



Prof. Dr. Claudio Gilberto Froehlich, a naturalistic legacy overcoming the biodiversity knowledge shortfalls

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ABSTRACT

The limited knowledge of biodiversity constrains conservation strategies in a wide range of questions. Overcoming and recognizing these knowledge deficits require integrated efforts by current researchers and constitute crucial challenges for the next generations. Prof. Dr. Claudio Froehlich was a pioneer in implementing a research program integrating ecology and taxonomy, especially in aquatic insects, in Brazil. This special issue was conceptualized to honor his prolific scientific career and constitutes a tribute to the pioneering in Brazilian aquatic entomology. A brief biography of Prof. Dr. Claudio Froehlich was presented as well as 13 papers facing the biodiversity knowledge shortfalls from five insect orders (Diptera, Ephemeroptera, Neuroptera, Plecoptera, Trichoptera), with behavior reports (Eltonian shortfall), 23 new species described (Linnean shortfall), and distribution records for several taxa (Wallacean shortfall).

Introduction

The planet is crossing the sixth mass extinction event, the Anthropocene extinction. Species loss is dramatically climbing due to anthropogenic disturbances, including climate change (Finn et al., 2023). The current extinction rates are around 1,000–10,000 higher than background extinction rates (Ceballos et al., 2020). Accelerated species loss and the current biodiversity knowledge deficits increase the difficulties in management and conservation decision-making (Löbl et al., 2023).

Our limited knowledge of biodiversity constrains conservation strategies in a wide range of questions. The elucidation of these biodiversity shortfalls is the first step to shed some light on ways to overcome the knowledge gaps and deal with their uncertainty (Hortal et al., 2015). In this way, the deficits were named to define best the research challenges and agenda, such as Linnean (taxonomic

deficits), Wallacean (distribution deficits), Prestonian (abundance deficits), Darwinian (evolutionary patterns deficits), Hutchinsonian (abiotic tolerances gaps), Raunkiaeran (ecological traits deficits), Eltonian (biotic interactions deficits), and Haeckelian or Müllerian shortfalls (semaphoronts unknown) (Cardoso et al., 2011; Hortal et al., 2015; Calor and Quinteiro, 2017; Faria et al., 2020).

A global agenda for advancing freshwater biodiversity research (Maasri et al., 2022) included 15 pressing priority needs, some of them concerning biodiversity knowledge shortfalls. Improving taxonomic and ecological knowledge of freshwater organisms is a primary requirement to improve monitoring processes across taxa and areas, offering a targeted approach to focus on the shortfalls to the conservation of freshwater ecosystems. This way, understanding the shortfalls as challenges is a critical and urgent task, especially considering megadiverse countries such as Brazil, and regarding taxa as diverse as insects (Calor et al., 2024).

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Biodiversity knowledge challenges from aquatic insect studies

When integrating Froehlich's career and this special issue, four aquatic insect taxa can be highlighted, Diptera (Chironomidae), Ephemeroptera, Plecoptera, and Trichoptera. In all of them, Prof. Claudio Gilberto Froehlich (CGF) published articles and trained the next generations of researchers. CGF also supported and encouraged students and researchers to explore other insect orders through postgraduation classes in Entomology courses and also through lectures, which revealed his pure love for nature.

The embryo of this special issue of *Revista Brasileira de Entomologia* in honor of Prof. Claudio Gilberto Froehlich (CGF) was the R. Mariano, J. Peters, and E. Domínguez presentation at the XV International Conference on Ephemeroptera and XIX International Symposium on Plecoptera, Aracruz, Espírito Santo, Brazil (2018). Their oral presentation entitled "Brief history of South American research on Ephemeroptera" showed the importance of CGF in the first steps of Brazilian mayfly research. Subsequently, A. Calor, L. C. Pinho, and R. Mariano started a manuscript draft about the CGF's legacy. But only at the Symposium of Neotropical Aquatic Insects in Iheus, Bahia, Brazil (2022), that R. Mariano and F. F. Salles (RBE Editor-in-chief) made the final proposal of this special issue in honor of CGF.

In this paper, information was mainly extracted from the special issue articles as well as from the Lattes and Acacia platforms (<http://plataforma-acacia.org/>), The Academic Family Tree (TAFT, <https://academictree.org/>), and "Catálogo Taxonômico da Fauna do Brasil" website (<http://fauna.jbrj.gov.br/fauna/listaBrasil>).

The taxonomy of Chironomidae in Brazil is marked by significant contributions from diverse researchers spanning the past two centuries, commencing with Christian R. W. Wiedemann's description of *Chironomus brasiliensis* in 1828. Notably, up until the 1980s, the research in this domain was predominantly occupied by a small group of scholars, including Sebastião José de Oliveira, along with the German researchers Ernst Fittkau and Friedrich Reiss. The field of chironomid taxonomy in Brazil experienced a noteworthy shift post-1980s, marked by a surge in species discoveries, largely due to the influential contributions of Susana Trivinho-Strixino. From the 2000s onward, the pace of species discovery accelerated significantly, as a result of substantial project initiatives such as Biota-FAPESP in São Paulo and PRONEX in Amazonas. The importance of the projects led by CGF at Biota-FAPESP in promoting research on the taxonomy of Chironomidae in Brazil is evidenced by the number of chironomidologists in these projects. A total of 88 taxonomists have undertaken the task of describing Brazilian chironomid species and 15 of them were participants of Froehlich's Biota-FAPESP initiatives. In the 21st century, we witnessed an unprecedented acceleration in species discoveries, facilitated by the emergence of new taxonomists nurtured within these projects and fortified by international collaborations. In the span of the last three decades, the number of recorded species in Brazil has increased from 125 (Trivinho-Strixino and Strixino, 1995) to 668 (Pinho et al., 2024). Consequently, Chironomidae now stands as the richest aquatic Diptera family in Brazil.

For many years, the taxonomy of Ephemeroptera in Brazil was in the hands of foreign researchers due to the absence of Brazilian experts in the field. The significant initial milestone for this order occurred in the late 19th century with Eaton's work entitled "Revisional Monograph" (1883–1888). After that period, descriptions were conducted in a fragmented manner, without the establishment of a comprehensive catalog of species present in Brazil. Between the 1910s and 1920s, Navás played a prominent role in describing species of aquatic insects in Brazil, with an emphasis on the states of Paraná, Rio de Janeiro, and São Paulo. However, until the 1930s, descriptions continued to be carried out by foreign researchers. It was only in 1969 that CGF marked

a milestone by describing the first Brazilian species, *Caenis cuniana*, a parthenogenetic mayfly (Froehlich, 1969a). In the 1980s, researchers from the Florida Agricultural & Mechanical University (Will Peter and Janice Peters) and the Universidad de Tucuman (Eduardo Domínguez) were the main contributors to articles describing species collected in Brazil. The first catalog to present records for Brazil was compiled by Hubbard in 1982, documenting 92 species in the order. Since the 1990s, Brazilian researchers have actively participated in describing new species, leading to a significant increase. Today, Brazil has several research centers dedicated to Ephemeroptera taxonomy, spread across almost all regions of the country (Cardoso et al., 2015). The number of species recorded in Brazil has reached 448, distributed among 83 genera and 10 families (Salles et al., 2023a).

By the mid-20th century, European authors had described 67 species of Plecoptera in Brazil, much like the scenario in Ephemeroptera and Chironomidae. Nowadays Brazilian researchers, notably Claudio Gilberto Froehlich, have made significant contributions. Prof. Froehlich's first work in the order was in 1960, a result of his postdoctoral research in Sweden supervised by Professor Dr. P. Brinck, entitled "Some gripopterygids and notonemourines (Plecoptera) from South America" (Froehlich, 1960). With this impactful work and the description of *Tupiperla* Froehlich (1969b) and some species of *Paragripopteryx* Enderlein, 1909 in the same decade, the studies of Plecoptera "Made in Brazil" finally began. Starting from that point, the following decades were dominated by Froehlich's descriptions, with 82 species described until 2013. CGF is responsible for the description of 81% of Neotropical stonefly species. Currently, the taxonomy of Plecoptera in Brazil encompasses two families, 9 genera, and 203 valid species.

The caddisfly taxonomy in Brazil started with "Insecta Brasiliensia" by Perty (1830-1834), including the first caddisfly described in the country: *Phryganea maculata* Perty, 1833 (now, *Macrostemum brasiliense* (Fischer, 1970)). During the 19th and 20th centuries, several authors contributed significantly to enhancing the knowledge of the Brazilian fauna (e.g., Banks, Brauer, Burmeister, McLachlan, Navás, Pictet, Ulmer). Four of them deserve special mention due to the high amount of new species they proposed and their thorough studies on caddisflies: Fritz Müller (a pioneer in Southern Brazil, who described 21 Brazilian caddisfly species), Oliver S. Flint Jr. (National Museum of Natural History, Smithsonian Institution, USA, who described more than 200 species from Brazil), Ralph Holzenthal and Roger Blahnik (both from the Insect Collection of the University of Minnesota, USA; who described more than 150 species from Brazil) (Santos et al., 2020). In the last two decades, a community of Brazilian caddisfly taxonomists was established and the caddisfly knowledge shortfalls have been faced. The knowledge about Brazilian caddisfly species rose from 378 species (Paprocki et al., 2004) to 934 species (Santos et al., 2024). This places Trichoptera as the most species-rich aquatic insect order in the country. However, estimations point out that this is only 50% of the Brazilian caddisfly diversity (Santos et al., 2020), which implies around 900 caddisfly species to be discovered.

Regardless of the taxonomic group, CGF often focused his efforts on encouraging young researchers in different ways. An example was the first edition of the "Symposium of Neotropical Aquatic Insects", which occurred in Salvador (Bahia state), in 2012, where CGF spent most of his time talking to young researchers who only knew him through scientific articles. The symposium's 7th edition will be held in Belém (Pará state) in 2025 and now represents a life-long event, that had editions from southern to northern Brazil.

"Froehlich's Autonomous Stonefly Republic" is "polyphyletic"!

Prof. Claudio Gilberto Froehlich's scientific production is not based only on insects but also deals with geoplanids, cnidarians, and

onychophorans. His contributions go beyond being one of the pioneers in Brazilian zoology, he is also a descendent of some of the most important lineages of naturalists, and the academic father of eight generations of Brazilian researchers (Mariano et al., 2024).

After his undergraduate course at Universidade de São Paulo, he was mentored by Dr. Ernst Gustav Gotthelf Marcus (1893–1968). Marcus' ascendancy connected CGF to some important names in natural history and biological sciences in Germany, such as Johann Friedrich Blumenbach (1752–1840), one of the comparative zoology and anthropology founders, and mentor of the next generation of German biologists, including Alexander von Humboldt; also to researchers from the French school, such as Étienne St. Hilaire (1772–1844), and Georges Cuvier (1769–1832), both from Muséum National Histoire Naturelle, Paris (TAFT, 2023).

CGF's descendency comprises 41 researchers in the first generation and more than 3,000 in eight generations (Damaceno et al., 2019). Such impressive data contributes to the foundation of aquatic entomology research groups in Brazil (more than 50% of first-generation) and other related areas. One of CGF's descendants is Dr. Ivan Sazima (Unicamp), who follows the productive way of his Ph.D. advisor, with 40 direct postgraduate students in the first generation and more than 1,300 descendants in seven generations (around 45% of CGF's descendency) (Damaceno et al., 2019).

Over time, CGF published 95 scientific articles, 21 book chapters, and two books on aquatic entomology. Initially, he worked on the taxonomy of terrestrial flatworms, describing 59 species of Geoplanidae

(Platyhelminthes). He also had studies on Cnidaria and Onychophora, proposing a revision of Brazilian species. However, he gained worldwide recognition when he entered the fascinating world of aquatic insects in the 1960s with the publication of "Some Gripopterygids and Notonemourines (Plecoptera) From South America" (Froehlich, 1960) and "*Caenis cuniana* sp. n., a parthenogenetic mayfly" (Froehlich, 1969a), seminal works in the diversity of Brazilian stoneflies and mayflies. In addition to his research, his main legacy was mentoring researchers in aquatic entomology.

Throughout his career, by mentoring students and actively working on his research, CGF provided important contributions to help reveal animal biodiversity. We presented this special issue to honor Prof. Dr. Claudio Gilberto Froehlich's career, exploring insect biodiversity, one of his passions. In this issue, 13 articles were published, and a brief account of the content of each one is provided in the following, connecting the results to help our challenge to face biodiversity knowledge shortfalls.

Content of the special issue

The special issue in honor of Prof. Dr. Claudio Gilberto Froehlich comprises 13 articles, one of them was a brief biography (Mariano et al., 2024), 11 articles facing the biodiversity knowledge shortfalls from five insect orders (Diptera, Ephemeroptera, Neuroptera, Plecoptera, Trichoptera), in which 23 new species are described (Fig. 1), and this last one.

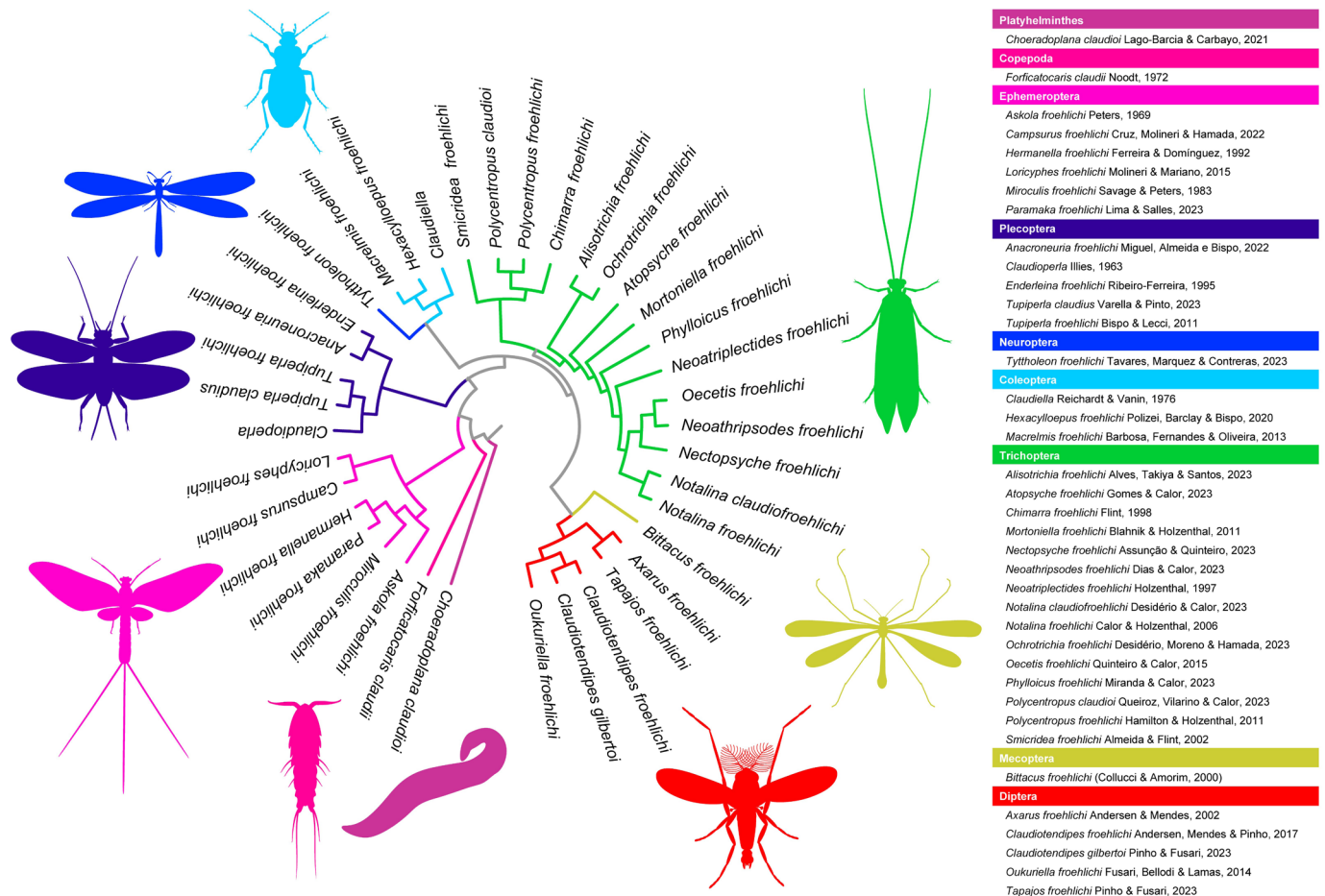


Figure 1 Taxa described in honor of Prof. Dr. Claudio Gilberto Froehlich, including 23 new species presented in the special issue. Relationships compiled from Misof et al. (2014), Thomas et al. (2020), Ogden et al. (2019) and Andersen et al. (2017).

In Diptera, Rafael et al. (2023) and Pinho and Fusari (2023) faced the Eltonian, Linnean, and Wallacean shortfalls. Rafael et al. (2023) presented evidence that the species *Hilarempis sigillata* Collin (1933) (Diptera: Empididae: Empidinae) might have nocturnal activities (instead of crepuscular), since specimens were collected until two hours after sunset, by the river Chanleufu, Chile. They also recorded specimens of *Hilarempis sigillata* preying on specimens of other Diptera (Chironomidae) and Neuroptera (Coniopterygidae). The biological and ecological data provided by the authors tackle the Eltonian shortfall, which addresses the lack of knowledge about species' interactions and how they might affect individual survival (Hortal et al., 2015). Pinho and Fusari (2023) describe and illustrate two new species of Chironomidae, *Tapajos froehlichii* Pinho & Fusari, 2023 and *Claudiotendipes gilbertoi* Pinho & Fusari, 2023, both belonging to the genera recently described and endemic to Neotropics. The immatures of *Tapajos* are unknown and reveal a typical case of Haeckelian shortfall.

The mayfly studies were represented by Lima et al. (2023) and Salles et al. (2023b). Lima et al. (2023) also present data concerning the Amazonian fauna of aquatic insects. They describe and illustrate the male and female imago of *Hydromastodon* cf. *mikei* (Thomas & Boutonnet, 2004 in Thomas et al., 2004) (Ephemeroptera: Leptophlebiidae) based on specimens from Pará state, which was originally described based on nymphs. They also propose a new species of leptophlebid, *Paramaka froehlichii* Lima & Salles, 2023, based on adult male specimens from Pará state. This article supplies information regarding the Linnean and Haeckelian shortfalls on the diversity and the life stages of organisms, respectively (Hortal et al., 2015; Faria et al., 2020). To address the gap in mayfly distribution, Salles et al. (2023b) curated a comprehensive database containing all datasets related to the distribution of mayflies in Brazil. The data is accessible at <https://edelponte.shinyapps.io/ephembrazil/>, providing distributional maps for mayfly species, genera, and families in Brazil. Anticipated outcomes include significant contributions to future studies in ecology and taxonomy, offering valuable insights for researchers and supporting conservation initiatives. This work stands as an important resource for advancing knowledge and understanding of mayfly populations in Brazil.

The Linnean and Wallacean shortfalls in Neuroptera were faced by Tavares et al. (2023b), who revised the antlion tribe Gnopholeontini (Myrmeleontidae) in Baja California, Mexico. In this region of high endemism, they update the distributional records, describe and illustrate specimens of five species, in three genera. They also describe and illustrate one new species, in a previously monotypic genus, *Tyttholeon froehlichii* Tavares, Marquez & Contreras, 2023b. Hence, in this article, their results tackle the Linnean and Wallacean shortfalls (Hortal et al., 2015), especially in a biodiversity hotspot, such as the Baja California Peninsula.

Plecoptera studies were represented in the issue by Duarte and Lecci (2024) and Varella and Pinto (2024). Duarte and Lecci (2024) offer a thorough scientometric analysis of Plecoptera, specifically focusing on Brazilian taxonomy. Their study encompasses data from the 20th century to the present, highlighting the initial descriptors of Plecoptera in Brazil. CGF has played a pivotal role in describing 82 of these species, either as a single author or in collaboration with other researchers. Additionally, they delve into discussions about the distribution and remarkable diversity of species. Varella and Pinto (2024) described a new species of *Tupiperla*, *T. claudius* from the protected area Mananciais da Serra in the Serra do Mar, also the first record for the genus to the state of Paraná.

Considering the biodiversity shortfalls in caddisfly studies, four papers dealt with different biodiversity knowledge shortfalls. Two of them (Alves et al., 2023; Desidério et al., 2023) focus on the two microcaddisfly genera, *Alisotrichia* Flint (1991) and *Ochrotrichia*

Mosely (1934); Assunção and Quinteiro (2023) focus on the long-horned caddisfly genus *Nectopsyche* Müller, 1879, and Calor et al. (2024) provide the summary of Laboratório de Entomologia Aquática Prof. Dr. Claudio Gilberto Froehlich (LEAq) team facing the Linnean and Wallacean shortfalls for the past 14 years, especially in caddisfly studies. Alves et al. (2023) describe and illustrate five new species of *Alisotrichia*, in the *orophila* species group, from Brazil (Alagoas, Bahia, Ceará, Paraíba, Pernambuco, and Sergipe states), consisting of the first records of the genus to Northeastern Brazil. The number of Brazilian species of *Alisotrichia* increased from five to ten, but the authors clearly state that the Linnean shortfalls are far from being overcome in this genus. Desidério et al. (2023) describe and illustrate three new species of *Ochrotrichia* from Brazil. All species were named in honor of three great Brazilian entomologists, *Ochrotrichia froehlichii* Desidério, Moreno & Hamada, 2023, *Ochrotrichia machadoi* Desidério, Moreno, Carvalho & Hamada, 2023 and *Ochrotrichia nessimiani* Desidério, Alves, Moreno & Hamada, 2023. This paper also presents the first record of *Ochrotrichia* for the Brazilian Central-West region and increases the number of species from one to four in the Cerrado biome. Assunção & Quinteiro (2023) describe and illustrate two new species of the genus *Nectopsyche* (Leptoceridae), one of them honors CGF, *Nectopsyche froehlichii*. They also provide four new species records of this striking-colored genus of caddisflies in the eastern Amazon, Pará state. This article supplies information that helps the facing of the Linnean and Wallacean, especially in a greatly endangered biome, the Amazon.

In Calor et al. (2024), the team and collaborators of LEAq provide a synthesis of 14 years of taxonomic research on insects, especially caddisflies, facing the Linnean and Wallacean shortfalls. This effort resulted in 63 described species of caddisflies (including eight presented in the special issue), eight mayflies, four stoneflies, and four neuropteran species (spongillafly and antlions). In addition, other biodiversity deficits were also addressed, such as Darwinian (e.g., Calor et al., 2016; Campos et al., 2019; Assmar et al., 2022; Duarte et al., 2022; Tavares et al., 2023a), Raunkiaeran and Eltonian shortfalls (e.g., Calderón et al., 2019; Rezende et al., 2019; Boyero et al., 2021). In the special issue, five new caddisfly species are presented in honor of CGF, the patron of LEAq. A checklist of caddisfly fauna from Bahia state is also presented, with 138 species, around 75% and 30% recorded and described by the LEAq team, respectively. Now, Bahia is Brazil's fifth most species-rich state, and the first in the Brazilian Northeast region.

The legacy of Prof. Claudio

At least for the past 10 years, it has almost been a *cliché* to state that the biodiversity crisis is an urgent issue to be dealt with, and there are not enough scientists to face the accelerating extinction rate while trying to understand its uniqueness. It is an essential requirement that humanity has appropriately trained human resources to tackle this issue. All of the articles published in this special issue are evidence that Brazil can produce quality data that deals with the biodiversity gaps, especially concerning aquatic insects. Unlike 30 years ago, the country currently has research groups that work on such endeavors established in all country regions, which makes biodiversity unveiling a less difficult task. Mariano et al. (2024) show that CGF was the cornerstone of a considerable part of these research groups. They are evidence that Brazil has the human resources to address the urge to know biodiversity aspects before the fauna goes extinct, even when megadiverse biomes, such as the Amazon, Cerrado, and Caatinga, are considered. Even though CGF has produced over 100 publications, the people he mentored (and all their academic descendants) are undoubtedly his major contribution to the efforts of describing and understanding aquatic insect biodiversity.



Figure 2 Distribution map of the new species described in the special issue in honor of Prof. Dr. Claudio Gilberto Froehlich.

The recognition of CGF's enormous contribution to the knowledge of animal diversity on Earth is demonstrated by the several species homages made after him, by his friends, either descendants or colleagues (Fig. 2). The legacy of Prof. Claudio is terrific, a prolific academic career (scientific production and mentoring students), established generously and politely to teach his students a deep love for nature.

Unfortunately, just a few days before the conclusion of the first draft of this manuscript, which should close the special issue in honor of Prof. Claudio Froehlich, we received the sad news that Prof. Claudio passed away peacefully, at his house, surrounded by his family, on November 27th, 2023, in a Froehlichian way.

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We sincerely thank Prof. Dr. Claudio Froehlich (*in memoriam*) for his direct and indirect mentorship and friendship. We thank Revista Brasileira de Entomologia, especially Prof. Dr. Frederico Falcão Salles (Editor-in-chief), and all the other coauthors of the special issue. We are grateful to Departamento de Biologia, especially Míriam Cristina Osório de Souza, Maria Isabel Protti de Andrade Balbi, and Sidnei Mateus, for friendship and encouragement; to Programa de Pós-graduação em Entomologia, USP, Ribeirão Preto, especially Renata Cavallari, for all support in the Special issue meeting. We thank Prof. Dr. Dalton Amorim for sharing information on CGF's career. We also thank the attendance of everyone in the tribute meeting to Prof. Claudio Froehlich, especially his son, Ricardo Froehlich, and his granddaughter, Alice Terra Froehlich.

Conflicts of interest

The authors declare no conflicts of interest.

Author contribution statement

ARC, FBQ, LCP and RM conceptualized the article, wrote and revised the manuscript.

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