.539, de 8 de outubro de 2015](#).



Documento assinado eletronicamente por **Jeferson Bugoni, Usuário Externo**, em 07/11/2024, às 14:20, conforme horário oficial de Brasília, com fundamento no art. 6º, § 1º, do [Decreto nº 8.539, de 8 de outubro de 2015](#).



Documento assinado eletronicamente por **Vinicius Lourenço Garcia de Brito, Professor(a) do Magistério Superior**, em 07/11/2024, às 21:28, conforme horário oficial de Brasília, com fundamento no art. 6º, § 1º, do [Decreto nº 8.539, de 8 de outubro de 2015](#).



A autenticidade deste documento pode ser conferida no site https://www.sei.ufu.br/sei/controlador_externo.php?acao=documento_conferir&id_orgao_acesso_externo=0, informando o código verificador **5828506** e o código CRC **82F4EBBE**.

AGRADECIMENTOS

Primeiramente, um grande obrigado a todos os meus amigos e familiares. Vocês foram meu porto seguro durante essa jornada, sempre prontos para oferecer apoio, palavras de incentivo e aquele abraço reconfortante quando a pressão aumentava. Não teria chegado até aqui sem vocês!

Aos meus colegas do CSEC, cada pausa para um café se transformou em um momento de descontração e troca de ideias que fez toda a diferença. As conversas e as fofocas durante esses encontros tornaram as longas horas de trabalho muito mais leves e divertidas. Um agradecimento especial aos amigos do CSEC Polinização, vocês são demais, tenho muito orgulho de ter feito parte dessa equipe maravilhosa!

Ingrid e Victor, vocês foram meus parceiros de coleta e tornaram cada expedição um momento incrível. Agradeço pela companhia, pelas risadas e pela disposição em enfrentar os desafios juntos. Pedro, mesmo nos dias em que o frio parecia vencer sua vontade de aparecer nas coletas (e você acabava dormindo e não aparecia), sua ajuda foi crucial. E Teresa, suas contribuições no campo foram incríveis. A presença de vocês sempre trouxe um ânimo a mais!

Um agradecimento também à CAPES e ao CNPq, que forneceram os recursos financeiros necessários para a realização deste trabalho. À Prefeitura de Belo Horizonte e à Fundação de Parques Municipais e Zoobotânica, pela permissão para realizar a coleta em suas áreas. Essa oportunidade me permitiu explorar Belo Horizonte e conhecer lindos parques, que se tornaram cenários da minha pesquisa.

Um agradecimento especial ao meu co-orientador Paulo, pelo apoio e suporte. E, claro, ao meu orientador Pietro. Você não foi apenas um orientador excepcional, mas se tornou um grande amigo e um segundo pai nessa cidade nova que, aos poucos, foi se tornando minha casa. Seu apoio constante e sua confiança em mim foram fundamentais para eu superar os desafios e crescer profissionalmente, aprendi muito com você!

Valeu, galera! Essa conquista é nossa!

ÍNDICE

RESUMO GERAL	01
ABSTRACT	02
INTRODUÇÃO GERAL	03
CAPÍTULO 1: Contrasting nation-wide citizen science and expert collected data on hummingbird–plant interactions.....	08
Abstract	09
Introdução	10
Material e Métodos	13
Resultados	17
Discussão	21
Conclusões	25
Referências Bibliográficas	26
CAPÍTULO 2: Consistent generalization of hummingbird-plant networks despite increasing vegetation cover across a tropical urban landscape	35
Abstract	36
Introdução	37
Material e Métodos	40
Resultados	46
Discussão	50
Conclusões.....	55
Referências Bibliográficas	56
CONCLUSÃO GERAL	66
REFERÊNCIAS GERAL	69

RESUMO

Bosenbecker, Camila 2024. Os beija-flores e as pessoas: desvendando a contribuição da ciência cidadã e o efeito da urbanização nas interações com as flores. Tese de Doutorado em Ecologia, Conservação e Biodiversidade. UFU. Uberlândia-MG. 76p.

Beija-flores são conhecidos por sua dieta especializada em néctar e desempenham um papel vital na manutenção dos ecossistemas pelo papel na polinização. No entanto, diversas espécies estão em declínio global, devido à perda de habitat e às mudanças climáticas. A transformação dos ambientes pela ação humana não apenas ameaça essa interação, mas também altera a composição das comunidades. Por outro lado, atividades humanas como a observação de aves despertam grande interesse, gerando registros de ciência cidadã que contribuem para o entendimento da biologia dessas aves. Essa prática popular ao redor do mundo tem enorme potencial para fornecer dados valiosos sobre biodiversidade. Com isso, esta tese investiga dois aspectos da relação das pessoas com as interações entre beija-flores e plantas: a ciência cidadã como ferramenta de contribuição ao conhecimento científico e o impacto da urbanização nessas interações. O primeiro capítulo explora o papel da ciência cidadã na complementação dos dados coletados por cientistas profissionais, utilizando a plataforma Wikiaves. Os resultados revelam que os dados gerados por cidadãos podem cobrir grandes áreas geográficas, capturando interações não observadas por cientistas. Embora existam limitações, como a falta de padronização dos dados e o foco em áreas urbanas, esses dados são promissores para estudos de biodiversidade e conservação. É importante ressaltar que a ciência cidadã não apenas documenta espécies comuns, mas também registra espécies ameaçadas, oferecendo uma rica fonte de informações para políticas públicas, além de incentivar a promoção do envolvimento do público geral na ciência. O segundo capítulo avalia as mudanças na estrutura das redes de interação planta-beija-flor ao longo de um gradiente de urbanização. Os resultados mostram que essas interações são em grande parte generalistas, com alta predominância de plantas não-nativas, independentemente do nível de urbanização. Apesar das redes urbanas se mostrarem generalistas, a presença de plantas nativas foi associada a uma maior especialização nas interações, sugerindo que a diversidade de plantas nativas desempenha um papel crucial na promoção de redes mais complexas e na sustentação de polinizadores em paisagens urbanas. Uma convergência entre os dois capítulos é que a ciência cidadã tem grande potencial para monitorar e conservar a biodiversidade em áreas urbanas. Ao engajar o público na coleta de dados, essa abordagem democratiza o conhecimento científico e fornece dados valiosos para pesquisadores e gestores ambientais. Além de gerar dados robustos, a ciência cidadã fortalece o vínculo entre a população e a natureza, promovendo conscientização e engajamento na preservação ambiental. Por outro lado, é crucial que os planejadores urbanos reconheçam a necessidade de integrar a conservação da biodiversidade no planejamento das cidades. Somente com políticas públicas adequadas e envolvimento da comunidade será possível reduzir os impactos negativos da urbanização e promover cidades mais sustentáveis e amigáveis à natureza.

Palavras-chave: ecologia urbana, observação de aves, plantas nativas, redes de interação, espaços verdes urbanos, Wikiaves.

ABSTRACT

Bosenbecker, Camila 2024. Hummingbirds and people: uncovering the contribution of citizen science and the effect of urbanization on interactions with flowers. MSc. thesis UFU. Uberlândia-MG. 76p.

Hummingbirds are known for their specialized nectar diet and play a vital role in maintaining ecosystems through pollination. However, these species are in decline globally due to habitat loss and climate change. Human-induced changes to their habitats not only threaten their interaction but also alter the composition of communities. On the other hand, some human activities, such as birdwatching, generate great interest, generating citizen science records that can contribute to a better understanding of hummingbird biology. This popular practice worldwide has enormous potential to provide valuable data on biodiversity. Therefore, this thesis investigates two aspects of the relationship between people and hummingbird-plant interactions: the potential of citizen science to contribute to scientific knowledge and the impact of urbanization on these interactions. The first chapter explores the role of citizen science in complementing the data collected by professional scientists using the Wikiaves platform. The results reveal that citizen-generated data can cover large geographical areas, capturing interactions not observed by scientists. Although there are limitations, such as the lack of data standardization and the focus on urban areas, these data are promising for biodiversity and conservation studies. It is important to emphasize that citizen science not only documents common species but also records of endangered species, offering a rich source of information for public policies as well as promoting general public involvement in science. The second chapter evaluates the changes in the structure of plant-hummingbird interaction networks along a gradient of urbanization. The results show that these interactions are largely generalized, with a high predominance of non-native plants, regardless of the level of urbanization. Although urban networks were generalized, the presence of native plants was associated with greater specialization in interactions, suggesting that native plant diversity plays a crucial role in promoting more complex networks and sustaining pollinators in urban landscapes. One convergence between the two chapters is that citizen science has great potential for monitoring and conserving biodiversity in urban areas. Engaging the public in data collection democratizes scientific knowledge and provides valuable data for researchers and environmental managers. In addition to generating robust data, citizen science strengthens the link between the population and nature, promoting awareness and engagement in environmental conservation. On the other hand, it is crucial that urban planners recognize the need to integrate biodiversity conservation into city planning. Only with appropriate public policies and community involvement will it be possible to reduce the negative impacts of urbanization and promote more sustainable and nature-friendly cities.

Keywords: birdwatching, interaction networks, native plants, urban ecology, urban green spaces, Wikiaves.

INTRODUÇÃO GERAL

Beija-flores estão entre os grupos de polinizadores mais carismáticos e representam uma das famílias (Trochilidae) mais diversas dentro da Classe Aves, destacando-se por sua extrema especialização na dieta à base de néctar das flores (Zanata et al. 2017). Ao estabelecer interações mutualísticas e, em alguns casos, não mutualísticas com milhares de espécies de plantas nas Américas esses polinizadores desempenham um papel essencial nos ecossistemas. Algumas plantas dependem dos beija-flores para sua polinização, enquanto os beija-flores, por sua vez, dependem do néctar dessas plantas para sua alimentação (Barreto et al., 2024). Essa relação de interdependência é vital, pois os polinizadores são responsáveis pela reprodução da maioria das espécies de plantas com flores (Ollerton et al., 2011). Assim, a presença desses polinizadores é fundamental para garantir a manutenção da biodiversidade desses ecossistemas.

No entanto, os beija-flores estão em declínio global, com 60% das espécies apresentando queda populacional (Leimberger et al., 2022). Este declínio pode levar à extinção de plantas que dependem diretamente deles para polinização, principalmente nos trópicos, onde plantas polinizadas por vertebrados são ainda mais dependentes de seus polinizadores (Ratto et al., 2018). A perda de habitat e as mudanças climáticas são as principais ameaças enfrentadas por esses polinizadores (Leimberger et al., 2022). As características ecológicas dos beija-flores, como sua grande mobilidade, tolerância a amplas condições ambientais e variação morfológica, os tornam polinizadores particularmente eficazes e vantajosos para muitas plantas (Barreto et al., 2024). Ainda assim, a queda na biodiversidade, observada nas últimas décadas (Butchart et al., 2010), impacta diretamente o funcionamento dos ecossistemas (Cardinale et al., 2012). Essa redução na biodiversidade é amplamente impulsionada pelas atividades humanas, que representam uma ameaça significativa à biodiversidade global (Vitousek et al., 1997; Seto

et al., 2012). As interações entre plantas e polinizadores têm sido impactadas negativamente pela crescente urbanização, uma das principais transformações do uso da terra decorrente de atividades humanas, resultando em homogeneização biótica e perda de espécies especializadas (McKinney 2006). Grandes centros urbanos podem ser considerados desertos biológicos devido à sua matriz que raramente volta a condições naturais após o processo de urbanização (Sandström et al. 2006; Marzluff e Ewing 2001).

Apesar dos impactos que a urbanização pode causar, alguns trabalhos vêm demonstrando que a presença de áreas verdes urbanas pode ajudar a reduzir seus efeitos negativos (Sandström et al. 2006, Fontana et al. 2011, Carbó-Ramírez e Zuria 2011). Áreas verdes podem fornecer diferentes serviços ecossistêmicos, como polinização, regulação de clima local, qualidade do ar e habitat para espécies (Ziter 2016); com importante função para a conservação da biodiversidade (Aronson et al. 2017). Através do planejamento da vegetação urbana podemos mitigar os impactos humanos, pois a manutenção de grandes árvores e o aumento da riqueza de plantas podem reduzir os efeitos negativos da urbanização sobre a biodiversidade (Pena et al. 2017). Para tanto, é importante que áreas urbanas possuam uma vegetação complexa estruturada com diferentes estratos, com grandes árvores e arbustos bem desenvolvidos (Sandström et al. 2006).

O planejamento de áreas verdes urbanas tem sido amplamente discutido na última década, pois esses locais podem incluir uma variedade de habitats, desde remanescentes de vegetação nativa até infraestruturas verdes projetadas (Aronson et al. 2017). É crucial considerar esses ambientes, pois eles podem favorecer diversas espécies de plantas, animais e outros organismos, impulsionando a diversidade em áreas antropizadas. Áreas verdes ricas e diversas, com uma grande variedade de plantas, têm o potencial de atrair polinizadores e beneficiar a biodiversidade. No entanto, planejar a composição de plantas

nesses ambientes é um desafio, pois, embora a floração prolongada e outros aspectos estéticos seja importante para a sociedade, sua função ecológica também deve ser considerada. Recentemente, estudos têm destacado a importância do uso de plantas ornamentais nativas em áreas verdes urbanas (Berthon et al., 2021). Essas plantas podem fornecer recursos essenciais e beneficiar a fauna local. Entretanto, a maioria das interações de beija-flores em ambientes urbanos pode envolver plantas não-nativas, que fornecem uma grande proporção de recursos de néctar ao longo do ano (Anselmo et al. 2023).

Se por um lado, a transformação dos ambientes pela ação humana afetam as interações entre animais e plantas, por outro, alguns grupos de animais atraem bastante atenção das pessoas por meio da atividade de observação e dos registros naturalísticos. Uma das práticas que mais se destaca nesse contexto é a observação de aves por amadores, conhecida internacionalmente como *birdwatching*, uma atividade amplamente popular em todo o mundo. Essa prática oferece um grande potencial para a ciência cidadã, gerando dados valiosos que ampliam o acesso às informações sobre padrões de biodiversidade (Theobald et al., 2015). A observação de aves é uma atividade que envolve milhões de pessoas (Sekercioglu, 2002), e pode inclusive envolver atividades de ciência cidadã (Barbosa et al., 2021). Tradicionalmente, estudos que avaliam interações de aves com as flores empregam técnicas clássicas como observação direta de espécies (Anselmo et al., 2023), amostragens de néctar (Tinoco et al., 2016) e até mesmo análise de carga de pólen (Castellanos et al., 2003), realizadas por pesquisadores. Essas técnicas, embora eficazes, possuem algumas limitações como restrição de cobertura espacial, desafios relacionados à precisão taxonômica de amostras fecais e pólen, além da necessidade de tempo de coleta e custos elevados. Neste contexto, a ciência cidadã emerge como uma ferramenta valiosa para enfrentar esses desafios. Através do engajamento de voluntários

na coleta de dados, a ciência cidadã é frequentemente utilizada para obter grandes volumes de informações permitindo a expansão da cobertura de dados (Silvertown, 2009), com baixos custos e promovendo o conhecimento científico ao público geral (Bonney et al., 2009).

Considerando esse contexto, esta tese de doutorado aborda duas frentes da relação entre as pessoas e os beija-flores, um deles busca preencher lacunas sobre interações ecológicas em ambientes urbanizados e outro, utiliza dados de ciência cidadã para entender como a observação de aves por entusiastas pode complementar o entendimento das interações acumulados pelos acadêmicos ao longo dos anos. Os trabalhos apresentados aqui fornecem insights para propor estratégias de manejo e conservação de locais antropizados, contribuindo para a preservação da biodiversidade de beija-flores.

A tese está estruturada em dois capítulos. O primeiro capítulo explora a contribuição da ciência cidadã para o entendimento das interações beija-flor-planta, utilizando o Brasil e a plataforma Wikiaves como um modelo de estudo. Mostramos que há uma grande complementação entre os dados coletados por cientistas e pelos observadores de aves, contribuindo para um melhor entendimento das interações entre beija-flores e plantas. O segundo capítulo avalia como a urbanização influencia essas interações em um grande centro urbano, Belo Horizonte, em Minas Gerais, também conhecida como a capital mundial do pão de queijo. Neste trabalho, mostramos que a organização da rede de interação entre beija-flores e plantas não apresenta grande variação, mesmo como aumento da cobertura vegetal na paisagem. Contudo, nossos resultados indicam que uma maior proporção de flores nativas esteve associada a uma maior especialização nas interações. Juntos, esses estudos oferecem visões complementares na interação entre pessoas e beija-flores (e suas flores), destacando os benefícios de envolver o público nas informações biológicas, assim como de fatores

ligados a urbanização que afetam as interações ecológicas e possíveis recomendações para a conservação destas interações e das funções ecossistêmicas associadas.

CAPÍTULO 1

Contrasting nation-wide citizen science and expert collected data on species interactions: hummingbird-plant interactions in Brazil

Camila Bosenbecker^{1,2}, Pedro Amaral Anselmo^{1,3}, Roberta Zuba Andreoli¹, Gustavo Hiroaki Shimizu⁴, Paulo Eugênio Oliveira² & Pietro Kiyoshi Maruyama^{1,2,3}

1. Centro de Síntese Ecológica e Conservação, Departamento de Genética Ecologia e Evolução – ICB, Universidade Federal de Minas Gerais, Belo Horizonte- MG, Brazil

2. Programa de Pós-Graduação em Ecologia, Conservação e Biodiversidade, Instituto de Biologia, Universidade Federal de Uberlândia, Uberlândia-MG, Brazil

3. Programa de Pós-Graduação em Ecologia, Conservação e Manejo da Vida Silvestre, Universidade Federal de Minas Gerais, Belo Horizonte- MG, Brazil

4. Departamento de Biologia Vegetal, Instituto de Biologia, Universidade Estadual de Campinas, Campinas-SP, Brazil

BOSENBECKER, Camila *et al.* Contrasting nation-wide citizen science and expert collected data on hummingbird–plant interactions. *Perspectives in Ecology and Conservation*, v. 21, n. 2, p. 164-171, 2023. <https://doi.org/10.1016/j.pecon.2023.03.004>

Abstract

Citizen science has the potential to increase the efficiency of scientific data collection. However, such initiatives often focus on unique taxa for each record, not necessarily involving interspecific interactions. Moreover, whether openly available unstructured citizen science data can contribute to better understand ecological patterns is still not well understood. Here, we identify hummingbird-plant interactions recorded by amateur birdwatchers in the most popular online platform in Brazil, Wikiaves. Then, we evaluated how this information can benefit our understanding of interactions in a large Tropical country by comparing with data generated by experts. We also constructed a nation-wide meta-network to identify the structural roles of hummingbirds and plants. In total, 3210 interactions were compiled, with better hummingbirds and geographic coverage of citizen data in relation to expert data. The interaction network showed a modular pattern, and some plant species found as most frequently interacting here were similar to those found by experts. Nevertheless, when comparing the plant partners for hummingbirds featured in both expert and citizen data, the proportion of plants in common were generally low (usually less than 40%), indicating that amateur birdwatchers are mostly recording interactions not captured by scientists. Finally, as in other cases of compilation of interaction data, we found that sampling intensity (here, number of photographs) is a strong driver of interaction records, highlighting the unique challenge of separating biologically meaningful patterns from sampling artifacts in citizen science data. Our study illustrates the richness of citizen-gathered biodiversity data available in a megadiverse country, which show great potential to complement expert collected data.

Keywords: birdwatching, Brazil, interaction networks, *Phaethornis pretrei*, pollinators, Wikiaves.

Introduction

Citizen science has gained popularity in recent decades, helping to advance scientific knowledge (Bonney et al., 2009). It consists of the participation of the general public in the construction of knowledge through the collection of information, including photographic records, and interpretation of results (Miller-Rushing et al., 2012). Research projects in ecology use citizen science data mainly to obtain large amounts of information, allowing expansion of data coverage (Silvertown, 2009). The partnership between experts and non-professionals has the potential to increase the efficiency of scientific data collection by providing more complex and comprehensive data (Roy et al., 2016). In addition, it allows the population to actively engage in science, improving scientific literacy and society's interest in the subject being investigated (Cohn, 2008; Stafford et al., 2010). The involvement of society in citizen science projects generally happens in two ways: (1) the public participating in a scientific project by producing specific and structured information for scientists; (2) the public can contribute through crowdsourcing, usually involving a large number of people, with an undefined audience providing data across wide geographic regions by using e.g., social media platforms (McKinley et al., 2017; Muñoz et al., 2020). In this context, the development of tools and internet platforms that assist in the dissemination of information obtained by the general public is one of the factors responsible for the growing amount of data collected by citizen scientists. Such platforms allow interactions among users through comments, discussions, and photo sharing, expanding social groups by facilitating the contribution of the population to science (Stafford et al., 2010; Tubelis, 2023).

A practice that is very popular worldwide and presents a great potential to contribute to citizen science is birdwatching, which is the act of observing and identifying birds in their native habitats (Sekercioglu, 2002). Birdwatching is among the most popular

type of ecotourism, and by collecting photographic and audio records of birds, identifying different species, and analyzing behavior, vocalizations, habits, migrations, and their interactions with other organisms, birdwatchers can also contribute with new scientific knowledge (Sekercioglu, 2002). Owing to their popularity, there are several different platforms that include information on occurrence and biology of birds such as the Cornell Lab of Ornithology's eBird (<https://ebird.org>) or broader initiatives such as iNaturalist (<https://www.inaturalist.org/>), which includes many different organisms. Such citizen science initiatives usually focus on single taxa in each record, and not necessarily on specific records of two or more organisms associated in ecological interactions, for which data generation can be more challenging (Groom et al., 2021, but see Marín-Gómez et al., 2022; Tubelis, 2023).

Pollination is a major interaction between plant and animals, which supports ecosystem functions across terrestrial ecosystems and also provides relevant ecosystem services (Ollerton et al., 2011). In this context, a previous study by Kremen et al. (2011) assessed the floral visitor abundance data collected by citizen scientists with data collected by professional scientists in an agricultural landscape in California-USA. Their results showed that citizen scientists collected observational data similar to that collected by professional scientists and equally useful for science. However, there are still few studies comparing citizen and expert generated interaction data (Kremen et al., 2011). Such projects may be especially relevant in the tropics, where there is a higher diversity of pollinators and plants, but which has been comparatively less studied (e.g., Maruyama et al., 2022). Brazil is considered one of the most biodiverse tropical countries in the world (Lewinsohn and Prado, 2005). This includes birds, with more than 1900 species cataloged in the country (Pacheco et al., 2021). Although not a formal citizen science initiative, in the sense that it was conceived to support a specific science project, the

Wikiaves website (www.wikiaves.com.br) is a popular platform in Brazil that receives more than 1000 bird media files daily, consisting in a large database with an important role in gathering information on Brazilian birds. The website encompasses information on behavioral records, distribution, reproduction, natural history, and migration (Cunha and Fontenelle, 2014; Tubelis, 2023). The easy access of scientists to this information has allowed them to carry out research projects to gather distribution and breeding biology data, records of rare species and even to evaluate ecological interactions (Cunha and Fontenelle, 2014; Tubelis and Sazima, 2021; Turella et al., 2022). As English literacy is generally low in Brazil, this Portuguese language platform is widely used by amateur birdwatchers, more so than other international platforms (Barbosa et al., 2021; Tubelis, 2023). We took advantage of this platform to investigate the usefulness of unstructured citizen science data on understanding plant-bird interactions. Birds provide essential ecosystem functions including pollination (Whelan et al., 2008), and among them hummingbirds are the most speciose and specialized group (Fleming and Muchhala, 2008; Zanata et al., 2017). Moreover, there are several compilations in hummingbird–plant community-wide interaction data already published in the literature, which include data from Brazil (Araujo et al., 2018; Dalsgaard et al., 2021; Maruyama et al., 2019). Therefore, we were able to effectively compare the data collected by scientists and non-scientists regarding these interactions in Brazil, as a biodiverse model country.

Here, we aim to identify patterns of hummingbird-plant interactions with data that have not been collected by scientists and evaluate how this information can benefit our understanding of these interactions. Specifically, we asked: (1) which species of hummingbirds and plants were most frequently recorded interacting?; (2) were legitimate interactions, with potential for pollination, recorded more often than illegitimate interactions (i.e., robbing and thieving)?; (3) what are the network roles played by

different hummingbird and plant species in the nationwide modular meta-network?; (4) how overlapping are the interactions of hummingbirds with plants recorded by non-scientists and previously reported data in the literature?; and finally (5) how sampling intensity, i.e., total number of photographic records for each hummingbird species, influences the characterization of interaction patterns? We hope that by answering these questions, we are able to highlight the strengths and challenges associated with the large amount of unstructured and seldom used citizen generated data to better understand species interactions and tropical biodiversity.

Materials and methods

Data collection: citizen science platforms

Eighty-nine species of hummingbirds are found in Brazil (Pacheco et al., 2021), and are among many of the records included in the Wikiaves platform (www.wikiaves.com.br), which is a Brazilian website created in 2008 with the objective of promoting birdwatching. Through the collaboration of users, it has become an online database with photographic and audio records and other information about Brazilian bird species. The site brings together the largest online community of birdwatchers in Brazil and allows the interaction of collaborators, which makes it an important tool for the amateur birdwatchers in the country (Dias, 2011; Tubelis, 2023).

We surveyed for the interaction events on the Wikiaves platform, entered between January 2008 (date of creation of the platform) until May 9, 2021, the day of the last access. We analyzed the photos of all hummingbird species recorded in Brazil (Pacheco et al., 2021). We considered as one record of interaction when the image showed an individual hummingbird and a flower. Only records made in Brazil were considered, and photos that referred to the same event (i.e., images made in the same location, date and

by the same author) were counted only once. We sought to identify the plant species associated with hummingbirds to the lowest taxonomic level possible, using keys and illustrated books. Plant species were classified as native or non-native and according to their habit (herbaceous, shrubby or arboreal) using the Flora e Funga do Brasil (2022) website and were identified to the lowest taxonomic level possible. Some plants were only classified at the level of genus, and in a few cases at the level of family. For simplicity, we refer to each recorded morphospecies as “species” henceforth. For example, the plants from the genus *Inga* could not be identified at the species level from the photographs due to the similarity in their flower morphology, so we probably lumped together several distinct species in our data. Additional information such as sex, age of the hummingbird (young, adult or undefined), author, locality where the interaction was observed, type of visit (legitimate or illegitimate), the date the photo was taken and date of publication in the platform were also compiled. We also classified hummingbird species according to red list status (IUCN, 2022).

The compiled hummingbird-plant interaction data were then compared with the interaction datasets previously reported by Araujo et al. (2018); Dalsgaard et al. (2021) and Maruyama et al. (2019), which compiled information of plant–hummingbird interactions at different localities in Brazil. Dalsgaard et al. (2021) also included localities from other countries, which were not considered here. The experts' data covered different Brazilian ecosystems, totaling 72 localities/communities (Atlantic Forest $n = 36$, Cerrado $n = 18$, Caatinga $n = 8$, Pampa $n = 4$, Pantanal $n = 3$, Campos Rupestres $n = 3$; Fig. 1, Table S2).

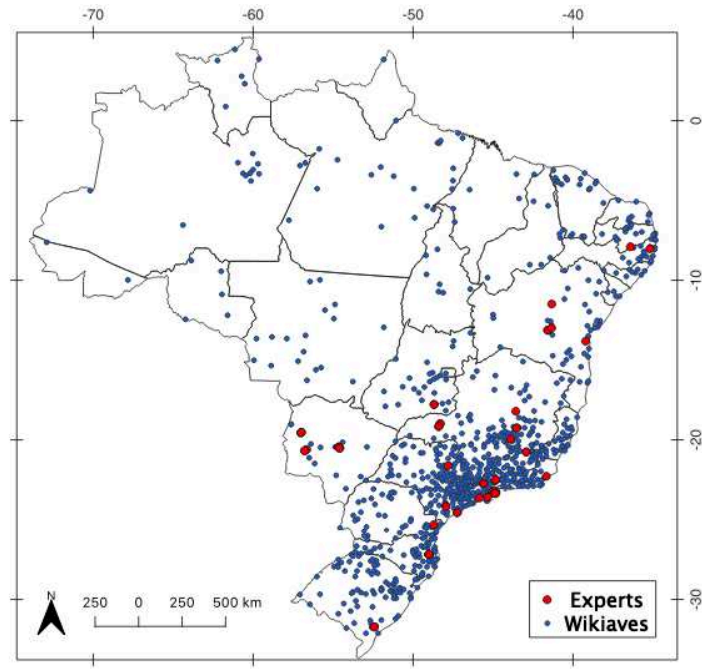


Fig 1: Distribution of hummingbird-plant photographic records extracted from the online platform Wikiaves (in blue), in contrast to localities where expert data were collected (in red) in Brazil.

Hummingbird-plant interaction networks

From the analyzed images, two matrices of quantitative interactions were constructed, considering the number of photos a specific hummingbird-plant combination was represented as a measure of the strength of the interactions. In the first matrix (Total Matrix), we considered all records of a hummingbird interacting with a flower (irrespective of legitimate or illegitimate), while in the second matrix (Pollination Matrix), the criterion was refined to consider only the records of hummingbirds accessing the flowers legitimately, i.e., touching the reproductive structures of the flower in the photos, with potential for pollination interactions.

Data Analysis

To characterize the hummingbird-plant meta-network structure and species role, we calculated modularity, which was calculated with the DIRTLPWb + algorithm

(Beckett, 2016). This algorithm identifies modules in weighted networks. Significances of metrics at the network level were assessed by comparing observed values with those generated by null models ($n = 1000$). Here we used the *r2dtable* null model, which constraints the network size and the marginal totals in the simulations (Dormann et al., 2008). The roles of the species in the modular network were identified using the "*c*" and "*z*" scores. Among-module-connectivity (*c*) indicates the role of species as connectors of different modules, while the within-module degree (*z*) indicates the relevance of each species within its module (Olesen et al., 2007). Species can then be categorized according to their role in the modular network by crossing the values of these two indices, as: connectors (high *c* and low *z* values), peripherals (low values of *c* and *z*), network hubs (high values of *c* and *z*) or module hubs (high *z* and low *c* values). Following Dormann and Strauss (2014), we used threshold values determined by using 95% quantiles from the null networks, with $z = 2.8$ and $c = 0.62$ as critical values to define species roles. In meta-networks spanning wide areas such as ours, interactions are expected to reflect both the geographic distribution and ecological attribute of species that determine interactions locally when species co-occur (Araujo et al., 2018). Thus, spatial co-occurrence is an essential first template for species to interact, determining the potential interactions that may or may not be realized according to other attributes, such as traits and abundances of species (Bartomeus et al., 2016). All network analyses were performed in the R package '*bipartite*' (Dormann et al., 2008).

To evaluate the overlap in plant partners interacting with hummingbirds between citizen and expert collected data, we estimated the proportion of plant species in common between the two sources in relation to the total number of plant species and hummingbirds which were found interacting in Wikiaves. Thus, if a hummingbird species *A* interacted with *n* number of plants in the Wikiaves platform, we estimated the proportion of these *n*

plants that also appeared interacting with hummingbird A in the expert data. Finally, we adjusted two simple linear regressions taking the total number of records for a hummingbird (i.e., number of photographs in Wikiaves) as the predictor variable: (1) with the number of observed plant species visited in the citizen data as the response variable, to evaluate sampling effects; and (2) with the richness of plants visited in the expert data, to evaluate the correspondence between the two datasets. The data were log transformed to improve the fit after checking the residuals. All analyses were conducted in R (R Core Team, 2020).

Results

In total, 3210 interactions were compiled from the Wikiaves platform (of which 634 interactions were nectar robbery and theft, 19.75%), distributed across all Brazilian states and biomes, in contrast to expert collected data (Fig. 1, Table S1). Of the 89 hummingbird species observed in Brazil, the online platform included records for 70 species. The species most frequently found interacting with flowers was *Phaethornis pretrei* (Fig. 2A), with 412 records, representing 12.83% of the images analyzed. The second and third most recorded species were *Chlorostilbon lucidus* with 322 records (10.03%) and *Florisuga fusca* with 207 records (6.44%). Two species were classified as threatened (*Phaethornis margarettae*, *Thalurania watertonii*) and one as vulnerable (*Phaethornis aethopygus*) by the IUCN Red List (IUCN, 2022). As for the plants, a total of 292 different morphospecies were identified, 161 at the species level (55.2%), 124 at the genus level (42.6%) and 7 at the family level (2.39%). Of the plants identified at the species level, 49.6% were classified as native, 40.3% as non-native, and for 9.93% we had no information. Within the native plants, 22 species were classified as endemic to Brazil. The plants presented predominantly shrubby habit (34.7%), followed by herbs

(24.8%) and trees (20.4%).

C. lucidus was the hummingbird species that interacted with the highest number of plants (98 species), which represents 34.5% of the total plant morphospecies identified. It was followed by *Eupetomena macroura* (85 species, Fig. 2B) and *P. pretrei* (79 species). From the plant perspective, the species recorded interacting with the highest number of hummingbirds (36 species, 51.42%) was *Inga sp.*, which could not be identified at the species level from the photographs owed to similarity in flower morphology within the genus. The second and third species that interacted most with hummingbird species were the non-native *Grevillea banksii* (30 hummingbird species, 42.85%) and the native *Lantana camara* (26 hummingbird species, 37.14%).

When comparing the geographical distribution of the data, although there seems to be a concentration of data towards the Atlantic coast, which parallels the country's demography, the citizen data covered 889 cities in Brazil, including many localities in the Brazilian Amazon not covered by expert data (Fig. 1). The experts' data covered only 36 cities.

The two interaction networks compiled showed a modular pattern with higher observed values than expected by the null model that incorporates species richness and marginal totals. The total interaction network (including legitimate and illegitimate interactions) had a modularity of $Q = 0.383$ ($p < 0.001$), with 15 modules (Fig. 2C). In this modular network, all hummingbird species acted as peripherals. When considering the plants, seven species were classified as module hubs (*Calliandra sp.*, *Dioclea sp.*, *Inga sp.*, *Isertia sp.*, *Ixora coccinea*, *L. camara*, *Vismia sp.*). The other 97.6% of the species were classified as peripherals, no species was identified as a network hub or connectors.

In the pollination network, modularity was slightly higher $Q = 0.413$ ($p < 0.001$),

with 23 modules, and all hummingbird species were classified as peripherals. For the plants side, eight species acted as module hubs (*Heliconia* sp., *Inga* sp., *I. coccinea*, *Ixora* sp., *L. camara*, *Odontonema* sp., *Prunus* sp., *Stiffia chrysanthia*). The other 96.9% of the plants were classified as peripherals, no species was identified as network hubs or connectors.

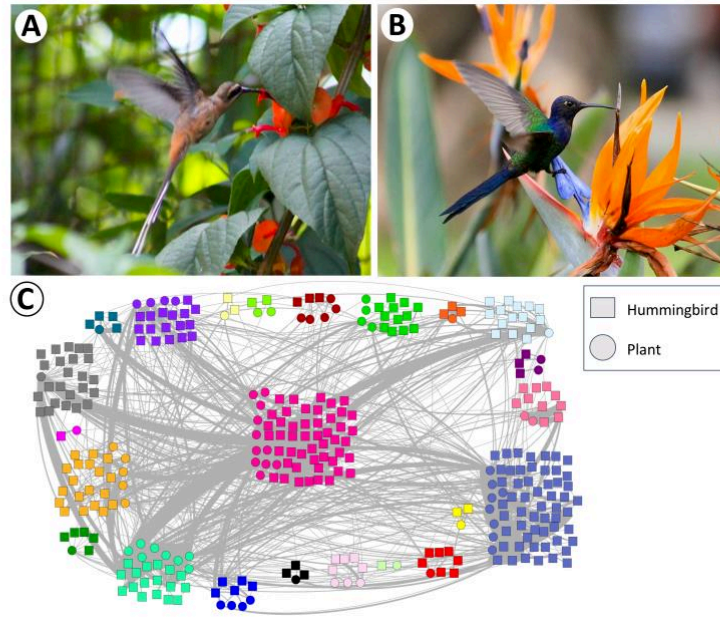


Fig. 2: Photographs illustrating interactions that we extracted from Wikiaves platform and the resulting interaction meta-network. Planalto Hermit, *Phaethornis pretrei* (A) interacting with *Holmskioldia sanguinea* (Lamiaceae). Swallow-tailed Hummingbird, *Eupetomena macroura* (B) interacting with *Strelitzia reginae* (Strelitziaceae). Hummingbird-plant interaction network from citizen science data (Total Matrix), different colors represent different modules, squares are hummingbirds and circle are plants (C).

From the 70 hummingbird species with records of interactions in the citizen science data, 40 species also had data on interactions in the expert data. In contrast, only one hummingbird species, *Chrysuronia brevirostris* had data collected by experts but not in the online platform. Moreover, 92 plant species (identified at the species

level) with record in the online platform were not present in the expert data. Regarding the comparison of the plants that hummingbird species interacted with between expert and citizen data, only 36 species of hummingbirds had plants in common between the two sources (Fig. 3). The hummingbird that presented the highest proportion of plants in common was *Phaethornis squalidus* with 66.6% of the plants in common (from the total of 3 plants it interacted with in the citizen data). The other species showed values below 40%. *E. macroura* was the species that presented the highest number of plants in common (16 species). However, this hummingbird interacted with 85 species of plants in Wikiaves data, reflecting in a proportion of 18.8% of plants in common with the experts.

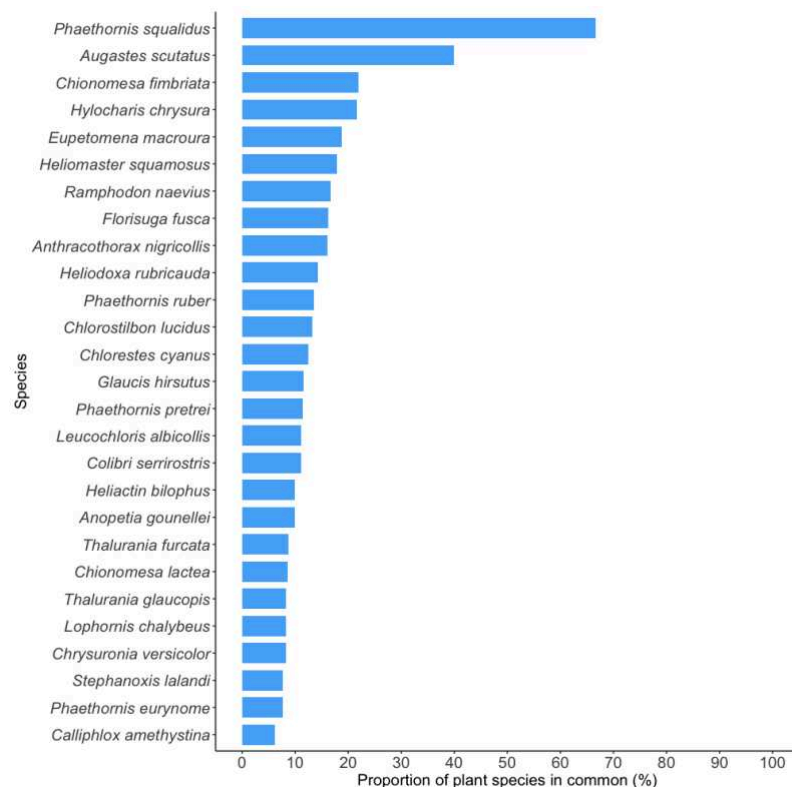


Fig. 3: Proportion of plants in common for the hummingbirds that showed some overlap in the identity of plants they interacted with between expert and citizen data. These proportions denote the ratio between plants in common divided by the total number of plants hummingbirds were

found interacting with in the Wikiaves online platform.

Finally, there was a strong positive relationship between the total number of hummingbird photographic records in the online platform and the richness of plant species visited by hummingbirds ($R^2 = 0.92$; $p < 0.001$, Fig. 4A). In addition, there was a positive but less strong relationship between the photographic records by the citizen scientists and the number of plant species hummingbirds interacted with as recorded by the experts ($R^2 = 0.45$; $p < 0.001$, Fig. 4B).

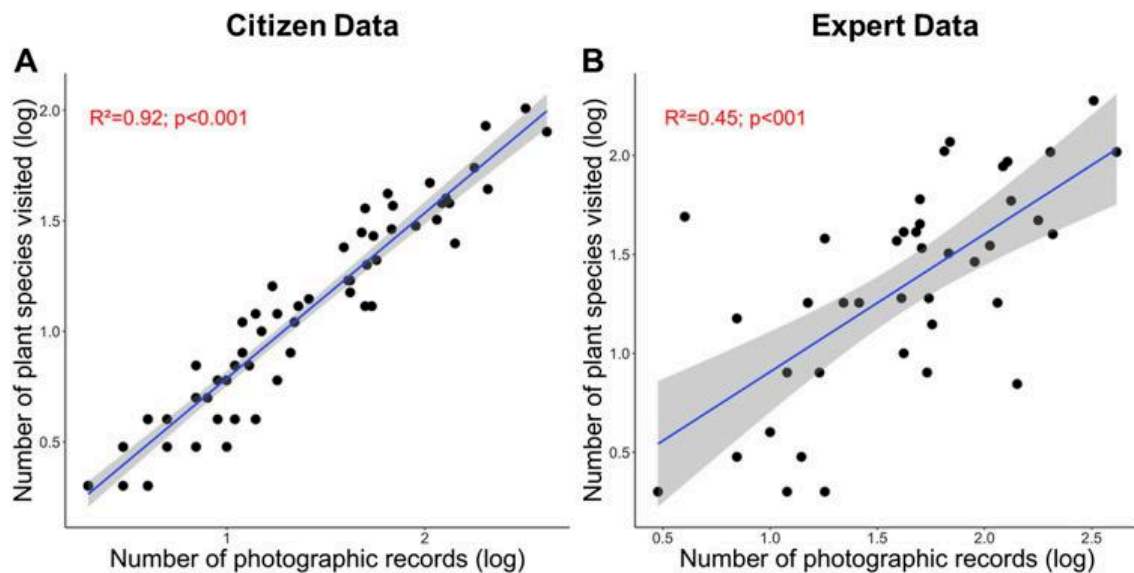


Fig. 4: (A) Relationship between number of plant species visited by hummingbirds and the number of photographic records in the Wikiaves platform (B) Relationship between the number of plant species visited by hummingbirds recorded by experts and the number of photographic records in Wikiaves.

Discussion

Here, by contrasting hummingbird-plant interaction data collected by amateur birdwatchers and trained scientists, we illustrate the richness of data available in online platforms. Importantly, the citizen science data showed higher hummingbird and

geographic coverage of interaction records, even including records from the Amazon Rainforest, where scientific information in plant-pollinator interactions, including hummingbirds, is comparatively scarce (Nascimento et al., 2020). Some plants found acting as module hubs are those also found as important for hummingbirds when considering expert data, e.g., *Inga* sp. (Araujo et al., 2018).

On a global scale, there is a gap in data collected by citizen scientists for different taxonomic groups in South America (Chandler et al., 2017). Furthermore, citizen science studies evaluating interactions are relatively rare, because there are often limitations in data collections involving more than one organism groups (Groom et al., 2021; but see e.g., Marín-Gómez et al., 2022; Heilmann-Clausen et al., 2016). The use of photographs can, however, mitigate some of these limitations (Groom et al., 2021), and the large amount of information we have compiled seems to confirm this potential. Some studies in the past had pointed out the importance of photographs in social media and science platforms (Pitman et al., 2021), which even allow for more detailed analyses, for example with studies on specific bird behaviors (Schunck et al., 2022; Tubelis and Sazima, 2021), and interaction network analysis as we did in the current study. One recent study from Mexico also evaluated hummingbird-plant interactions from photographic platforms (iNaturalist and eBird) across urban areas in the Mexico City and quantified the use of native and non-native plants by these birds, among other patterns (Marín-Gómez et al., 2022). Such studies further illustrate how these platforms may contribute to answer relevant ecological questions at different spatial scales.

Our method, like other uses of unstructured data, can suffer from biases such as lack of standardization in data collection (Bayraktarov et al., 2019), or over-sampling of more common species in less natural areas, such as urban areas, since potentially these environments are the most commonly photographed due to the easier access for amateurs.

Even so, when we compared our database with that of the experts, we observed many hummingbirds only recorded in the online database, including species classified as endangered (*P. margarettae*, *T. watertonii*) and vulnerable (*P. aethopygus*) by the IUCN Red List (IUCN, 2022). The presence of these species in the online platform data indicates that even though there are possible biases in the citizen data, there are potential benefits for covering a larger number of species in comparison to expert data, even including endangered species. Especially considering that many vertebrate pollinator species, including some hummingbirds, show a tendency of decline and worsening in endangered status (Regan et al., 2015), information on their food plants is highly valuable.

As shown for the country wide Brazilian meta-network based on expert data (Araujo et al., 2018) we also found that the citizen science meta-network showed a modular pattern. But when species were classified into their modules, all hummingbird species were classified as peripherals in both citizen data networks. The hummingbird *P. pretrei*, however, had a z-score value of 2.74, slightly lower than the critical value of 2.8 determined by the null model, making this species almost a module-hub. This species has a wide distribution occurring in five Brazilian biomes and was the species that recorded the highest number of interactions with plants, interacting with 79 plant species. Interestingly, this species is also one of the most frequently interacting hummingbirds in Brazil based on expert data (Araujo et al., 2018), indicating that citizen science data capture both geographical and ecological information about species interactions (see Araujo et al., 2018).

A good part of the plants for which species identity was recovered was classified as non-native (40.3%), potentially reflecting the fact that a large part of birdwatchers is concentrated mostly in transformed/urbanized areas (Barbosa et al., 2021). Such places often show a high number of ornamental and non-native species attractive to the fauna

and pollinators (Aronson et al., 2014, Nascimento et al., 2020, Silva et al., 2023, but see Vitorino et al., 2021). Of the seven species from the Total network and the 8 species from the Pollination network that acted as module hubs, most species or genera are plants that are commonly found as ornamental plants across the urban landscape in Brazil (Nascimento et al., 2020). This reinforces the notion that a considerable proportion of the photographs in Wikiaves may be coming from more altered habitats. Moreover, this high proportion of non-native plants may represent future research opportunities with this unique dataset for factors facilitating the incorporation of novel food resources by hummingbirds.

It should be noted that the number of plants that a given hummingbird interacted with was strongly related to the number of photos a species had, indicating a sampling effect (see also Marín-Gómez et al., 2022). Nevertheless, such result may also have a biological meaning, if we reasonably assume that the most photographed species are possibly abundant species that interacted with more plant species (Simmons et al., 2019). Previous studies using compilation of interaction information over large geographic extent have shown that sampling intensity affected interaction data (Nascimento et al., 2020), but such tendencies also reflect the geographic range sizes of species, which can be an important determinant of interaction diversity in country-wide networks (Araujo et al., 2018). That the number of photographic records in the citizen science platform was less strongly related to the number of plant species experts found interacting with hummingbirds, underscores both the similarities and uniqueness of each dataset.

Citizen science data are not yet fully incorporated into mainstream science, but show strong promises because the availability of these data can provide broad access to information about biodiversity patterns (Theobald et al., 2015). Moreover, professional scientists alone are not always able to provide data at the speed that policy decisions are

made (Theobald et al., 2015). Hence, citizen science offers complementarity of data to scientists, since amateurs can contribute with information and build huge databases, helping to solve conservation issues (Fontaine et al., 2021). As shown here, these efforts may even cover species of conservation concern, which are often little known owed to their rarity and difficulty in recording their natural history, including interactions (Regan et al., 2015). In addition, citizen science can help modern science in broadening its epistemological worldviews, bringing scientists closer to non-scientists and providing close-to-nature experience for society (Fontaine et al., 2021). In this regard, it is noteworthy that birdwatchers express their satisfaction for participating in activities that add knowledge, enhance their skills, bring personal well-being and also contribute to science (Greenwood, 2007). This is probably true also in a megadiverse and in development country such as Brazil.

Conclusion

We hope that our study will serve as an additional step for furthering research making use of citizen science platforms, as they present considerable wealth of data. In the specific case of Wikiaves, it is a platform that includes a large amount of data, presenting records of wide distribution, and is being fed daily as a source of new data for one of the most biodiverse countries in the world. Furthermore, the extensive database of interactions between plants and hummingbirds presented here contains relevant information that can be used with the purpose of expanding the knowledge of the interactions between pollinators and plants in Brazil. The findings here could potentially also be extended to other relevant bird groups associated with other ecosystem functions, such as frugivorous seed dispersers. Finally, we hope that the results found here will encourage data collection practices by non-scientists and implementation of specific citizen science projects, in order to better bridge society and science produced in

academia in countries such as Brazil, where such initiatives are only beginning to take shape.

Acknowledgements

We dedicate this study to all the passionate birdwatchers who over the years contributed their time and effort in popularizing the practice of “passarilhar”, through their participation in Wikiaves. We also thank Didi Impopar for her valuable suggestions. This study was funded by FAPEMIG (RED-00253-16), Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—Brazil (CAPES)—Finance Code 001; CNPq (IC UFMG Edital 04/2019 & IC Edital 04/2020) and a Ph.D. scholarship to CB (Processo 160722/2020-9).

References

- Araujo, A.C., Martín González, A.M., Sandel, B., Maruyama, P.K., Fischer, E., Vizentin-Bugoni, J., de Araújo, F.P., Coelho, A.G., Faria, R.R., Kohler, G., Las-Casas, F.M.G., Lopes, A.V., Machado, A.O., Machado, C.G., Machado, I.C., McGuire, J.A., Moura, A.C., Oliveira, G.M., Oliveira, P.E., Rocca, M.A., Rodrigues, L. da C., Rodrigues, M., Rui, A.M., Sazima, I., Sazima, M., Varassin, I.G., Wang, Z., Dalsgaard, B., Svenning, J.C., 2018. Spatial distance and climate determine modularity in a cross-biomes plant–hummingbird interaction network in Brazil. *J. Biogeogr.* 45, 1846–1858. <https://doi.org/10.1111/jbi.13367>
- Aronson, M.F.J., La Sorte, F.A., Nilon, C.H., Katti, M., Goddard, M.A., Lepczyk, C.A., Warren, P.S., Williams, N.S.G., Cilliers, S., Clarkson, B., Dobbs, C., Dolan, R., Hedblom, M., Klotz, S., Kooijmans, J.L., Kühn, I., MacGregor-Fors, I., McDonnell, M., Mörtberg, U., Pyšek, P., Siebert, S., Sushinsky, J., Werner, P., Winter, M., 2014. A global analysis

of the impacts of urbanization on bird and plant diversity reveals key anthropogenic drivers. *Proc. R. Soc. B Biol. Sci.* 281, 20133330. <https://doi.org/10.1098/rspb.2013.3330>

Barbosa, K.V. de C., Develey, P.F., Ribeiro, M.C., Jahn, A.E., 2021. The contribution of citizen science to research on migratory and urban birds in Brazil. *Ornithol. Res.* 29, 1–11. <https://doi.org/10.1007/s43388-020-00031-0>

Bayraktarov, E., Ehmke, G., O'Connor, J., Burns, E.L., Nguyen, H.A., McRae, L., Possingham, H.P., Lindenmayer, D.B., 2019. Do Big Unstructured Biodiversity Data Mean More Knowledge? *Front. Ecol. Evol.* 6, 1–5. <https://doi.org/10.3389/fevo.2018.00239>

Beckett, S.J., 2016. Improved community detection in weighted bipartite networks. *R. Soc. Open Sci.* 3, 140536. <https://doi.org/10.1098/rsos.140536>

Bonney, R., Cooper, C.B., Dickinson, J., Kelling, S., Phillips, T., Rosenberg, K. V., Shirk, J., 2009. Citizen science: A developing tool for expanding science knowledge and scientific literacy. *Bioscience* 59, 977–984. <https://doi.org/10.1525/bio.2009.59.11.9>

Chandler, M., See, L., Copas, K., Bonde, A.M.Z., López, B.C., Danielsen, F., Legind, J.K., Masinde, S., Miller-Rushing, A.J., Newman, G., Rosemartin, A., Turak, E., 2017. Contribution of citizen science towards international biodiversity monitoring. *Biol. Conserv.* 213, 280–294. <https://doi.org/10.1016/j.biocon.2016.09.004>

Cohn, J.P., 2008. Citizen Science: Can Volunteers Do Real Research? *Bioscience* 58, 192–197. <https://doi.org/10.1641/B580303>

Cunha, F.C.R., Fontenelle, J.C.R., 2014. Registros de tumulto em aves no Brasil: uma revisão usando a plataforma WikiAves. *Atualidades Ornitológicas* 177, 46–53.

Dalsgaard, B., Maruyama, P.K., Sonne, J., Hansen, K., Zanata, T.B., Abrahamczyk, S., Alarcón, R., Araujo, A.C., Araújo, F.P., Buzato, S., Chávez-González, E., Coelho, A.G., Cotton, P.A., Díaz-Valenzuela, R., Dufke, M.F., Enríquez, P.L., Martins Dias Filho, M., Fischer, E., Kohler, G., Lara, C., Las-Casas, F.M.G., Rosero Lasprilla, L., Machado, A.O., Machado, C.G., Maglianesi, M.A., Malucelli, T.S., Marín-Gómez, O.H., Martínez-García, V., Mendes de Azevedo-Júnior, S., da Silva Neto, E.N., Oliveira, P.E., Ornelas, J.F., Ortiz-Pulido, R., Partida-Lara, R., Patiño-González, B.I., Najara de Pinho Queiroz, S., Ramírez-Burbano, M.B., Rech, A., Rocca, M.A., Rodrigues, L.C., Rui, A.M., Sazima, I., Sazima, M., Simmons, B.I., Tinoco, B.A., Varassin, I.G., Vasconcelos, M.F., Vizentin-Bugoni, J., Watts, S., Kennedy, J.D., Rahbek, C., Schleuning, M., Martín González, A.M., 2021. The influence of biogeographical and evolutionary histories on morphological trait-matching and resource specialization in mutualistic hummingbird–plant networks. *Funct. Ecol.* 35, 1120–1133. <https://doi.org/10.1111/1365-2435.13784>

Dias, R., 2011. A biodiversidade como atrativo turístico: o caso do Turismo de Observação de Aves no município de Ubatuba (SP). *Rev. Bras. Ecoturismo* 4, 111–122. <https://doi.org/10.34024/rbecotur.2011.v4.5906>

Dormann, C.F., Gruber, B., Fründ, J., 2008. Introducing the bipartite package: Analysing ecological networks. *R News* 8, 8–11.

Dormann, C.F., Strauss, R., 2014. A method for detecting modules in quantitative bipartite networks. *Methods Ecol. Evol.* 5, 90–98. <https://doi.org/10.1111/2041-210X.12139>

Fleming, T.H., Muchhala, N., 2008. Nectar-feeding bird and bat niches in two worlds: pantropical comparisons of vertebrate pollination systems. *J. Biogeogr.* 35, 764–780. <https://doi.org/10.1111/j.1365-2699.2007.01833.x>

Flora e Funga do Brasil., 2022. URL <http://floradobrasil.jbrj.gov.br/> (Accessed 6.22.22).

Fontaine, C., Fontaine, B., Prévot, A.-C., 2021. Do amateurs and citizen science fill the gaps left by scientists? *Curr. Opin. Insect Sci.* 46, 83–87. <https://doi.org/10.1016/j.cois.2021.03.001>

Greenwood, J.J.D., 2007. Citizens, science and bird conservation. *J. Ornithol.* 148, 77–124. <https://doi.org/10.1007/s10336-007-0239-9>

Groom, Q., Pernat, N., Adriaens, T., de Groot, M., Jelaska, S.D., Marčiulyrienė, D., Martinou, A.F., Skuhrovec, J., Tricarico, E., Wit, E.C., Roy, H.E., 2021. Species interactions: next-level citizen science. *Ecography (Cop.)*. 44, 1781–1789. <https://doi.org/10.1111/ecog.05790>

Heilmann-Clausen, J., Maruyama, P.K., Bruun, H.H., Dimitrov, D., Læssøe, T., Frøslev, T.G., Dalsgaard, B., 2016. Citizen science data reveal ecological, historical and evolutionary factors shaping interactions between woody hosts and wood-inhabiting fungi. *New Phytol.* 212, 1072–1082. <https://doi.org/10.1111/nph.14194>

IUCN, 2022. The IUCN Red List of Threatened Species. Version 2021-3. URL <https://www.iucnredlist.org> (Accessed 6.22.22)

Kremen, C., Ullmann, K.S., Thorp, R.W., 2011. Evaluating the Quality of Citizen-Scientist Data on Pollinator Communities. *Conserv. Biol.* 25, 607–617. <https://doi.org/10.1111/j.1523-1739.2011.01657.x>

Lewinsohn, T.M., Prado, P.I., 2005. How many species are there in Brazil? *Conserv. Biol.* 19, 619–624. <https://doi.org/10.1111/j.1523-1739.2005.00680.x>

Marín-Gómez, O.H., Rodríguez Flores, C., Arizmendi, M. del C., 2022. Assessing

ecological interactions in urban areas using citizen science data: Insights from hummingbird–plant meta-networks in a tropical megacity. *Urban For. Urban Green.* 74, 127658. <https://doi.org/10.1016/j.ufug.2022.127658>

Maruyama, P.K., Bonizário, C., Marcon, A.P., D’Angelo, G., da Silva, M.M., da Silva Neto, E.N., Oliveira, P.E., Sazima, I., Sazima, M., Vizentin-Bugoni, J., dos Anjos, L., Rui, A.M., Marçal Júnior, O., 2019. Plant-hummingbird interaction networks in urban areas: Generalization and the importance of trees with specialized flowers as a nectar resource for pollinator conservation. *Biol. Conserv.* 230, 187–194. <https://doi.org/10.1016/j.biocon.2018.12.012>

Maruyama, P.K., Silva, J.L.S., Gomes, I.N., Bosenbecker, C., Cruz-Neto, O., Oliveira, W., Fernandes Cardoso, J.C., Steward, A.B., Lopes, A.V., 2022. A global review of urban pollinators and implications for maintaining pollination services in tropical cities. *Ecol. Trop. Cities Nat. Soc. Sci. Appl. to Conserv. Urban Biodivers.* <https://doi.org/https://doi.org/10.32942/osf.io/bpyvd>

McKinley, D.C., Miller-Rushing, A.J., Ballard, H.L., Bonney, R., Brown, H., Cook-Patton, S.C., Evans, D.M., French, R.A., Parrish, J.K., Phillips, T.B., Ryan, S.F., Shanley, L.A., Shirk, J.L., Stepenuck, K.F., Weltzin, J.F., Wiggins, A., Boyle, O.D., Briggs, R.D., Chapin, S.F., Hewitt, D.A., Preuss, P.W., Soukup, M.A., 2017. Citizen science can improve conservation science, natural resource management, and environmental protection. *Biol. Conserv.* 208, 15–28. <https://doi.org/10.1016/j.biocon.2016.05.015>

Miller-Rushing, A., Primack, R., Bonney, R., 2012. The history of public participation in ecological research. *Front. Ecol. Environ.* 10, 285–290. <https://doi.org/10.1890/110278>

Muñoz, L., Hausner, V.H., Runge, C., Brown, G., Daigle, R., 2020. Using crowdsourced

spatial data from Flickr vs. PPGIS for understanding nature's contribution to people in Southern Norway. *People Nat.* 2, 437–449. <https://doi.org/10.1002/pan3.10083>

Nascimento, V.T., Agostini, K., Souza, C.S., Maruyama, P.K., 2020. Tropical urban areas support highly diverse plant-pollinator interactions: An assessment from Brazil. *Landsc. Urban Plan.* 198, 103801. <https://doi.org/10.1016/j.landurbplan.2020.103801>

Olesen, J.M., Bascompte, J., Dupont, Y.L., Jordano, P., 2007. The modularity of pollination networks. *Proc. Natl. Acad. Sci.* 104, 19891–19896. <https://doi.org/10.1073/pnas.0706375104>

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>

Pacheco, J.F., Silveira, L.F., Aleixo, A., Agne, C.E., Bencke, G.A., Bravo, G.A., Brito, G.R.R., Cohn-Haft, M., Maurício, G.N., Naka, L.N., Olmos, F., Posso, S.R., Lees, A.C., Figueiredo, L.F.A., Carrano, E., Guedes, R.C., Cesari, E., Franz, I., Schunck, F., de Q. Piacentini, V., 2021. Annotated checklist of the birds of Brazil by the Brazilian Ornithological Records Committee—second edition. *Ornithol. Res.* 29, 94–105. <https://doi.org/10.1007/s43388-021-00058-x>

Pitman, N.C.A., Suwa, T., Ulloa Ulloa, C., Miller, J., Solomon, J., Philipp, J., Vriesendorp, C.F., Derby Lewis, A., Perk, S., Bonnet, P., Joly, A., Tobler, M.W., Best, J.H., Janovec, J.P., Nixon, K.C., Thiers, B.M., Tulig, M., Gilbert, E.E., Campostrini Forzza, R., Zimbrão, G., Ranzato Filardi, F.L., Turner, R., Zuloaga, F.O., Belgrano, M.J., Zanotti, C.A., de Vos, J.M., Hettwer Giehl, E.L., Paine, C.E.T., Texeira de Queiroz, R., Romoleroux, K., Hilo de Souza, E., 2021. Identifying gaps in the photographic record of the vascular plant flora of the Americas. *Nat. Plants* 7, 1010–1014.

<https://doi.org/10.1038/s41477-021-00974-2>

R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL <https://www.R-project.org/>.

Regan, E.C., Santini, L., Ingwall-King, L., Hoffmann, M., Rondinini, C., Symes, A., Taylor, J., Butchart, S.H.M., 2015. Global Trends in the Status of Bird and Mammal Pollinators. *Conserv. Lett.* 8, 397–403. <https://doi.org/10.1111/conl.12162>

Roy, H.E., Baxter, E., Saunders, A., Pocock, M.J.O., 2016. Focal Plant Observations as a Standardised Method for Pollinator Monitoring: Opportunities and Limitations for Mass Participation Citizen Science. *PLoS One* 11, e0150794. <https://doi.org/10.1371/journal.pone.0150794>

Schunck, F., Rodrigues, K.E., da Silva, M.A.G., Prates, C., Albano, C., Piacentini, V.Q., 2022. A novel mode of bathing behavior of hummingbirds recorded in the Brazilian ruby *Heliodoxa rubricauda* and allies (Aves: Trochilidae). *Acta Ethol.* <https://doi.org/10.1007/s10211-022-00393-2>

Sekercioglu, C.H., 2002. Impacts of birdwatching on human and avian communities. *Environ. Conserv.* 29, 282–289. <https://doi.org/10.1017/S0376892902000206>

Silvertown, J., 2009. A new dawn for citizen science. *Trends Ecol. Evol.* 24, 467–471. <https://doi.org/10.1016/j.tree.2009.03.017>

Simmons, B.I., Vizentin-Bugoni, J., Maruyama, P.K., Cotton, P.A., Marín-Gómez, O.H., Lara, C., Rosero-Lasprilla, L., Maglianesi, M.A., Ortiz-Pulido, R., Rocca, M.A., Rodrigues, L.C., Tinoco, B.A., Vasconcelos, M.F., Sazima, M., Martín González, A.M., Sonne, J., Rahbek, C., Dicks, L. V., Dalsgaard, B., Sutherland, W.J., 2019. Abundance drives broad patterns of generalisation in plant–hummingbird pollination networks. *Oikos*

128, 1287–1295. <https://doi.org/10.1111/oik.06104>

Stafford, R., Hart, A.G., Collins, L., Kirkhope, C.L., Williams, R.L., Rees, S.G., Lloyd, J.R., Goodenough, A.E., 2010. Eu-Social Science: The Role of Internet Social Networks in the Collection of Bee Biodiversity Data. *PLoS One* 5, e14381. <https://doi.org/10.1371/journal.pone.0014381>

Theobald, E.J., Ettinger, A.K., Burgess, H.K., DeBey, L.B., Schmidt, N.R., Froehlich, H.E., Wagner, C., HilleRisLambers, J., Tewksbury, J., Harsch, M.A., Parrish, J.K., 2015. Global change and local solutions: Tapping the unrealized potential of citizen science for biodiversity research. *Biol. Conserv.* 181, 236–244. <https://doi.org/10.1016/j.biocon.2014.10.021>

Tubelis, D.P., Sazima, I., 2021. Nuptial gifts among Brazilian cuckoos: an outline based on citizen science. *Ornithol. Res.* 29, 188–192. <https://doi.org/10.1007/s43388-021-00072-z>

Turella, I.Z., da Silva, T.L., Rumpel, L., Marini, M.Â., 2022. Breeding biology of swallow-tailed hummingbird (*Eupetomena macroura*) based on citizen science data. *Ornithol. Res.* <https://doi.org/10.1007/s43388-022-00098-x>

Whelan, C.J., Wenny, D.G., Marquis, R.J., 2008. Ecosystem Services Provided by Birds. *Ann. N. Y. Acad. Sci.* 1134, 25–60. <https://doi.org/10.1196/annals.1439.003>

Zanata, T.B., Dalsgaard, B., Passos, F.C., Cotton, P.A., Roper, J.J., Maruyama, P.K., Fischer, E., Schleuning, M., Martín González, A.M., Vizentin-Bugoni, J., Franklin, D.C., Abrahameczyk, S., Alárcon, R., Araujo, A.C., Araújo, F.P., Azevedo-Junior, S.M. de., Baquero, A.C., Böhning-Gaese, K., Carstensen, D.W., Chupil, H., Coelho, A.G., Faria, R.R., Hořák, D., Ingversen, T.T., Janeček, Š., Kohler, G., Lara, C., Las-Casas, F.M.G.,

Lopes, A. V., Machado, A.O., Machado, C.G., Machado, I.C., Maglianesi, M.A., Malucelli, T.S., Mohd-Azlan, J., Moura, A.C., Oliveira, G.M., Oliveira, P.E., Ornelas, J.F., Riegert, J., Rodrigues, L.C., Rosero-Lasprilla, L., Rui, A.M., Sazima, M., Schmid, B., Sedláček, O., Timmermann, A., Vollstädt, M.G.R., Wang, Z., Watts, S., Rahbek, C., Varassin, I.G., 2017. Global patterns of interaction specialization in bird-flower networks. *J. Biogeogr.* 44, 1891–1910. <https://doi.org/10.1111/jbi.13045>

CAPÍTULO 2

Consistent generalization of plant-hummingbird networks despite increasing vegetation cover across a tropical urban landscape

Camila Bosenbecker^{a,b*}, Pedro Amaral Anselmo^{a,c}, Teresa Mol Fonseca^a, João Carlos Pena^d, Paulo Eugênio Oliveira^b & Pietro Kiyoshi Maruyama^{a,b,c}

a. Centro de Síntese Ecológica e Conservação, Departamento de Genética Ecologia e Evolução – ICB, Universidade Federal de Minas Gerais, Belo Horizonte- MG, Brazil

b. Programa de Pós-Graduação em Ecologia, Conservação e Biodiversidade, Instituto de Biologia, Universidade Federal de Uberlândia, Uberlândia-MG, Brazil

c. Programa de Pós-Graduação em Ecologia, Conservação e Manejo da Vida Silvestre, Universidade Federal de Minas Gerais, Belo Horizonte- MG, Brazil

d. Laboratório de Ecologia Espacial e Conservação, Departamento de Biodiversidade, Instituto de Biociências, Universidade Estadual Paulista Júlio de Mesquita Filho, Rio Claro, SP, Brazil

BOSENBECKER, Camila et al. Consistent generalization of plant-hummingbird networks despite increasing vegetation cover across a tropical urban landscape. *Urban Forestry & Urban Greening*, p. 128498, 2024. <https://doi.org/10.1016/j.ufug.2024.128498>

Abstract

Human activities, particularly urbanization, profoundly impact ecosystems often resulting in biotic homogenization. Whether or not urban landscapes can sustain diverse pollinator and plant communities is an important question to be addressed. Here, we investigated the influence of urbanization on plant-hummingbird interaction networks in a large tropical city, Belo Horizonte, Brazil. We recorded 13198 legitimate interactions between seven hummingbirds and 57 plant species across 12 local networks. Urban landscapes exhibited predominantly generalized networks, maintaining this pattern across varying vegetation cover and floral resource abundance. Although some functionally specialized hummingbirds with long bills were recorded performing more specialized interactions, urban environments did not generally support specialized networks. Nevertheless, network specialization did increase with the proportion of native nectar plants, emphasizing their importance for maintaining some specialized interactions. Furthermore, we observed a positive effect of plant richness, but not of flower abundance, on hummingbird abundance, indicating that it is not only the amount of flowers, but the diversity of floral resources that may be a key factor in maintaining hummingbirds. Therefore, promoting a diverse assemblage of native plants in urban green areas is crucial for sustainable pollinator communities. Our study highlights that while a biodiverse urban landscape will require careful urban vegetation planning considering both floral resource diversity and availability, vegetation cover per se may not be sufficient to mitigate the negative impacts of urbanization. Maintaining a diverse vegetation with different life forms, flowering phenology, and especially of native plants across the urban landscape is needed to create welcoming spaces for pollinators.

Keywords: Brazil; urban green spaces; native plants; interaction networks; pollinator conservation; urban ecology

Introduction

Human activities have impacts on the composition and structure of ecosystems, reducing species diversity and often leading to the uniformization of biological communities, *i.e.*, biotic homogenization (McKinney, 2006; Mckinney and Lockwood, 1999). Urbanization is one of the main impacts causing intense land use changes, and urban landscapes are often characterized as “biological deserts” (McKinney, 2006; Sandström et al., 2006). Nevertheless, urban landscapes may support considerable diversity of animals with important ecosystem functions, such as pollinators (Silva et al., 2023; Theodorou, 2022). In recent years, there has been a decline in pollinator populations worldwide (Liang et al., 2023; Ollerton, 2017), and recent studies have highlighted the potential of green spaces, including wooded streets and avenues, as biological refuges for pollinator species inhabiting urban environments (Baldock, 2020; Theodorou et al., 2020). In this sense, maintaining green areas in cities can be important for supporting pollinator diversity at the landscape scale to conserve critical ecosystem functions (Coetzee et al., 2018; Stewart et al., 2018).

Plant-pollinator interaction networks can be characterized by their structural organization, based on metrics such as modularity, nestedness, and specialization. Modularity is characterized by the presence of species that exploit a subset of resources within their module; nestedness indicates that a subgroup of specialist species is connected to generalists and generalists are connected to each other (Bascompte et al., 2003; Olesen et al., 2007); and complementary specialization is an index that describes the exclusivity of interactions at the network level (Blüthgen et al. 2006). Despite recent research indicating that, in response to human impacts on a global scale, nestedness increases while modularity decreases (Takemoto and Kajihara, 2016), it is still unclear how the urbanization affects the structural patterns of urban interaction networks.

In this context, some studies show the relationship between landscape characteristics and ecological interactions, with higher levels of urbanization, usually defined by the amount of impervious surface, leading to the generalization of ecological networks (Marín-Gómez et al., 2022; Schneiberg et al., 2020). Therefore, urbanization have a negative impact on plant-pollinator interaction networks, leading to a decrease in species richness and abundance (Ellis et al., 2023; Liang et al., 2023b), as well as interaction specialization (Maruyama et al. 2019). As a result, only generalist pollinators are able to persist in many urban landscapes (Silva et al., 2021; Wenzel et al., 2020). These results, looking the other way around, indicate that if natural vegetation cover increases, plant-pollinator communities will increase in diversity and specialization. This relationship can be expected since the availability of vegetation/floral resources has an important role in maintaining the biodiversity of urban environments, including of pollinators (Gomes et al., 2023), showing a positive effect on pollinator richness (Liang et al., 2023b; Stewart et al., 2018). However, part of these floral resources are non-native ornamental species, which may not be as beneficial to the urban fauna as native plants (Berthon et al., 2021). Added to that, many of the interactions with non-native plants are illegitimate and do not characterize potential pollination, thus with no potential to contribute to plant reproduction (Anselmo et al., 2023). On the other hand, non-native plants can alter the seasonal availability of resources for pollinators, *e.g.*, filling periods of flower scarcity and being important for pollinator persistence and survival (Anselmo et al., 2023; Harrison and Winfree, 2015; Staab et al., 2020). Therefore, plant-pollinator interactions in urban landscapes may be very distinct from those found in more natural ecosystems.

Among pollinators, hummingbirds are the most specialized birds in floral nectar feeding (Stiles, 1981; Zanata et al., 2017), interacting with a large number of plants that depend on them for reproduction (Dalsgaard et al., 2021). Plants that show specific traits

for bird pollination, or for avoiding visitation by insects, are defined as ornithophilous plants and can provide a "private niche" for hummingbirds (Lunau et al., 2011). This may also be the case in urban environments, where specialized plants seem to be more frequently used by these birds (Maruyama et al., 2019; Nascimento et al., 2020). Despite the importance of hummingbirds, and vertebrates in general as pollinators (Ratto et al., 2018), few studies have explored the effects of urbanization on their interactions with flowers (Maruyama et al., 2021; Silva et al., 2023). It is therefore important to carry out studies on plant-hummingbird interaction networks in urban areas, allowing for a more comprehensive understanding of how plant-pollinator interactions are structured across increasingly anthropized areas around the world.

Here, we investigated changes in the structure of plant-hummingbird networks along a gradient of urbanization in a large tropical city in Brazil (Fig. 1). We expected higher richness and abundance of hummingbirds, resulting in a higher frequency of interactions and less nested networks when the landscape has a higher proportion of vegetation cover. We also expected an increase in specialization and modularity of networks, that is, higher partitioning of floral resources by hummingbirds with more native plants in less urbanized landscapes.

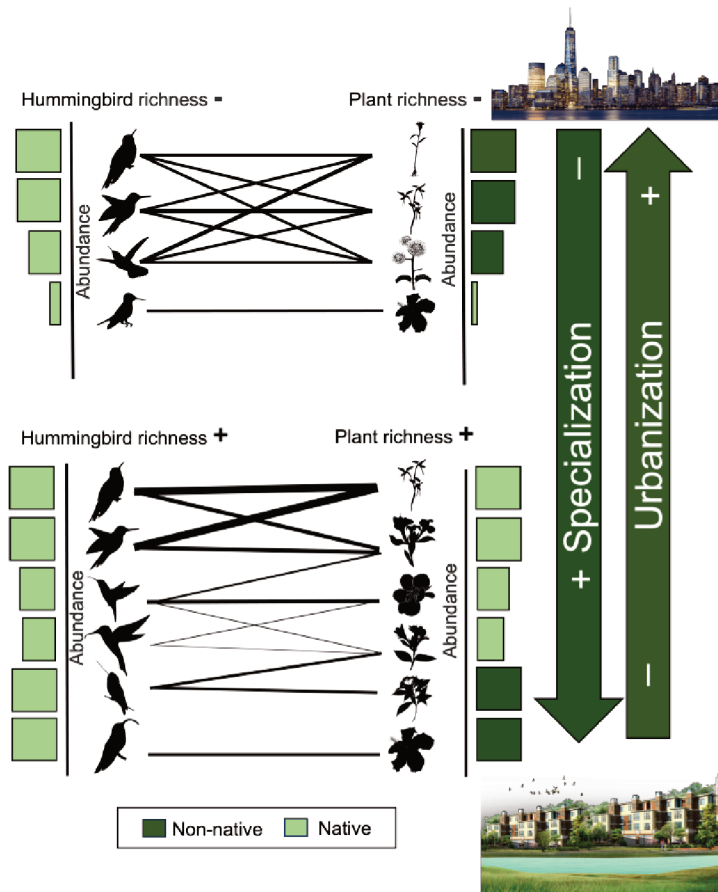


Fig. 1: Graphical representation of the working hypotheses on the effect of urbanization on the plant-hummingbird interaction networks in the city of Belo Horizonte (Minas Gerais, Brazil). We expected that landscapes with a higher degree of urbanization would show a lower richness and higher abundance of generalist hummingbirds, resulting in a lower frequency of interactions, and more nested networks. We also expected a decrease in specialization and modularity, that is, greater network generalization in more urbanized landscapes.

Materials and methods

Urbanization gradient

Data collection was carried out in the city of Belo Horizonte, state of Minas Gerais, in Brazil (19.88S, 43.94W). The city has approximately 2.530.000 inhabitants (www.cidades.ibge.gov.br) and was known in the early decades of the 20th century as the "garden city" due to the high density of trees, gardens, and public squares in the city

(Duarte, 2007; Gomes et al., 2023). Currently, Belo Horizonte has a total area of 331.354 km² with 274.04 km² of urbanized area (www.cidades.ibge.gov.br). The climate of the region is characterized as high-altitude tropical, with dry winters and rainy summers, rainfall is around 1.600 mm per year, most frequent from October to March, and the average temperature during the year varies between 19 and 24 °C (Alvares et al., 2013).

We defined twelve distinct 1km radius buffers across Belo Horizonte, representing landscapes with different degrees of urbanization characterized by the proportion of impermeable surfaces (Fig. 2). The land cover data was obtained through a supervised classification of PlanetScope satellite imagery with 3m resolution and four spectral bands (Bhakti et al., 2023; Planet Labs PBC, 2021). The proportion of impermeable surfaces among these landscapes varied from 16.3% to 83.7%, hence describing a gradient of urbanization intensity (Fig S1, Table S1). At each landscape, it is possible to find a variety of green infrastructure elements such as parks, small public green spaces, gardens, and wooded streets. In addition to the proportion of impermeable surfaces, other variables such as woody cover, herbaceous cover, and a description of the soundscape were also extracted from each of these landscapes (Fig S1). The latter combines three geospatial layers: motorized traffic volume, height of buildings, and distribution of commercial shops, resulting in a raster surface describing the “noisiness”, as an integrated measure of human activity (see Bhakti et al., 2020). All landscape metrics, with the exception of the soundscape, were calculated using the package *landscapemetrics* in the R programming environment (Hesselbarth et al., 2024).

Plant-hummingbird interaction data were collected through eight expeditions, one per month, in each of the sampled landscapes, four during the rainy season (January to April 2022) and four during the dry season (May to July and October 2022). In each landscape, two observers walked along a one km transect, always in the morning when

hummingbird activities are higher, taking approximately four hours to cover the entire transect. During these walks, focal observations were made for 20 to 30 minutes on each plant individual that could attract hummingbirds, *i.e.* flowers with nectar production irrespective of fitting to ornithophily syndrome (Maruyama et al., 2013). Interactions between hummingbirds and flowers were recorded when hummingbirds were observed visiting the flowers and classified as legitimate visits when the hummingbird contacted the reproductive part of the flower or illegitimate otherwise.

Hummingbird species abundances were defined as the frequency of the occurrence (Vizentin-Bugoni et al., 2014), summing the number of days each species was present in each area across all expedition days; varying from zero to eight in each area. We used frequency of occurrence as an estimate of abundance since not all hummingbirds were recorded across transect walks, but only when observing the flowers. We also extracted information on the bill lengths of hummingbirds from Dalsgaard et al. (2021).

To quantify the abundance of flowers, we counted the number of fresh flowers on each plant along the transects. In the case of plants that produced a large number of flowers, we quantified the average number of flowers per subsample of the canopy, which were then multiplied to obtain an estimated number of flowers per individual. The availability of flowers was used as an indicator of the abundance of floral resources for hummingbirds. Plants were identified to the lowest possible taxonomic level and classified according to their origin (native or non-native) and life form (shrub, tree, and other) according to Flora and Funga of Brazil (reflora.jbrj.gov.br). We also calculated the proportion of native species with which the hummingbirds interacted, dividing the number of native species by the total number of plants with which they interacted. In addition, plants were classified in relation to their pollination syndrome, as ornithophilous, which have tubular, narrow flowers with a large amount of nectar and

contrasting colors, or as non-ornithophilous when these characteristics were not present (Cronk and Ojeda, 2008).

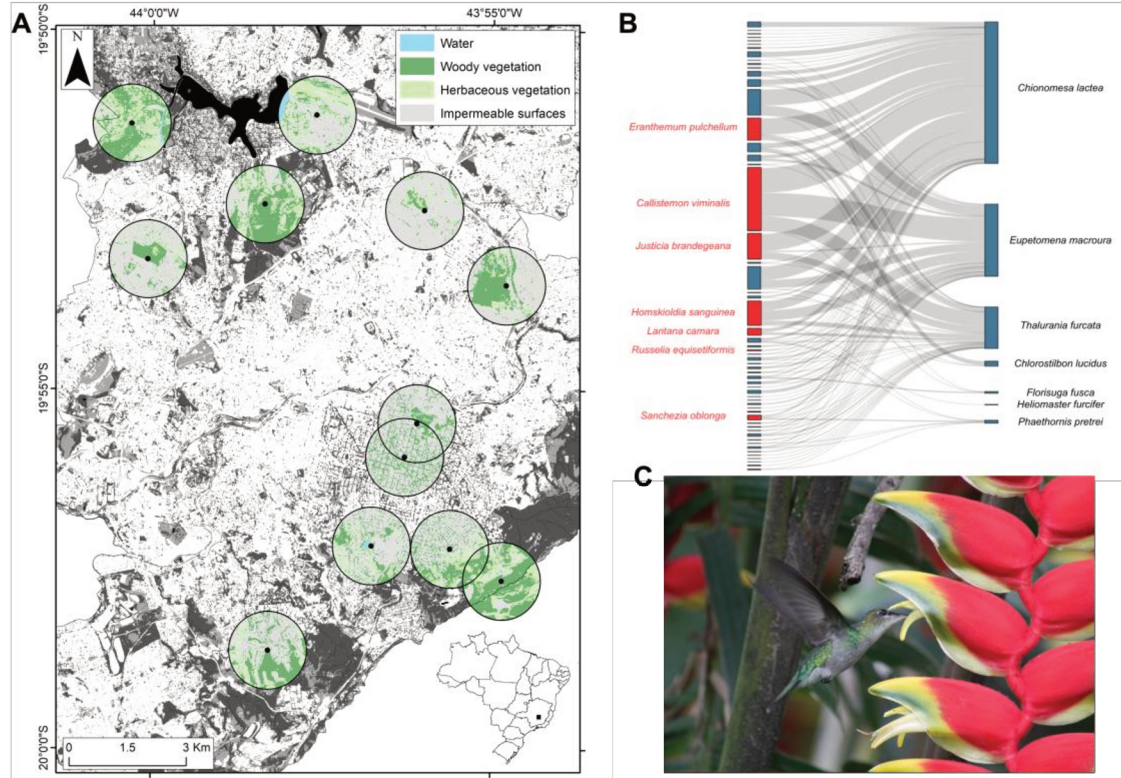


Fig. 2: (A) Data collection was conducted in the city of Belo Horizonte, state of Minas Gerais, Brazil. The sampled landscapes were defined by a 1 km radius buffer, encompassing areas with different levels of urbanization. A total of 12 local-networks were constructed, each corresponding to a sampled landscape. (B) Meta-network depicting legitimate interactions between plants and hummingbirds in urban areas of Belo Horizonte. Line width represents the frequency of interactions, with all hummingbird and module hub plant species identified. All module hub plant species (in red) are non-natives to the study area. (C) A female Fork-tailed Woodnymph, *Thalurania furcata* (module-hub) interacting with *Heliconia rostrata* (Heliconiaceae).

Plant-hummingbird networks

Quantitative interaction matrices were constructed considering the number of

visits to each flower as a measure of the strength of the interactions. We took a multiscale approach to analyze plant-hummingbird interactions. First, to evaluate the role of species across the urban landscape in the city of Belo Horizonte, we built a meta-network compiling the interactions across all the landscapes, considering only legitimate interactions, *i.e.* hummingbirds touching the reproductive part of the plant. Then, to assess the effect of the urbanization gradient on the plant-hummingbird interaction networks, 12 local-networks were built, one for each sampled landscape. We estimated the sampling completeness for all the interaction networks, contrasting the observed value with the one calculated through the Chao 1 estimator (Chacoff et al., 2012; Vizentin-Bugoni et al., 2016).

Complementary metrics that characterize aspects of network structure such as nestedness, modularity, and specialization were calculated for all networks. Nestedness is characterized by the presence of a subgroup of more connected generalist species and specialist species connected to generalists, and was calculated using the wNODF metric (Almeida-Neto et al., 2008). wNODF values range from 0 to 100, with the latter indicating higher nestedness. Modularity (Q) is observed when different species exploit different subsets of resources. We used the DIRTLPAbw+ algorithm (Beckett, 2016), which identifies modules in weighted networks and maximizes the conformation of modules in which species interact mainly within their module and not between different modules. Values range from zero to one, with the latter indicating higher modularity. To assess the significance of the network-level metrics, we compared the observed values with those generated by the r2dtable null model ($n = 1000$) (Dormann et al., 2008).

The " c " and " z " scores were used to identify the roles of species in the modular meta-network. The connectivity score between modules (c) indicates the role of species as connectors between different modules, while the degree within a module (z) indicates

the relevance of each species within its module (Olesen et al., 2007). Based on these two indices, species can be categorized according to their role in the modular network as follows: connectors (high values of c and low values of z), peripherals (low values of c and z), network hubs (high values of c and z) or modular hubs (high values of z and low values of c). To define the roles of the species, we used the threshold values determined based on the 95% quantiles of the null networks ($z = 1.12$ and $c = 0.72$) (Dormann and Strauss, 2014).

We also calculated complementary specialization (H_2'), which measures the degree of specialization of interactions in networks. H_2' ranges from zero to one, where zero indicates high generalization and one high specialization (Blüthgen et al., 2006). The significance of the metrics at the network level was assessed by comparing the observed values with those generated by null models. Finally, species-level specialization (d') was computed to assess the exclusivity of a species' interactions, accounting for the random selection of partners. All network analyses were carried out in the R package '*bipartite*' (Dormann et al. 2008).

Data analysis

Considering the data from the local-networks, we used Linear Models (LMs) to investigate the relationship between the local scale predictor variables (plant richness, flower abundance, proportion of native plants) and the landscape scale variables with the response variables (modularity, specialization, abundance and richness of hummingbirds) (Table S1). If the data did not meet the assumptions of normality and homogeneity, we performed a logarithmic transformation on the data.

In order to avoid multiple testing, we first conducted a Pearson correlation analysis (Quinn and Keough, 2002) between the landscape variables (Fig. S1). Variables with a high correlation ($r > 0.70$) were removed from the subsequent analysis (Amado De

Santis et al., 2023). We were left with a total of five predictor variables after this procedure: proportion of impermeable surfaces, soundscape, largest patch index of herbaceous vegetation, edge density of woody vegetation, mean patch size of impermeable surface cover (table S2).

At the local-scale, we ran Linear Mixed Models using the *lme4* package (Bates et al., 2015) and constructed models separately for plants and hummingbirds, for each response variable. In the models for plants, we used species-level specialization as the response variable, with plant origin, pollination syndrome, and habit (trees, shrubs or herbs) as predictor variables. For hummingbirds, bill length and the proportion of visits made to native plants in relation to total number of visits were used as predictors, with species-level specialization as the response variable. To account for species recorded in more than one network/landscape, we included species identity as a random factor in the analysis. We used the *Anova()* function in the *car* package to calculate the Chi-statistics and obtain the significance for each fixed factor (Fox and Weisberg, 2011).

Results

Meta-network of plants and hummingbirds

We recorded 15075 interactions between seven hummingbird and 66 plant species, in total. Of these, 13198 interactions between seven hummingbird and 57 plant species (41 non-natives and 16 natives; Fig. 2B) were legitimate, comprising the meta-network of Belo Horizonte. The hummingbirds that carried out the highest number of interactions were *Chionomesa lactea*, *Eupetomena macroura* and *Thalurania furcata*, while the most visited plants were the non-native species *Callistemon rigidus*, *Bauhinia variegata*, *Justicia brandegeana*, and *Holmskioldia sanguinea*. The meta-network showed a significant modular pattern but with low modularity $Q_w = 0.21$ ($p < 0.05$). It had

four modules, with the hummingbird *Thalurania furcata* (Fig. 2C) and seven non-native plants, *Callistemon viminalis*, *Eranthemum pulchellum*, *Holmskioldia sanguinea*, *Justicia brandegeana*, *Lantana camara* and *Russelia equisetiformis*, *Sanchezia oblonga* classified as module-hubs. All other species were classified as peripheral, and no species were identified as a network-hub or connector.

Local networks in the urban landscape

All 12 local networks showed a significant pattern of modularity (Q_w) and specialization (H_2'), but not of nestedness (wNODF; Table S1). These networks had a small variation in their sampling completeness, but all showed values close to 100% (Table S1). All interaction networks were rather generalized, with values of specialization (H_2') 0.47 ± 0.15 (mean $\pm$ SD), except for Serra do Curral, the least urbanized location among all networks ($H_2' = 0.79$; Table S1).

At the landscape level, neither modularity ($R^2 = 0.19$, $p = 0.15$) nor specialization ($R^2 = 0.01$, $p = 0.66$) showed a significant relationship with proportion of impermeable surfaces. Additionally, while the richness of hummingbirds was negatively affected by urbanization ($R^2 = 0.34$, $p < 0.05$; Fig. 3A), their abundances, measured as the frequency of occurrences, was not ($R^2 = 0.19$, $p = 0.15$). Finally, the proportion of native plants used by hummingbirds decreased with increased “noisiness” in the landscape, *i.e.* soundscape ($R^2 = 0.34$, $p < 0.05$; Fig. 3B).

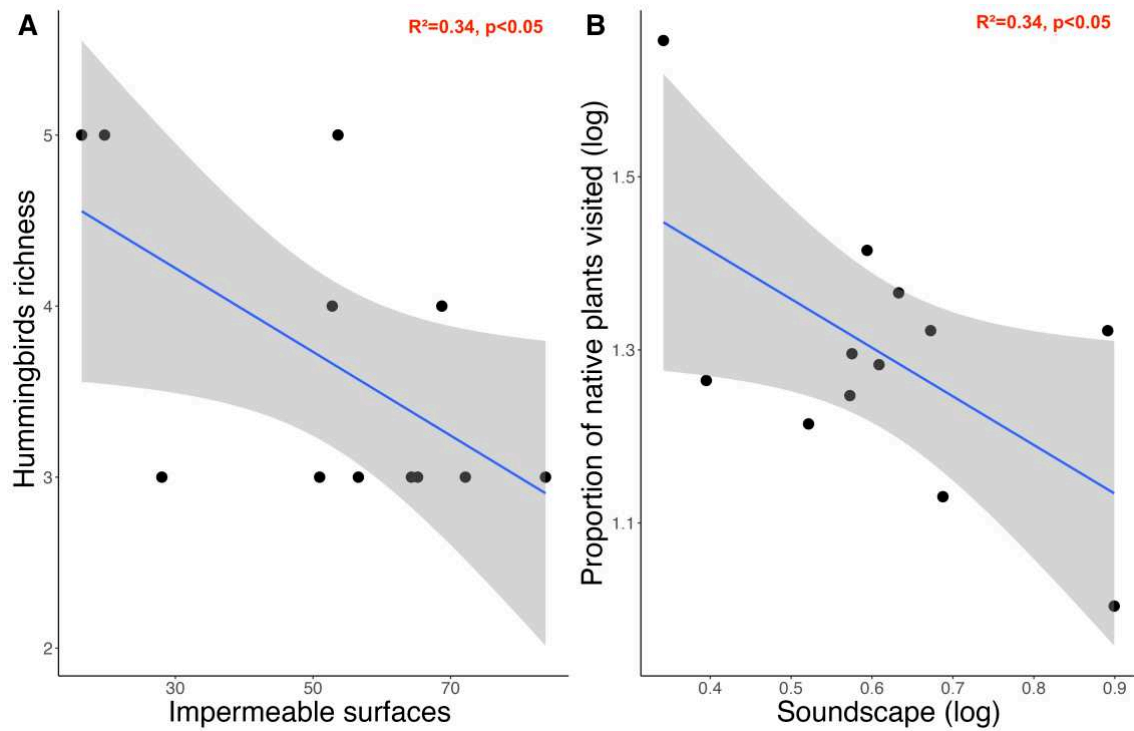


Fig. 3: (A) Relationship between hummingbird richness and proportion of impermeable surfaces, a proxy for urbanization, in the city of Belo Horizonte, supporting our hypothesis of a significant negative relationship ($R^2 = 0.34$, $p < 0.05$). (B) Relationship between the proportion of native plants visited and Soundscape (log-transformed), showing that in noisier habitats hummingbirds make use of more non-native nectar sources ($R^2 = 0.34$, $p < 0.05$).

Considering local scale predictors, no significant relationship was found between hummingbird abundance and the number of available flowers ($R^2 = 0.19$, $p = 0.15$). However, we did observe a positive relationship where hummingbird abundance increased with increasing plant richness ($R^2 = 0.69$, $p < 0.001$; Fig. 4A). When we evaluated the origin of the plants that the hummingbirds interacted with, complementary specialization (H_2') increased as the proportion of native species increased ($R^2 = 0.43$, $p < 0.05$; Fig. 4B). On the other hand, modularity (Q) showed no significant relationship with the origin of the plants ($R^2 = 0.04$, $p = 0.50$).

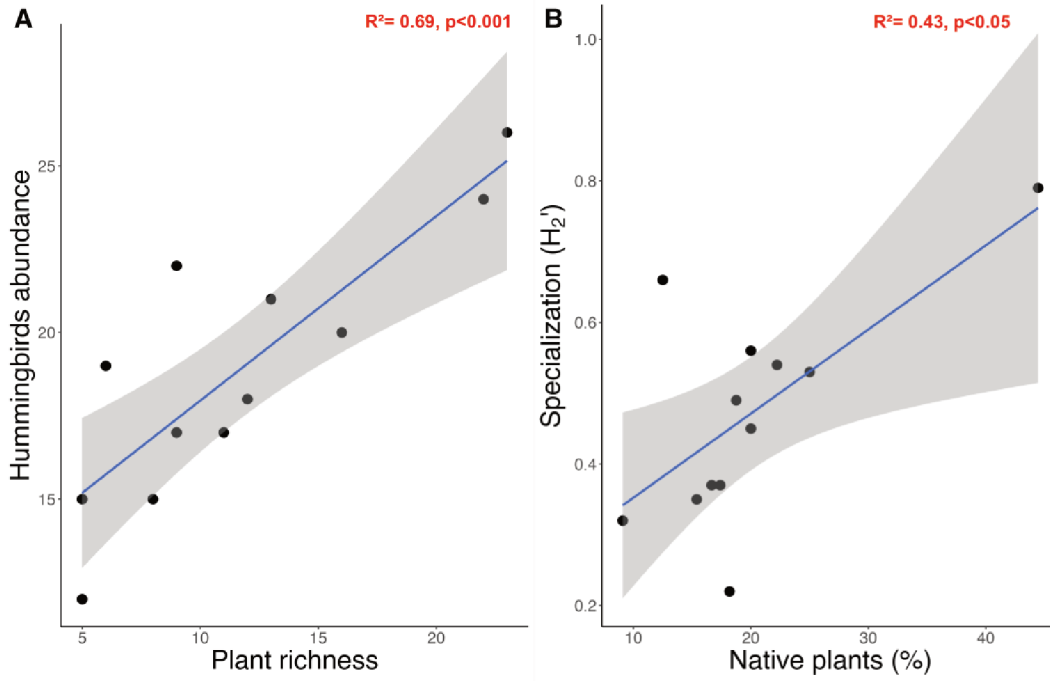


Fig. 4: (A) Relationship between hummingbird abundance and plant richness and (B) the influence of the proportion of native plant species (%) on complementary specialization (H_2') in the city of Belo Horizonte.

At the species-level, hummingbirds bill length was positively associated with specialization (d') ($\chi^2 = 17.22$, $R^2_m = 0.29$, $R^2_c = 0.29$, $p < 0.001$; Fig. 5A). Additionally, the number of interactions with native plants showed a positive relationship with hummingbird specialization ($\chi^2 = 7.03$, $R^2_m = 0.14$, $R^2_c = 0.33$, $p < 0.001$; Fig. 5B).

As for the plants, native species showed greater specialization (d') than the non-natives ($\chi^2 = 4.60$, $R^2_m = 0.04$, $R^2_c = 0.28$, $p = 0.03$; Fig. 6A), but specialization did not differ according to pollination syndrome (Fig. 6B) or plant habit (Fig. 6C).

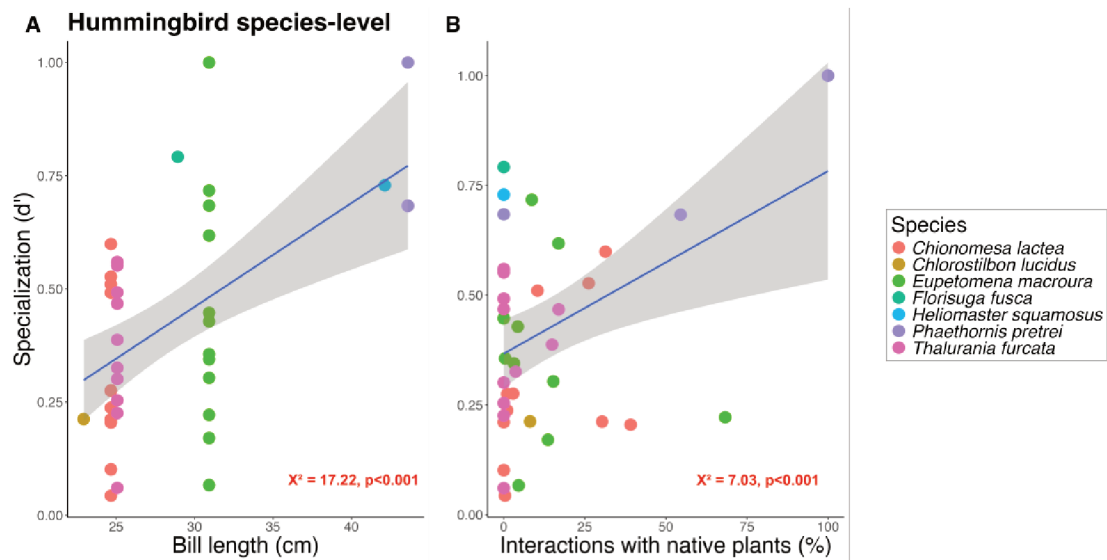


Fig. 5: Species-level patterns of hummingbird specialization: (A) Positive association with bill length ($p < 0.001$) and with (B) the number of interactions with native plants (%) ($p < 0.001$) in the city of Belo Horizonte. Different colors represent different hummingbird species.

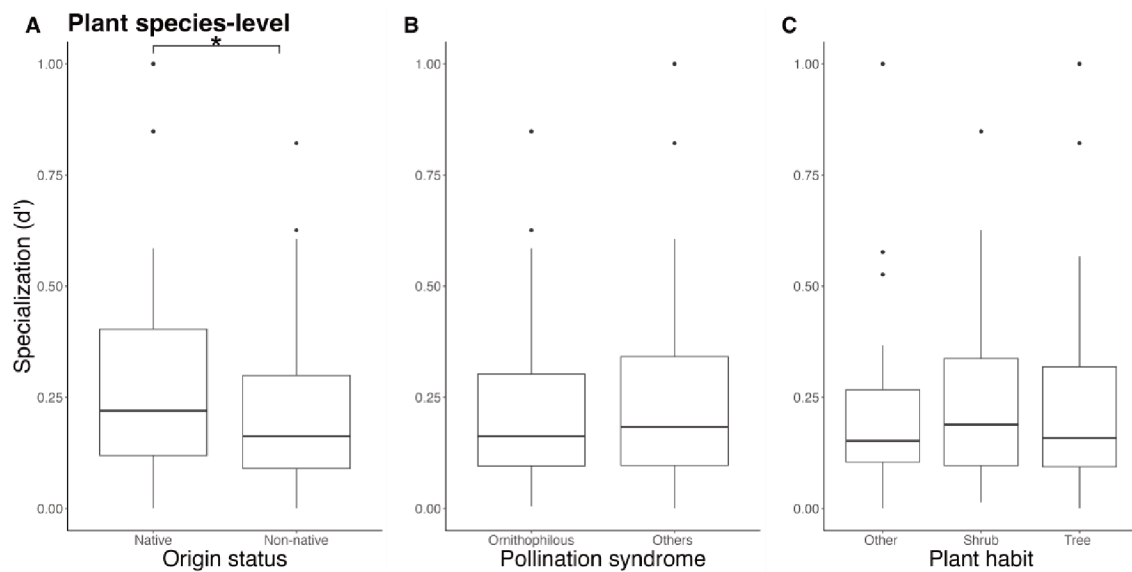


Fig. 6: The relationship of species-level specialization (d') with plant characteristics: (A) origin status, (B) pollination syndrome and (C) plant habit in the city of Belo Horizonte, Minas Gerais. Significant results are indicated by * ($p < 0.05$).

Discussion

The urban landscape of Belo Horizonte comprises mostly generalized urban plant-

hummingbird interactions, both for the general meta-network and for each local network. Our results confirm previous findings that urban environments have generalized plant-pollinator networks (Anselmo et al., 2023; Maruyama et al., 2019; Staab et al., 2020), and here we further these findings by showing that this generalization is maintained across the urban landscape with varying degrees of impermeable surfaces and diversity/abundance of floral resources. Urbanization can act as an environmental filter for birds and their interactions, where only a subset of more generalized species can persist, especially in highly urbanized areas (Amado De Santis et al., 2023; Pena et al., 2023; Schneiberg et al., 2020). Although some functionally specialized hummingbirds with long bills were recorded during our study, such as *Phaethornis pretrei* and *Helimaster squamosus*, which also realized more specialized interactions (higher d' values), urban environments did not generally support specialized networks at the community level when compared with natural environments (Maruyama et al. 2024). In the highly urbanized areas of our study, *Phaethornis pretrei* and *Helimaster squamosus*, two species with the longest bills, were absent. These functionally specialized species often need specific floral resources that may not be available in urban landscapes. The absence of these hummingbirds highlights the impact of urbanization as an environmental filter that tends to favor more generalized species capable of exploiting a wider range of resources (Maruyama et al., 2019).

The interaction networks indicated high generalization regardless of the level of urbanization across the landscape, showing different levels of vegetation cover and resource abundance. We emphasize that, although green area cover is a relevant factor, its presence may not be sufficient to promote more specialized and functional communities. This arises from the need to consider not only the presence of vegetation but also the specific type of vegetation present in these environments. Urban sites must

have a high diversity of plants (Liang et al., 2023), with different species, guaranteeing resources for all pollinators. In addition, the promotion of plants with different life forms may benefit pollinators (Maruyama et al., 2019; Nascimento et al., 2020).

Although mostly generalized, network specialization increased with the proportion of native plants in the communities, highlighting the importance of native plants for network specialization in urban environments. Our results contribute to the finding that increasing the proportion of non-native plants can lead to a more generalized interaction network (Amado De Santis et al., 2023). The result that the proportion of non-native plants used by hummingbirds increases with soundscape further shows that human activity/urbanization led to more generalized ecological communities. In urbanized areas, a prevalence of non-native ornamental plants is common (Harrison and Winfree, 2015). Consequently, hummingbirds may visit more non-native plants as these are more available in modified areas, suggesting that plant-pollinator interactions are influenced by the urban landscaping and greening practices. It is thus worth noting that areas with higher human activity (higher noisiness, *i.e.* soundscape) are also areas with higher proportion of non-native species being used by hummingbirds. Therefore, multiple effects of urbanization, such as introduction of non-native plants and other disturbances captured by soundscape, indirectly converge in specific areas. Species-level specialization (d') of hummingbirds also increased as the number of interactions with native plant species increased, emphasizing the importance of native flora to support specialized interactions for hummingbirds. Since there are many native plant species with potential for ornamental urban landscaping in Brazil (Moro and Castro, 2015), they can be promoted to sustain more specialized interaction networks. On the other hand, native plants also showed greater species level specialization (d') than non-natives, thus native plants in urban environments are also involved in more specialized interactions than non-native

plants, being relevant as resource for specific consumer species (Zaninotto et al., 2023).

Although higher urbanization was related to reduced hummingbird richness, it did not significantly affect hummingbird abundance. However, we did observe a positive effect of plant richness, but not of flower abundance, on hummingbird abundance, indicating that it is not the quantity of flowers, but the diversity of plants that may be a key factor in maintaining hummingbirds. In addition, the resources offered by plants and their seasonality can have a strong influence on the presence of pollinators and their interactions in urban areas (Liang et al., 2023b). Therefore, an interesting strategy would be to include different native species, diversifying the quantity and quality of floral resources made available to pollinators in cities (Gomes et al., 2023), since increasing the richness of native plants in the urban environment can result in greater animal diversity (Berthon et al., 2021).

At the same time, we observed a greater predominance of non-native plants in the meta-network from the city of Belo Horizonte. In addition, non-native plants were more frequently visited by hummingbirds than native plants and were the only module-hubs in the meta-network, indicating their importance as a resource within their own interaction modules (Olesen et al., 2007). The plant species that acted as module-hubs, which were also the species most visited by hummingbirds, were commonly used as ornamental plants in urban gardens. Urban sites often feature ornamental non-native plants that are attractive to pollinators (Nascimento et al., 2020; Silva et al., 2023; Vitorino et al., 2021) and the ability of pollinators to use ornamental and non-native plants is likely to be an important condition for their persistence in urban environments (Harrison and Winfree, 2015). Hence, although native plants contribute to higher specialization of interactions, these are not the dominant floral resources in the urban landscape.

In addition, the higher importance of non-native plants in the modules reflects the

presence of more generalist hummingbirds, which tend to include non-native plants in their interactions more frequently (Maruyama et al., 2016), since non-native species tend to have less restrictive morphologies and are therefore more generalist than native plants (Amado De Santis et al., 2023). This indicates the higher attractiveness of non-native plants to pollinators (Wenzel et al., 2020) and their importance for hummingbird persistence in such areas (Anselmo et al., 2023). Studies also showed that native plants, in turn, do not flower all year round, leaving gaps in their supply of resources that are filled in by non-native plants with longer flowering periods (*e.g.* Anselmo et al., 2023). Our findings highlight the need for strategies that consider not only the diversity of floral resources but also the temporal distribution of flowers, ensuring continuous resources for hummingbirds throughout the seasons.

Finally, anthropogenic changes have the potential to influence many life history traits of birds. Studies show that migration behavior can be altered (Buchan et al., 2022; Greig et al., 2017), while Coetzee et al., (2018) note that nectarivorous birds are affected by habitat homogenization and the ability to nest in trees in urbanized locations. High human population density in urbanized areas can lead to a decline in juvenile hummingbird survival and adult recruitment, indicating a direct threat to their persistence in cities (English et al., 2024). However, human impacts can be mitigated with careful planning of urban vegetation. Maintaining large trees and increasing plant diversity can mitigate the negative effects of urbanization on bird biodiversity (Pena et al., 2023). In this context, it is crucial that urban gardens maintain structured and complex vegetation, increasing the functional diversity of plants, rather than cultivating just few single species, thus supporting specialized pollinators (Deguines et al., 2016). In addition, considering trait matching that drive interactions between species is vital for pollinator conservation in modified landscapes, thus creating urban green spaces that are welcoming to different

pollinators (Adedoja and Mallinger, 2023).

Despite these findings, it is important to acknowledge that our study was conducted within the unique urban environment of Belo Horizonte, Brazil. This geographic specificity may limit the generality of our results, especially considering other urban areas with distinct ecological, climatic, or socio-economic conditions. Although the trend of higher generalization in urban areas when compared to surrounding natural areas has been often reported (Maruyama et al. 2024), urban landscapes across the globe vary significantly, so that interaction networks need not to be consistently generalized across varying degree of urbanization in the landscape, as found here. In fact, elsewhere and with other systems, interaction networks do vary in their specialization level across the cityscape (*e.g.*, Schneiberg et al. 2022). Thus, extending similar research to diverse urban contexts worldwide would be essential to broaden our understanding on how urbanization affect species interactions.

Conclusion

In summary, we highlight the high generalization of plant-hummingbird networks throughout the landscape, regardless of variations in the characteristics and vegetation cover of urban landscapes. Although there is a high predominance of non-native and introduced plants in cities, our results indicate the importance of native plants in promoting more specialized interactions. Our findings suggest that native species can contribute to increased network specialization and sustain more diverse pollinator communities in urban areas.

Looking to the future, there is fertile ground for research to delve into the factors that shape the dynamics of interaction networks in urban environments. The local loss of specialized species, as observed by Schneiberg et al., (2020), signals the homogenization

of these ecosystems. Investigating how specific native plant species influence the networks, considering seasonal variations, could elucidate the reasons behind the observed generalization in hummingbird networks. Long-term monitoring of these networks could further clarify their temporal dynamics, contributing to management and conservation practices for pollinators in urban areas. We recommend that urban planning strategically incorporates a high diversity of native plant species, which may be the key to establishing more functionally specialized networks in urban ecosystems.

Acknowledgments

We thank the Prefeitura de Belo Horizonte and the Fundação de Parques Municipais e Zoobotânica (FPMZB) for their support. Special thanks to Ingrid Gomes and Victor Duarte for their assistance in the field. This study was funded by FAPEMIG (RED-00039-23, APQ-01151-22); CNPq (Ph.D. scholarship to CB, #160722/2020-9; M.Sci. scholarship to PAA, #88882.184213/2011-01; PIBIC CNPq edital 2022 PRPq/UFMG to TMF), and FAPESP (JCP #2018/00107-3; 2021/10195-0).

References

- Adedija, O.A., Mallinger, R.E., 2023. Can trait matching inform the design of pollinator-friendly urban green spaces? A review and synthesis of the literature. *Ecosphere*. <https://doi.org/10.1002/ecs2.4734>
- Almeida-Neto, M., Guimarães, P., Guimarães, P.R., Loyola, R.D., Ulrich, W., 2008. A consistent metric for nestedness analysis in ecological systems: reconciling concept and measurement. *Oikos* 117, 1227–1239. <https://doi.org/10.1111/j.0030-1299.2008.16644.x>
- Alvares, C.A., Stape, J.L., Sentelhas, P.C., de Moraes Gonçalves, J.L., Sparovek, G.,

2013. Köppen's climate classification map for Brazil. *Meteorol. Zeitschrift* 22, 711–728. <https://doi.org/10.1127/0941-2948/2013/0507>
- Amado De Santis, A.A., Lomáscolo, S.B., Chacoff, N.P., 2023. Effects of urbanization on the structure of plant-flower visitor network at the local and landscape levels in the northern Argentinian Yungas forest. *Front. Sustain. Cities* 5. <https://doi.org/10.3389/frsc.2023.1086076>
- Anselmo, P.A., Cardoso, J.C.F., Siqueira, P.R., Maruyama, P.K., 2023. Non-native plants and illegitimate interactions are highly relevant for supporting hummingbird pollinators in the urban environment. *Urban For. Urban Green.* 86, 128025. <https://doi.org/10.1016/j.ufug.2023.128025>
- Baldock, K.C.R., 2020. Opportunities and threats for pollinator conservation in global towns and cities. *Curr. Opin. INSECT Sci.* 38, 63–71. <https://doi.org/10.1016/j.cois.2020.01.006>
- Bascompte, J., Jordano, P., Melián, C.J., Olesen, J.M., 2003. The nested assembly of plant–animal mutualistic networks. *Proc. Natl. Acad. Sci.* 100, 9383–9387. <https://doi.org/10.1073/pnas.1633576100>
- Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting Linear Mixed-Effects Models Using lme4. *J. Stat. Softw.* 67. <https://doi.org/10.18637/jss.v067.i01>
- Beckett, S.J., 2016. Improved community detection in weighted bipartite networks. *R. Soc. Open Sci.* 3, 140536. <https://doi.org/10.1098/rsos.140536>
- Berthon, K., Thomas, F., Bekessy, S., 2021. The role of 'nativeness' in urban greening to support animal biodiversity. *Landsc. Urban Plan.* <https://doi.org/10.1016/j.landurbplan.2020.103959>
- Bhakti, T., Pena, J.C., Moura, A.C.M., Pujoni, D., Saliba, L., Rodrigues, M., 2023. Urban biodiversity suitability index: decoding the relationships between cities and

- birds. *Urban Ecosyst.* 27, 305–319. <https://doi.org/10.1007/s11252-023-01446-5>
- Bhakti, T., Rossi, F., de Oliveira Mafia, P., de Almeida, E.F., Fujaco, M.A.G., de Azevedo, C.S., 2020. Preservation of historical heritage increases bird biodiversity in urban centers. *Environ. Dev. Sustain.* <https://doi.org/10.1007/s10668-020-00993-7>
- Blüthgen, Nico, Menzel, F., Blüthgen, Nils, 2006. Measuring specialization in species interaction networks. *BMC Ecol.* 6, 1967–1976. <https://doi.org/10.1186/1472-6785-6-9>
- Buchan, C., Franco, A.M.A., Catry, I., Gamero, A., Klvaňová, A., Gilroy, J.J., 2022. Spatially explicit risk mapping reveals direct anthropogenic impacts on migratory birds. *Glob. Ecol. Biogeogr.* 31, 1707–1725. <https://doi.org/10.1111/geb.13551>
- Chacoff, N.P., Vázquez, D.P., Lomáscolo, S.B., Stevani, E.L., Dorado, J., Padrón, B., 2012. Evaluating sampling completeness in a desert plant-pollinator network. *J. Anim. Ecol.* 81, 190–200. <https://doi.org/10.1111/j.1365-2656.2011.01883.x>
- Coetzee, A., Barnard, P., Pauw, A., 2018. Urban nectarivorous bird communities in Cape Town, South Africa, are structured by ecological generalisation and resource distribution. *J. Avian Biol.* 49, 1–11. <https://doi.org/10.1111/jav.01526>
- Cronk, Q., Ojeda, I., 2008. Bird-pollinated flowers in an evolutionary and molecular context. *J. Exp. Bot.* 59, 715–727. <https://doi.org/10.1093/jxb/ern009>
- Dalsgaard, B., Maruyama, P.K., Sonne, J., Hansen, K., Zanata, T.B., Abrahamczyk, S., Alarcón, R., Araujo, A.C., Araújo, F.P., Buzato, S., Chávez-González, E., Coelho, A.G., Cotton, P.A., Díaz-Valenzuela, R., Dufke, M.F., Enríquez, P.L., Martins Dias Filho, M., Fischer, E., Kohler, G., Lara, C., Las-Casas, F.M.G., Rosero Lasprilla, L., Machado, A.O., Machado, C.G., Maglianesi, M.A., Malucelli, T.S., Marín-Gómez, O.H., Martínez-García, V., Mendes de Azevedo-Júnior, S., da Silva

- Neto, E.N., Oliveira, P.E., Ornelas, J.F., Ortiz-Pulido, R., Partida-Lara, R., Patiño-González, B.I., Najara de Pinho Queiroz, S., Ramírez-Burbano, M.B., Rodrigo Rech, A., Rocca, M.A., Rodrigues, L.C., Rui, A.M., Sazima, I., Sazima, M., Simmons, B.I., Tinoco, B.A., Varassin, I.G., Vasconcelos, M.F., Vizentin-Bugoni, J., Watts, S., Kennedy, J.D., Rahbek, C., Schleuning, M., Martín González, A.M., 2021. The influence of biogeographical and evolutionary histories on morphological trait-matching and resource specialization in mutualistic hummingbird–plant networks. *Funct. Ecol.* 35, 1120–1133.
<https://doi.org/10.1111/1365-2435.13784>
- Deguines, N., Julliard, R., de Flores, M., Fontaine, C., 2016. Functional homogenization of flower visitor communities with urbanization. *Ecol. Evol.* 6, 1967–1976.
<https://doi.org/10.1002/ece3.2009>
- Dormann, C.F., Gruber, B., Fründ, J., 2008. Introducing the bipartite package: Analysing ecological networks. *R News* 8, 8–11.
<https://doi.org/https://doi.org/10.1186/1472-6785-6-9>
- Dormann, C.F., Strauss, R., 2014. A method for detecting modules in quantitative bipartite networks. *Methods Ecol. Evol.* 5, 90–98. <https://doi.org/10.1111/2041-210X.12139>
- Duarte, R.H., 2007. À sombra dos fícus: cidade e natureza em Belo Horizonte. *Ambient. Soc.* 10, 25–44. <https://doi.org/10.1590/S1414-753X2007000200003>
- Ellis, E.E., Edmondson, J.L., Maher, K.H., Hipperson, H., Campbell, S.A., 2023. Negative effects of urbanisation on diurnal and nocturnal pollen-transport networks. *Ecol. Lett.* <https://doi.org/10.1111/ele.14261>
- English, S.G., Wilson, S., Zhao, Q., Bishop, C.A., Moran, A.J., 2024. Demographic mechanisms and anthropogenic drivers of contrasting population dynamics of

- hummingbirds. *Biol. Conserv.* 289, 110415.
<https://doi.org/10.1016/j.biocon.2023.110415>
- Fox, J., Weisberg, S., 2011. Multivariate Linear Models in R. R Dev. Core Team 31.
- Gomes, I.N., Bosenbecker, C., Silva, V.H.D., Cardoso, J.C.F., Pena, J.C., Maruyama, P.K., 2023. Spatiotemporal availability of pollinator attractive trees in a tropical streetscape: unequal distribution for pollinators and people. *Urban For. Urban Green.* 83, 127900. <https://doi.org/10.1016/j.ufug.2023.127900>
- Greig, E.I., Wood, E.M., Bonter, D.N., 2017. Winter range expansion of a hummingbird is associated with urbanization and supplementary feeding. *Proc. R. Soc. B Biol. Sci.* 284, 20170256. <https://doi.org/10.1098/rspb.2017.0256>
- Harrison, T., Winfree, R., 2015. Urban drivers of plant-pollinator interactions. *Funct. Ecol.* 29, 879–888. <https://doi.org/10.1111/1365-2435.12486>
- Hesselbarth, M.H.K., Sciaini, M., With, K.A., Wiegand, K., Nowosad, J., 2019. landscapemetrics : an open-source R tool to calculate landscape metrics. *Ecography (Cop.)*. 42, 1648–1657. <https://doi.org/10.1111/ecog.04617>
- Liang, H., He, D., Theodorou, P., Yang, F., 2023a. The effects of urbanization on pollinators and pollination : A meta- - analysis 1–14.
<https://doi.org/10.1111/ele.14277>
- Liang, H., He, Y.D., Theodorou, P., Yang, C.F., 2023b. The effects of urbanization on pollinators and pollination: A meta-analysis. *Ecol. Lett.* 26, 1629–1642.
<https://doi.org/10.1111/ele.14277>
- Lunau, K., Papiorek, S., Eltz, T., Sazima, M., 2011. Avoidance of achromatic colours by bees provides a private niche for hummingbirds. *J. Exp. Biol.* 214, 1607–1612.
<https://doi.org/10.1242/jeb.052688>
- Marín-Gómez, O.H., Rodríguez Flores, C., Arizmendi, M. del C., 2022. Assessing

- ecological interactions in urban areas using citizen science data: Insights from hummingbird–plant meta-networks in a tropical megacity. *Urban For. Urban Green.* 74, 127658. <https://doi.org/10.1016/j.ufug.2022.127658>
- Maruyama, P.K., Bonizário, C., Marcon, A.P., D’Angelo, G., da Silva, M.M., da Silva Neto, E.N., Oliveira, P.E., Sazima, I., Sazima, M., Vizentin-Bugoni, J., dos Anjos, L., Rui, A.M., Marçal Júnior, O., 2019. Plant-hummingbird interaction networks in urban areas: Generalization and the importance of trees with specialized flowers as a nectar resource for pollinator conservation. *Biol. Conserv.* 230, 187–194. <https://doi.org/10.1016/j.biocon.2018.12.012>
- Maruyama, P.K., Oliveira, G.M., Ferreira, C., Dalsgaard, B., Oliveira, P.E., 2013. Pollination syndromes ignored: importance of non-ornithophilous flowers to Neotropical savanna hummingbirds. *Naturwissenschaften* 100, 1061–1068. <https://doi.org/10.1007/s00114-013-1111-9>
- Maruyama, P.K., Silva, J.L.S., Gomes, I.N., Bosenbecker, C., Cruz-Neto, O., Oliveira, W., Cardoso, J.C.F., Stewart, A.B., Lopes, A.V., 2021. A global review of urban pollinators and implications for maintaining pollination services in tropical cities.
- Maruyama, P.K., Vizentin-Bugoni, J., Sonne, J., Martín González, A.M., Schleuning, M., Araujo, A.C., Baquero, A.C., Cardona, J., Cardona, P., Cotton, P.A., Kohler, G., Lara, C., Malucelli, T., Marín-Gómez, O.H., Ollerton, J., Rui, A.M., Timmermann, A., Varassin, I.G., Zanata, T.B., Rahbek, C., Sazima, M., Dalsgaard, B., 2016. The integration of alien plants in mutualistic plant-hummingbird networks across the Americas: The importance of species traits and insularity. *Divers. Distrib.* 22, 672–681. <https://doi.org/10.1111/ddi.12434>
- McKinney, M.L., 2006. Urbanization as a major cause of biotic homogenization. *Biol. Conserv.* 127, 247–260. <https://doi.org/10.1016/j.biocon.2005.09.005>

- Mckinney, M.L., Lockwood, J.L., 1999. Biotic homogenization : a few winners replacing many losers in the next mass extinction. *Perspectives (Montclair)*. 14, 450–453.
- Moro, M.F., Castro, A.S.F., 2015. A check list of plant species in the urban forestry of Fortaleza, Brazil: where are the native species in the country of megadiversity? *Urban Ecosyst.* 18, 47–71. <https://doi.org/10.1007/s11252-014-0380-1>
- Nascimento, V.T., Agostini, K., Souza, C.S., Maruyama, P.K., 2020. Tropical urban areas support highly diverse plant-pollinator interactions: An assessment from Brazil. *Landsc. Urban Plan.* 198, 103801. <https://doi.org/10.1016/j.landurbplan.2020.103801>
- Olesen, J.M., Bascompte, J., Dupont, Y.L., Jordano, P., 2007. The modularity of pollination networks. *Proc. Natl. Acad. Sci.* 104, 19891–19896. <https://doi.org/10.1073/pnas.0706375104>
- Ollerton, J., 2017. Pollinator Diversity: Distribution, Ecological Function, and Conservation. *Annu. Rev. Ecol. Evol. Syst.* 48, 353–376. <https://doi.org/10.1146/annurev-ecolsys-110316-022919>
- Pena, J.C., Ovaskainen, O., MacGregor-Fors, I., Teixeira, C.P., Ribeiro, M.C., 2023. The relationships between urbanization and bird functional traits across the streetscape. *Landsc. Urban Plan.* 232, 104685. <https://doi.org/10.1016/j.landurbplan.2023.104685>
- Planet Labs PBC, 2021. Planet Application Program Interface: In Space for Life on Earth [WWW Document].
- Quinn, G.P., Keough, M.J., 2002. Experimental design and data analysis for biologists. Cambridge University Press, United Kingdom.
- Ratto, F., Simmons, B.I., Spake, R., Zamora-Gutierrez, V., MacDonald, M.A.,

- Merriman, J.C., Tremlett, C.J., Poppy, G.M., Peh, K.S.H., Dicks, L. V., 2018. Global importance of vertebrate pollinators for plant reproductive success: a meta-analysis. *Front. Ecol. Environ.* 16, 82–90. <https://doi.org/10.1002/fee.1763>
- Sandström, U.G., Angelstam, P., Mikusiński, G., 2006. Ecological diversity of birds in relation to the structure of urban green space. *Landsc. Urban Plan.* 77, 39–53. <https://doi.org/10.1016/j.landurbplan.2005.01.004>
- Schneiberg, I., Boscolo, D., Devoto, M., Marcilio-Silva, V., Dalmaso, C.A., Ribeiro, J.W., Ribeiro, M.C., de Camargo Guaraldo, A., Niebuhr, B.B., Varassin, I.G., 2020. Urbanization homogenizes the interactions of plant-frugivore bird networks. *Urban Ecosyst.* 23, 457–470. <https://doi.org/10.1007/s11252-020-00927-1>
- Silva, J.L.S., de Oliveira, M.T.P., Cruz-Neto, O., Tabarelli, M., Lopes, A.V., 2021. Plant–pollinator interactions in urban ecosystems worldwide: A comprehensive review including research funding and policy actions. *Ambio* 50, 884–900. <https://doi.org/10.1007/s13280-020-01410-z>
- Silva, V.H.D., Gomes, I.N., Cardoso, J.C.F., Bosenbecker, C., Silva, J.L.S., Cruz-Neto, O., Oliveira, W., Stewart, A.B., Lopes, A. V, Maruyama, P.K., 2023b. Diverse urban pollinators and where to find them. *Biol. Conserv.* <https://doi.org/10.1016/j.biocon.2023.110036>
- Staab, M., Pereira-Peixoto, M.H., Klein, A.-M., 2020. Exotic garden plants partly substitute for native plants as resources for pollinators when native plants become seasonally scarce. *Oecologia* 194, 465–480. <https://doi.org/10.1007/s00442-020-04785-8>
- Stewart, A.B., Sritongchuay, T., Teartisup, P., Kaewsomboon, S., Bumrungsri, S., 2018. Habitat and landscape factors influence pollinators in a tropical megacity, Bangkok, Thailand. *PeerJ* 6, e5335. <https://doi.org/10.7717/peerj.5335>

- Stiles, F.G., 1981. Geographical Aspects of Bird-Flower Coevolution, with Particular Reference to Central America. *Ann. Missouri Bot. Gard.* 68, 323–351.
- Takemoto, K., Kajihara, K., 2016. Human impacts and climate change influence nestedness and modularity in food-web and mutualistic networks. *PLoS One* 11, e0157929. <https://doi.org/10.1371/journal.pone.0157929>
- Temeles, E.J., Koulouris, C.R., Sander, S.E., Kress, W.J., 2009. Effect of flower shape and size on foraging performance and trade-offs in a tropical hummingbird. *Ecology* 90, 1147–1161. <https://doi.org/10.1890/08-0695.1>
- Theodorou, P., 2022. The effects of urbanisation on ecological interactions. *Curr. Opin. Insect Sci.* 52, 100922. <https://doi.org/10.1016/j.cois.2022.100922>
- Theodorou, P., Radzevičiūtė, R., Lentendu, G., Kahnt, B., Husemann, M., Bleidorn, C., Settele, J., Schweiger, O., Grosse, I., Wubet, T., Murray, T.E., Paxton, R.J., 2020. Urban areas as hotspots for bees and pollination but not a panacea for all insects. *Nat. Commun.* 11, 576. <https://doi.org/10.1038/s41467-020-14496-6>
- Vitorino, B.D., Frota, A.V.B. da, Maruyama, P.K., 2021. Ecological determinants of interactions as key when planning pollinator-friendly urban greening: A plant-hummingbird network example. *Urban For. Urban Green.* 64, 127298. <https://doi.org/10.1016/j.ufug.2021.127298>
- Vizentin-Bugoni, J., Maruyama, P.K., Debastiani, V.J., Duarte, L. da S., Dalsgaard, B., Sazima, M., 2016. Influences of sampling effort on detected patterns and structuring processes of a Neotropical plant-hummingbird network. *J. Anim. Ecol.* 85, 262–272. <https://doi.org/10.1111/1365-2656.12459>
- Vizentin-Bugoni, J., Maruyama, P.K., Sazima, M., 2014. Processes entangling interactions in communities: forbidden links are more important than abundance in a hummingbird–plant network. *Proc. R. Soc. B Biol. Sci.* 281, 20132397.

<https://doi.org/10.1098/rspb.2013.2397>

Wenzel, A., Grass, I., Belavadi, V. V, Tschardtke, T., 2020. How urbanization is driving pollinator diversity and pollination – A systematic review. *Biol. Conserv.*

<https://doi.org/10.1016/j.biocon.2019.108321>

Zanata, T.B., Dalsgaard, B., Passos, F.C., Cotton, P.A., Roper, J.J., Maruyama, P.K., Fischer, E., Schleuning, M., Martín González, A.M., Vizentin-Bugoni, J., Franklin, D.C., Abrahamczyk, S., Alárcon, R., Araujo, A.C., Araújo, F.P., Azevedo-Junior, S.M. de., Baquero, A.C., Böhning-Gaese, K., Carstensen, D.W., Chupil, H., Coelho, A.G., Faria, R.R., Hořák, D., Ingversen, T.T., Janeček, Š., Kohler, G., Lara, C., Las-Casas, F.M.G., Lopes, A. V., Machado, A.O., Machado, C.G., Machado, I.C., Maglianesi, M.A., Malucelli, T.S., Mohd-Azlan, J., Moura, A.C., Oliveira, G.M., Oliveira, P.E., Ornelas, J.F., Riegert, J., Rodrigues, L.C., Rosero-Lasprilla, L., Rui, A.M., Sazima, M., Schmid, B., Sedláček, O., Timmermann, A., Vollstädt, M.G.R., Wang, Z., Watts, S., Rahbek, C., Varassin, I.G., 2017. Global patterns of interaction specialization in bird–flower networks. *J. Biogeogr.* 44, 1891–1910. <https://doi.org/10.1111/jbi.13045>

Zaninotto, V., Thebault, E., Dajoz, I., 2023. Native and exotic plants play different roles in urban pollination networks across seasons. *Oecologia* 201, 525–536.

<https://doi.org/10.1007/s00442-023-05324-x>

CONCLUSÃO GERAL

Por meio dos dois estudos realizados nesta tese foi possível avaliar a relação das pessoas com os beija-flores e suas interações com flores sob diferentes perspectivas. Esses trabalhos demonstraram como o acúmulo de conhecimento sobre essas interações pode ser complementado tanto por cientistas quanto por cidadãos engajados, que contribuem através da ciência cidadã. Além disso, os estudos também evidenciam o impacto das mudanças no estilo de vida moderno e da expansão dos grandes centros urbanos sobre essas interações. Isso levanta preocupações sobre as possíveis implicações para a conservação dessas espécies em ambientes urbanos, destacando a necessidade de abordagens de conservação integradas e voltadas para a coexistência harmoniosa entre fauna e áreas urbanizadas.

No primeiro capítulo, mostramos a ciência cidadã como ferramenta para fornecer dados complementares sobre interações ecológicas, comparando dados coletados por amadores com dados gerados por cientistas profissionais. Ao examinar as interações entre beija-flores e plantas registrados por amadores, observamos que os dados da ciência cidadã capturam interações muitas vezes não observadas por cientistas. Nesse sentido, a utilização de plataformas de ciência cidadã, como o Wikiaves no Brasil, pode abranger áreas pouco estudadas, facilitando a coleta de dados em áreas de difícil acesso, como a Floresta Amazônica, ampliando o alcance geográfico das observações. Apesar da existência de limitações na utilização de dados coletados por amadores, como a falta de padronização e a concentração de registros em áreas urbanas, esses dados se mostraram promissores para estudos de biodiversidade e conservação. Além de capturarem informações sobre espécies comuns, também registram a presença de espécies ameaçadas. Além disso, essas iniciativas fornecem uma fonte rica e abrangente de informações e promovem o envolvimento ativo e engajamento da população na ciência,

contribuindo para a educação e alfabetização científica.

No segundo capítulo, avaliamos as mudanças na estrutura das redes de interação ao longo de um gradiente de urbanização em uma grande cidade tropical no Brasil. Observamos que as interações planta-beija-flor em Belo Horizonte são em grande parte generalistas, com alta predominância de plantas não-nativas, independentemente do nível de urbanização na paisagem. A proporção de plantas não-nativas usadas por beija-flores aumentou com a paisagem sonora, já que estas plantas estão mais disponíveis em áreas urbanas modificadas. Isso mostra que as interações planta-polinizador são fortemente influenciadas pelas práticas de paisagismo urbano. Embora as redes observadas em áreas urbanas tenham se mostrado generalistas, a presença de plantas nativas foi associada a uma maior especialização nas interações, sugerindo que a diversidade de plantas nativas pode desempenhar um papel crucial na promoção de redes mais complexas e na sustentação de comunidades de polinizadores em paisagens urbanas, reforçando a importância da flora nativa para a manutenção de interações especializadas. Outro aspecto observado foi que, apesar da redução da riqueza de beija-flores em áreas mais urbanizadas, sua abundância não foi diretamente afetada. Pelo contrário, a abundância de beija-flores aumentou à medida que a riqueza de plantas disponíveis também aumentou, indicando que a diversidade de plantas, e não a quantidade de flores, é um fator essencial na manutenção dessas aves polinizadoras em ambientes urbanos.

Uma convergência entre os dois estudos é que a utilização da ciência cidadã parece ser especialmente eficiente para o monitoramento e conservação da biodiversidade em ambientes urbanos. Ao permitir que cidadãos comuns contribuam ativamente com a coleta de dados sobre espécies, especialmente em projetos como a observação de aves, essa abordagem democratiza o conhecimento científico e amplia a quantidade de informações disponíveis para pesquisadores e gestores ambientais. Além de gerar dados

valiosos, a ciência cidadã fortalece o vínculo entre a população e a natureza, promovendo a conscientização e o engajamento na preservação ambiental. Estes dados inclusive poderiam ser melhor aproveitados para fundamentar a conservação de polinizadores em paisagens urbanas, fornecendo informações robustas para cientistas, planejadores e tomadores de decisão. Também, é crucial que os planejadores urbanos e a sociedade em geral reconheçam a necessidade de integrar a conservação da biodiversidade na administração e planejamento das nossas cidades. Somente através de políticas públicas adequadas, iniciativas de conservação efetivas e envolvimento da comunidade, será possível reduzir os impactos negativos da urbanização sobre as espécies nativas e promover cidades mais sustentáveis e favoráveis à coexistência com a natureza.

REFERÊNCIAS GERAL

Anselmo, P.A., Cardoso, J.C.F., Siqueira, P.R., Maruyama, P.K., 2023. Non-native plants and illegitimate interactions are highly relevant for supporting hummingbird pollinators in the urban environment. *Urban For. Urban Green.* 86, 128025. <https://doi.org/10.1016/j.ufug.2023.128025>

Aronson, M.F., Lepczyk, C.A., Evans, K.L., Goddard, M.A., Lerman, S.B., MacIvor, J.S., Nilon, C.H., Vargo, T., 2017. Biodiversity in the city: key challenges for urban green space management. *Front. Ecol. Environ.* 15, 189–196. <https://doi.org/10.1002/fee.1480>

Barbosa, K.V. de C., Develey, P.F., Ribeiro, M.C., Jahn, A.E., 2021. The contribution of citizen science to research on migratory and urban birds in Brazil. *Ornithol. Res.* 29, 1–11. <https://doi.org/10.1007/s43388-020-00031-0>

Barreto, E., Boehm, M.M.A., Ogutcen, E., Abrahamczyk, S., Kessler, M., Bascompte, J., Dellinger, A.S., Bello, C., Dehling, D.M., Duchenne, F., Kaehler, M., Lagomarsino, L.P., Lohmann, L.G., Maglianesi, M.A., Morlon, H., Muchhala, N., Ornelas, J.F., Perret, M., Salinas, N.R., Smith, S.D., Vamosi, J.C., Varassin, I.G., Graham, C.H., 2024. Macroevolution of the plant–hummingbird pollination system. *Biol. Rev.* 99, 1831–1847. <https://doi.org/10.1111/brv.13094>

Berthon, K., Thomas, F., Bekessy, S., 2021. The role of ‘nativeness’ in urban greening to support animal biodiversity. *Landsc. Urban Plan.* 205, 103959. <https://doi.org/10.1016/j.landurbplan.2020.103959>

Bonney, R., Cooper, C.B., Dickinson, J., Kelling, S., Phillips, T., Rosenberg, K. V., Shirk, J., 2009. Citizen Science: A Developing Tool for Expanding Science

Knowledge and Scientific Literacy. *Bioscience* 59, 977–984.
<https://doi.org/10.1525/bio.2009.59.11.9>

Butchart, S., Walpole, M., Collen, B., Strien, A. Van, Scharlermann, J.P., Almond, R.E., Baillie, J.E.M., Bomhard, B., Brown, C., Bruno, J., Carpenter, K.E., Carr, G., Chanson, J., Chenery, A.M., Jorge, C.J., Davidson, N.C., Dentener, F., Foster, M., Galli, A., Galloway, J., Piero, G., Richard, D.G., Marc, H., Valerie, K., Jean-Francois, L., Fiona, L., Monica, H.M., Thomasina, E.E.O., Daniel, P., Suhel, Q., Carmen, R., John, R.S., Benjamin, S., Dian, S., Damon, S.-S., Simon, N.S., Andy, S., Meagn, T., Tristan, D.T., Jean-Christophe, V., Reg, W., 2010. Global Biodiversity: Indicators of Recent Declines. *Science* (80-.). 328, 1164–1168.

Carbó-Ramírez, P., Zuria, I., 2011. The value of small urban greenspaces for birds in a Mexican city. *Landsc. Urban Plan.* 100, 213–222.
<https://doi.org/10.1016/j.landurbplan.2010.12.008>

Cardinale, B.J., Duffy, J.E., Gonzalez, A., Hooper, D.U., Perrings, C., Venail, P., Narwani, A., Mace, G.M., Tilman, D., Wardle, D.A., Kinzig, A.P., Daily, G.C., Loreau, M., Grace, J.B., Larigauderie, A., Srivastava, D.S., Naeem, S., 2012. Biodiversity loss and its impact on humanity. *Nature* 486, 59–67. <https://doi.org/10.1038/nature11148>

Castellanos, M.C., Wilson, P., Thomson, J.D., 2003. Pollen transfer by hummingbirds and bumblebees, and the divergence of pollination modes in penstemon. *Evolution* (N. Y). 57, 2742–2752. <https://doi.org/10.1111/j.0014-3820.2003.tb01516.x>

Fontana, S., Sattler, T., Bontadina, F., Moretti, M., 2011. How to manage the urban green to improve bird diversity and community structure. *Landsc. Urban Plan.* 101, 278–285. <https://doi.org/10.1016/j.landurbplan.2011.02.033>

Leimberger, K.G., Dalsgaard, B., Tobias, J.A., Wolf, C., Betts, M.G., 2022. The evolution, ecology, and conservation of hummingbirds and their interactions with flowering plants. *Biol. Rev.* 97, 923–959. <https://doi.org/10.1111/brv.12828>

Marzluff, J.M., Ewing, K., 2001. Restoration of Fragmented Landscapes for the Conservation of Birds: A General Framework and Specific Recommendations for Urbanizing Landscapes, in: *Urban Ecology*. Springer US, Boston, MA, pp. 739–755. https://doi.org/10.1007/978-0-387-73412-5_48

McKinney, M.L., 2006. Urbanization as a major cause of biotic homogenization. *Biol. Conserv.* 127, 247–260. <https://doi.org/10.1016/j.biocon.2005.09.005>

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>

Pena, J.C. de C., Martello, F., Ribeiro, M.C., Armitage, R.A., Young, R.J., Rodrigues, M., 2017. Street trees reduce the negative effects of urbanization on birds. *PLoS One* 12, e0174484. <https://doi.org/10.1371/journal.pone.0174484>

Ratto, F., Simmons, B.I., Spake, R., Zamora-Gutierrez, V., MacDonald, M.A., Merriman, J.C., Tremlett, C.J., Poppy, G.M., Peh, K.S.H., Dicks, L. V., 2018. Global importance of vertebrate pollinators for plant reproductive success: a meta-analysis. *Front. Ecol. Environ.* 16, 82–90. <https://doi.org/10.1002/fee.1763>

Sandström, U.G., Angelstam, P., Mikusiński, G., 2006. Ecological diversity of birds in relation to the structure of urban green space. *Landsc. Urban Plan.* 77, 39–53. <https://doi.org/10.1016/j.landurbplan.2005.01.004>

Sekercioglu, C.H., 2002. Impacts of birdwatching on human and avian

communities. *Environ. Conserv.* 29, 282–289.
<https://doi.org/10.1017/S0376892902000206>

Seto, K.C., Güneralp, B., Hutya, L.R., 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proc. Natl. Acad. Sci.* 109, 16083–16088. <https://doi.org/10.1073/pnas.1211658109>

Silvertown, J., 2009. A new dawn for citizen science. *Trends Ecol. Evol.* 24, 467–471. <https://doi.org/10.1016/j.tree.2009.03.017>

Theobald, E.J., Ettinger, A.K., Burgess, H.K., DeBey, L.B., Schmidt, N.R., Froehlich, H.E., Wagner, C., HilleRisLambers, J., Tewksbury, J., Harsch, M.A., Parrish, J.K., 2015. Global change and local solutions: Tapping the unrealized potential of citizen science for biodiversity research. *Biol. Conserv.* 181, 236–244. <https://doi.org/10.1016/j.biocon.2014.10.021>

Tinoco, B.A., Graham, C.H., Aguilar, J.M., Schleuning, M., 2016. Effects of hummingbird morphology on specialization in pollination networks vary with resource availability. *Oikos* 126, 52–60. <https://doi.org/10.1111/oik.02998>

Vitousek, P.M., Mooney, H.A., Lubchenco, J., Melillo, J.M., 1997. Human Domination of Earth's Ecosystems. *Science* (80). 277, 494–499. <https://doi.org/10.1126/science.277.5325.494>

Ziter, C., 2016. The biodiversity–ecosystem service relationship in urban areas: a quantitative review. *Oikos* 125, 761–768. <https://doi.org/10.1111/oik.02883>