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New records of Odonata (Insecta) for the extreme northwest of the Brazilian Amazon

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All relevant data are within the paper and its Supporting Information files.

Abstract. Brazil hosts a wide range of Odonata species, including many hitherto undescribed ones, especially in remote and unexplored regions where logistics are difficult. The northwestern Brazilian Amazon is an example of this situation, and many locations still need to be sampled there and have their taxonomic inventories compiled. Against this background, this study aimed to survey the Odonata species in the municipality of São Gabriel da Cachoeira, located in the extreme northwest of the Western Amazon. The survey was conducted at 11 water bodies, where 67 Odonata species were recorded, including four new records for the state of Amazonas and seven new records for Brazil. Pioneering studies like this are important for enhancing our understanding of the region's biodiversity and contribute to conservation efforts.

Key words. Dragonfly, *Heteragrion*, *Mnesarete*, *Progomphus*, Amazônia, São Gabriel da Cachoeira

Introduction

The order Odonata is composed of predatory aquatic insects that have long been of interest to scientists mainly due to their important ecological roles in aquatic and terrestrial ecosystems (Paulson, 2019). They belong to the Paleoptera group that dates to the Carboniferous, being one of the most ancient orders of winged insects (Misof et al., 2014). They can be found on all continents except Antarctica (Córdoba-Aguilar et al., 2023) and comprise about 6322 described species in 965 genera (Paulson et al., 2023). The Neotropical region is particularly rich in Odonata, hosting more than 1700 species (Olaya, 2019).

Brazil has the highest number of recorded Odonata species of all Neotropical countries, with a count of approximately 884 according to IUCN (2023). However, due to the country's vast territory and logistical challenges, the actual diversity at many locations still remains to be discovered or is under-sampled (Penn et al., 2017), indicating that the number of Odonata species in Brazil is likely to be even

higher. An analysis conducted in the early 2000s showed that for about 70% of the Brazilian territory, there are no satisfactory distribution data for odonates (De Marco & Vianna, 2005). Despite the recent advances and increasing numbers of studies in many areas of Brazil (Carvalho-Soares et al., 2022; Juen & De Marco, 2012; Koroiva et al., 2017; Miranda-Filho et al., 2022), the distribution of several Odonata species remains poorly known (Bastos et al., 2019; Nóbrega & De Marco, 2011).

According to Brasil et al. (2018), the average species richness of Odonata at streams in the Brazilian Amazon ranges from four to seven species. However, the distribution of most species is restricted, and species composition varies significantly between sites, indicating high beta diversity. In the last eight years, there has been an increase by 102 species recorded from the state of Amazonas (Garcia Júnior et al., 2022). This number rose from 262 recorded species in 2014 to 364 in 2022, an increase of 38.93% (Garcia Júnior et al., 2022; Neiss & Hamada, 2014). However, as with the rest of the country, collection efforts are not evenly distributed across the state. A recent survey conducted in Amazonas state revealed that municipalities with large territories, such as São Gabriel da Cachoeira (SGC), remain under-sampled taxonomically, making these areas a priority for Odonata research (Koroiva et al., 2020).

SGC, also known as "Cabeça do Cachorro" ("Dog's Head"), located in the extreme northwest of Brazil, stands out by its high biodiversity, as is observed in various groups of animals (Cipola & Viana, 2023; Hamada et al., 2006; Lourenço, 2005; Nogueira et al., 2014). Therefore, it is reasonable to presume that numerous species are yet to be discovered, and that some have not yet been adequately documented from the state of Amazonas or Brazil in general. Considering this situation, the aim of this study was to conduct a survey of Odonata species in the municipality of SGC in Amazonas State, Brazil. Furthermore, this study aims to discuss the spatial distribution of the collected Odonata species and contribute to reducing the knowledge gaps, such as the Linnean and Wallacean shortfalls, regarding the occurrence of Odonata in the Amazon region (Hortal et al., 2015).

Material and methods

Study area

SGC is the third-largest municipality in Brazil, occupying 2.8% of the northern territory (Fig. 1). Approximately 80% of SGC is made up of protected areas, such as the Pico da Neblina National Park, Morro dos Seis Lagos

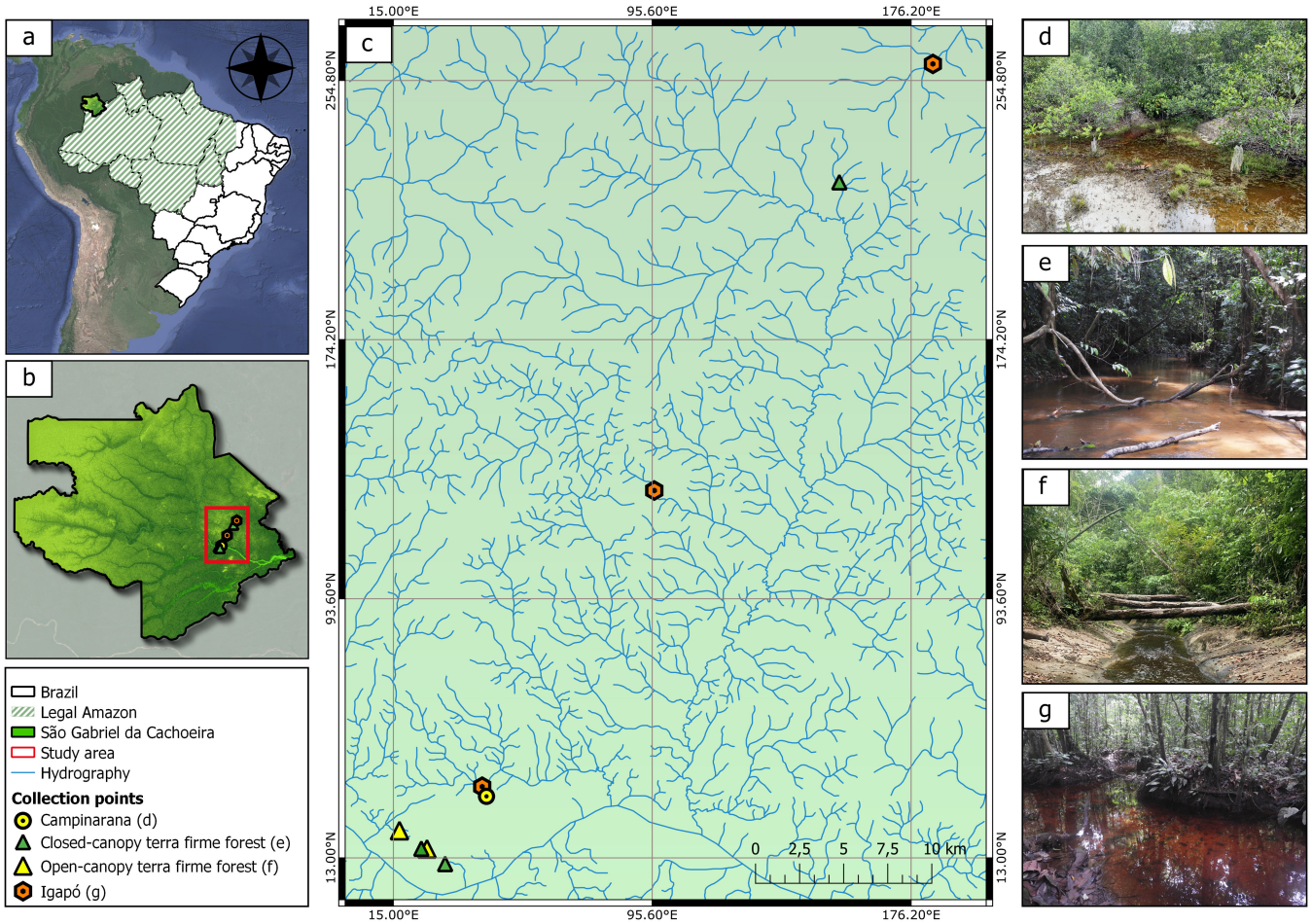

Figure 1. Location of the municipality of São Gabriel da Cachoeira (SGC) and sampling points: (a) Legal Amazon highlight; (b) São Gabriel da Cachoeira; (c) spatial distribution of sampled units; (d) Campinarana environment; (e) closed canopy terra firme forest; (f) open canopy terra firme forest; (g) Igapó environment.

Table 1. Sampled points, environmental information, and geographic coordinates.

Locality	Depth (cm)	Width (cm)	Current	Bank	Habitat description	Coordinates
P1	39	470	Slow	Sand/rock/ leaf litter	Upland forest with tall trees, open canopy with a high degree of insolation, and clear water.	LAT 0.0696 LON -66.7964
P2	25	480	Slow	Mud/leaf litter	Igapó forest, mostly inundated throughout the year, with medium-sized trees and closed canopy, a low degree of insolation, and dark water.	LAT 0.0177 LON -66.8914
P3	21	318	Slow	Mud/leaf litter	Located in the lower part of the forest, with tall and spaced trees, closed canopy with little light penetration, and dark waters.	LAT -0.1554 LON -67.0213
P4	25	570	Moderate	Sand/rock/ leaf litter	Igapó forest, mostly inundated throughout the year, with medium-sized trees and open canopy, a high degree of insolation, and dark water.	LAT 0.1560 LON -66.7995
P5	48	430	Slow	Mud/leaf litter	Igapó forest, mostly inundated throughout the year, with medium-sized trees and closed canopy, a low degree of insolation, and dark water.	LAT 0.0177 LON -66.8913
P6	68	530	Slow	Sand/leaf litter	Igapó forest, mostly inundated throughout the year, with medium-sized trees and closed canopy, low incidence of sunlight, and dark water with reddish tones.	LAT -0.1330 LON -66.9791
P6.1	31	300	Slow	Sand/leaf litter	Igapó forest, mostly inundated throughout the year, with medium-sized trees and closed canopy, a low degree of insolation and dark, reddish water.	LAT -0.1331 LON -66.9792
P7	–	–	Still water	Mud	Campinarana, formed by shrubs and small trees, with a a very high degree of insolation, and mainly accumulated rainwater without a continuous flow.	LAT -0.1378 LON -66.9796
P8	34	74	Slow	Sand/mud/ leaf litter	Located in the lower part of the forest, with tall and spaced trees, closed canopy with little light penetrating, and dark, reddish water.	LAT -0.1647 LON -67.0072
P9	20	160	Moderate	Rock	Upland forest with tall trees, open canopy with a high degree of insolation, and clear water.	LAT -0.1646 LON -67.0101
P10	40	79	Moderate	Sand/rock/ leaf litter	Upland forest with tall trees, open canopy with a high degree of insolation, and clear water.	LAT -0.1724 LON -66.9980

Biological Reserve, and Indigenous Lands. This renders this region one of the most comprehensively conserved ones in the country, yet at the same time one that has so far been little explored (IBGE, 2020). According to the Köppen-Geiger classification, the climate of the region can be described as representing the hot and humid Af type, with an average annual temperature of 25°C, no dry season, an intense rainfall regime with a minimum annual precipitation of 2500 mm and a maximum of 3800 mm (Alvares et al., 2013). It is situated on the banks of the upper Rio Negro, which originates in Colombia and flows in an east-northeastly direction through Venezuela until it reaches the Piedra del Cocuí, a rock formation from the Precambrian era that serves as a border triangle between Brazil, Colombia, and Venezuela, then continues towards Manaus until it joins the Amazon River. Although it has few meanders along its course, its drainage channel is well defined, and it has extensive areas of seasonally flooded land (i.e., igapós) along the banks of the main channel and many of its tributaries (Penn & Allen, 2001). The vegetation is composed of ombrophilous Terra Firme Forest, campinaranas, igapó forest, and altitude fields (Ab'Saber, 2002).

List compilation: primary data collection

Collections were made by means of active searches at eleven sampling points, selected as per the possibility of access to trails within the forest (Table 1). An entomological net was used to capture specimens. Collections were made between 27 November and 2 December 2021 at streams and ponds, always on sunny days, between 11:00 am and 2:00 pm; these are considered ideal weather conditions for the activity of most Odonata species (Calvão et al., 2018). Subsequently, specimens were wrapped in paper envelopes, soaked in absolute alcohol for 24 hours for fixation, then left to dry by natural evaporation and stored in standardized envelopes (Cezário et al., 2021). All collected individuals were eventually deposited in the collection of the Laboratory of Ecology and Conservation (LABECO) of the Federal University of Pará (Mendoza-Penagos et al., 2022a).

Identification and taxonomic treatment

The following publications were used for the taxonomic identification of our records: Belle (1962, 1973, 1984,

1992), Borror (1931, 1942), Costa & Santos (1997), De Marmels (1983, 1989, 1999), Garrison (1990, 1999, 2006, 2009), Garrison & von Ellenrieder (2017, 2018), Guillermo-Ferreira et al. (2014), Hedström & Sahlén (2001), Jurzitza (1982), Lencioni (1999), Pessacq (2014), Ris (1930), Stand-Pérez et al. (2019), Vilela et al. (2018), and von Ellenrieder (2013).

Photos were taken with a Leica M205A stereo microscope equipped with a Leica DFC 450 camera and processed in Photoshop® software. All measurements were taken with the ImageJ® software, in millimeters, (mm) and excluded anal appendages.

Data collection

The species list was made from the compilation of primary data (specimens collected in the field) and secondary data obtained from recent studies that contain information on the occurrence and distribution of species present in the state of Amazonas (Koroiva et al., 2020). A complementary search was conducted in databases such as the Global Biodiversity Information Facility (GBIF, https://www.gbif.org/), SpeciesLink (http://splink.Cria.org.br/), Catálogo Taxonômico da Fauna do Brasil (http://fauna.jbrj.gov.br/), Sistema de Avaliação do Risco de Extinção da Biodiversidade (SALVE, http://salve.icmbio.gov.br/), and the Sistema de Informação sobre a Biodiversidade Brasileira (SiBBr, https://www.sibbr.gov.br/), applying a filter for species already known from the municipality of SGC. Information on the conservation status of the species was sourced from The International Union for Conservation of Nature (IUCN, https://www.iucnredlist.org/) and the Livro Vermelho da Fauna Brasileira Ameaçada de Extinção (ICMBio, 2018). Complementary data with descriptions of females and larvae were obtained from specialized literature (Garrison et al., 2006, 2010; Lencioni, 2005, 2006). Additionally, a search was also run in Google Scholar (http://scholar.google.com), where we used the search string (Odonata* AND "São Gabriel da Cachoeira").

Data analysis

To evaluate the efficiency of our sampling effort, two rarefactions (interpolation) and prediction (extrapolation) curves were generated (Chao & Jost, 2012). In the first one, we analyzed species diversity by the number of individuals collected, and in the latter the diversity of species per sampling point. For this, we used q = 0, which expresses the observed richness with a 95% confidence interval. A bootstrap approach was used for all curves, with 1000 repetitions per number of individuals collected and 50 repetitions per sampling point. Rarefaction and extrapolation analyses were computed with "iNEXT" (Hsieh et al., 2016) and the "ggplot2" (Wickham et al., 2016) package of the R statistical software (R Core Team, 2019).

Results

Altogether, 67 species were recorded, 53 from primary data and 20 from secondary records (Supplementary Table S1) with only six of the secondary records also being represented among our samples: *Chalcopteryx scintillans* McLachlan, 1870; *Neoneura luzmarina* De Marmels, 1989; *Erythrodiplax lativittata* Borror, 1942; *Perithemis lais* (Perty, 1834); *Uracis imbuta* (Burmeister, 1839); and *Uracis ovipositrix* Calvert, 1909. Four new records were added to the known Amazonas State inventory: *Anomisma abnorme* McLachlan, 1877; *Epipleoneura ocuene* De Marmels, 1989; *Staurophlebia reticulata* (Burmeister, 1839); and *Phyllogomphoides fuliginosus* (Hagen in Selys, 1854). Furthermore, six records turned out to be new for Brazil: *Mnesarete metallica* Selys, 1869; *Argia appendiculata* Garrison & von Ellenrieder, 2015; *Epipleoneura fernandezi* Rácenis, 1960; *Heteragrion chlorotaeniatum* De Marmels, 1989; *Palaemnema* cf. *peruviana* Ris, 1918; and *Progomphus racenisi* De Marmels, 1983 (Figs 2, 3). Finally, two recently described species were identified: *Perilestes jueni* Mendoza-Penagos & Vilela, 2022, and *Dimeragrion baniwa* Mendoza-Penagos, Gonçalves & Vilela, 2023.

Considering our primary data, the number of estimated species for SGC was 72.99 ± 11.66 (mean ± SE) and the observed richness was 30.01 ± 10.68 species. When analyzing the collection efficiency (average observed richness/average estimated richness), the value was 53.44%. This suggests that the existing biodiversity has not yet been fully explored, and that Odonata richness in this region may be even higher, thus pointing to the need for further studies and sampling efforts. The rarefaction curve was non-asymptotic, indicating that total species richness will increase with additional sampling effort (Fig. 4).

Discussion

Studies in remote regions of the Amazon have been crucial to increasing the knowledge of Odonata distribution (especially of rare species) and revealing new ones (Bota-Sierra et al., 2015; De Marmels, 1989). A recent survey conducted in San José del Guaviare, Colombia, resulted in an important discovery: the new species *Perissolestes rupestris* Flórez, Bota-Sierra & Cano-Cobos, along with three new records for the country (Flórez et al., 2023). In addition, a species list compiled by the Department of Guanía, near SGC, based on specimens collected between 2014 and 2021, yielded four new occurrence records for the Colombian Amazon and five for Colombia (Aristizábal-Botero et al., 2022). These results highlight the enormous potential of this region for new discoveries, filling knowledge gaps on Odonata distribution and providing valuable information on the local diversity of species.

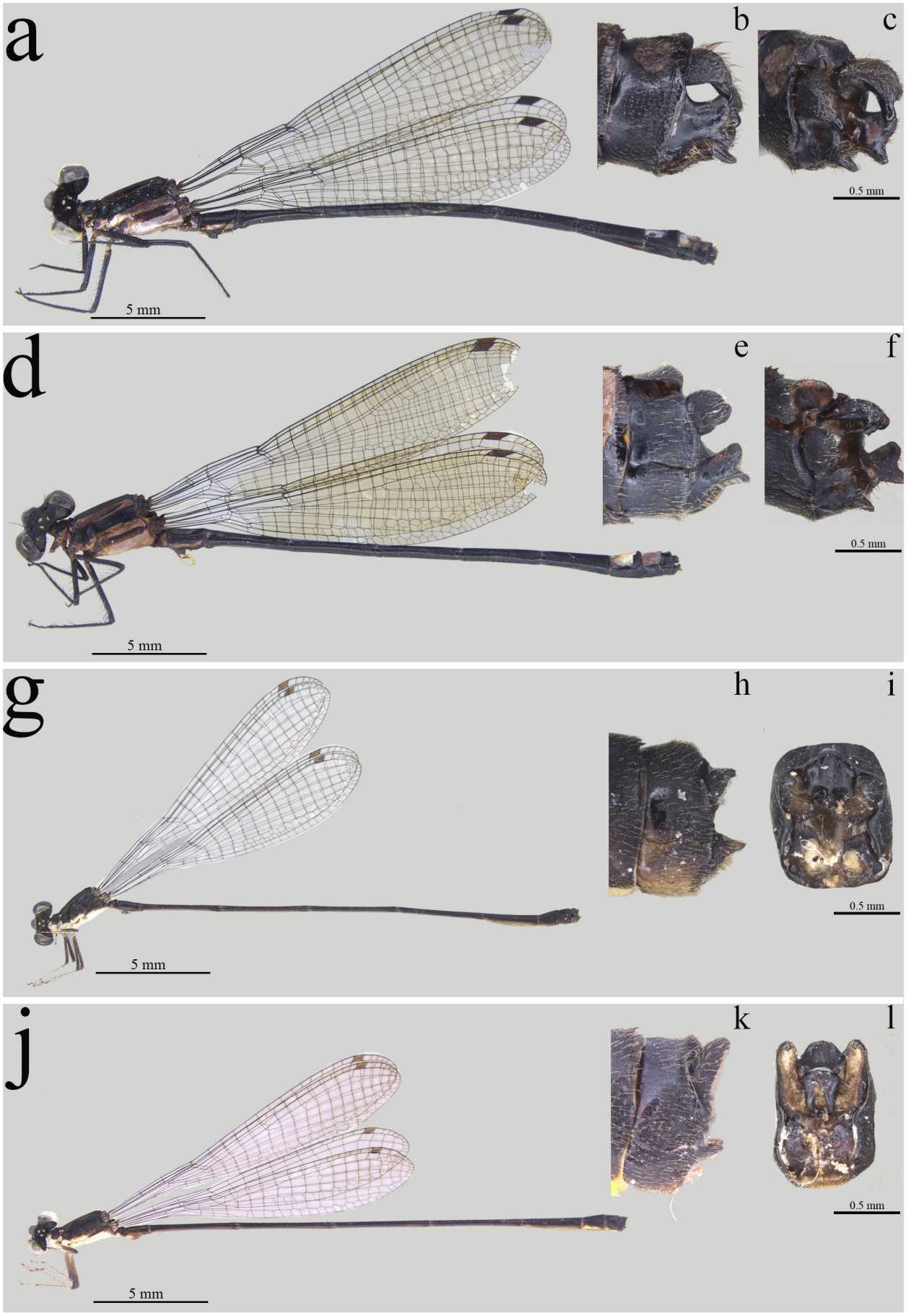

Figure 2. New records: *Argia appendiculata*: (a) lateral view of male, (b) lateral view of cercus, (c) lateroposterior view of cercus; *A. loutoni*: (d) lateral view of male, (e) lateral view of cercus, (f) lateroposterior view of cercus; *Epipleoneura fernandezi*: (g) lateral view of male, (h) lateral view of cercus, (i) posterior view of cercus; *E. ocuene*: (j) lateral view of male, (k) lateral view of cercus, (l) posterior view of cercus.

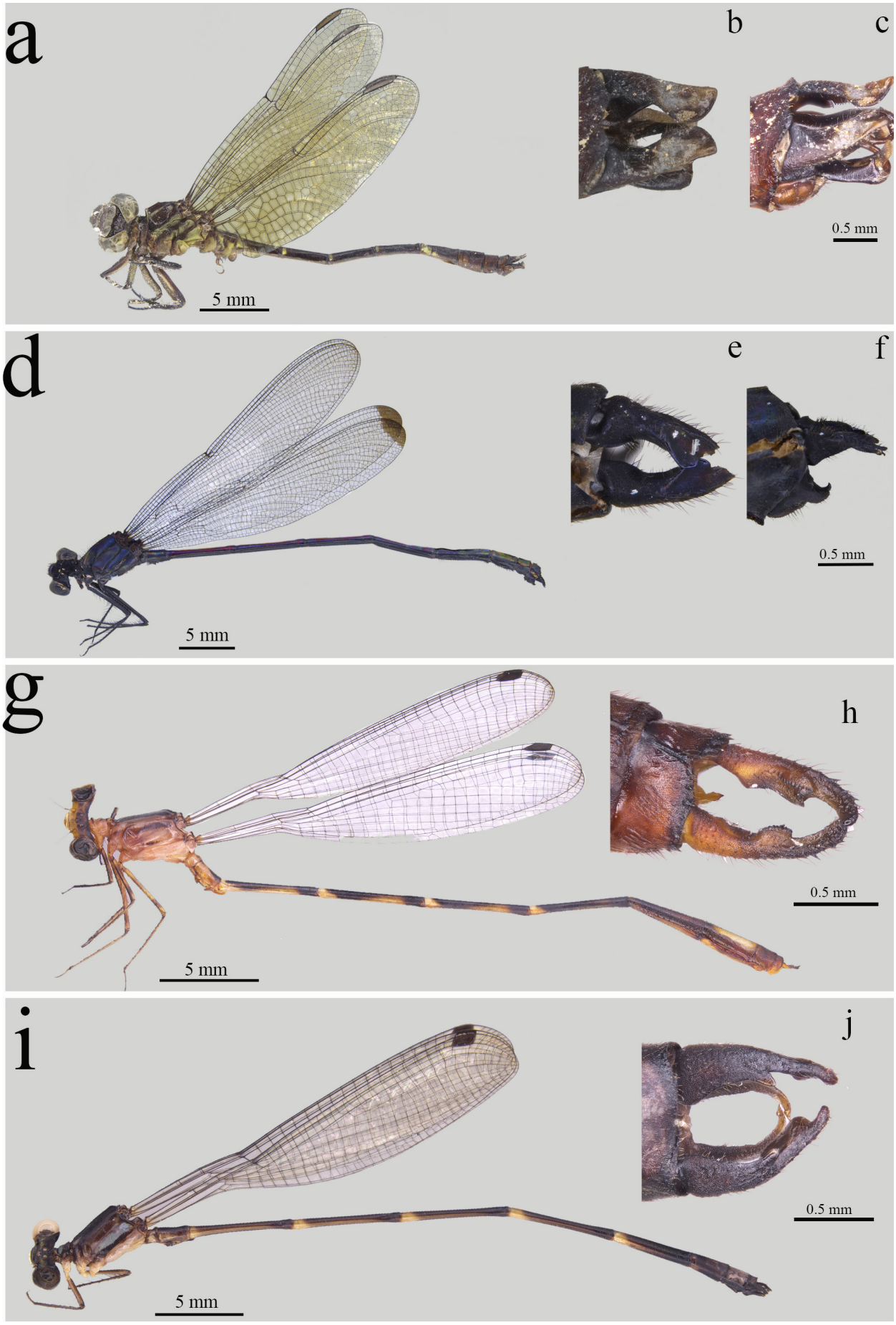

Figure 3. New records: *Progomphus racenisi*: (a) lateral view of male, (b) dorsal view of cercus, (c) lateral view of cercus; *Mnesarete metallica*: (d) lateral view of male, (e) dorsal view of cercus, (f) lateral view of cercus; *Heteragrion chlorotaeniatum*: (g) lateral view of male, (h) dorsal view of cercus; *Palaemnema* cf. *peruviana*: (i) lateral view of male, (j) dorsal view of cercus.

SGC is one of the largest municipalities in Brazil, with an area comparable to that of Greece and larger than countries such as Portugal, Belgium and Croatia (IBGE, 2020). However, the diversity of Odonata previously recorded from this region amounted only to 20 species due to a lack of sampling in locations that are remote and difficult access, far from the main collection centers (Koroiva et al., 2020). Through the sampling efforts undertaken by these studies, it was possible to contribute to the knowledge of the Odonata fauna of this region by adding 45 new records to SGC.

In this study, we recorded species that are associated with preserved environments, such as *E. fernandezi* and *H. chlorotaeniatum*, at small and shallow forest streams (De Marmels, 1989; Rochas et al., 2022). We also recorded species, such as *P. racenisi*, whose distribution ranges seemed to be restricted to the northeastern parts of the Amazon between the Atlantic Ocean and Venezuela (De Marmels, 1983). In addition, we have recorded species with populations at streams near the Andes such as *P.* cf. *peruviana*. Hence, the SGC region must be regarded as a significant biogeographic transition zone linking the Amazonian and Andean provinces. As a result, further research in this region could enhance our comprehension of the evolutionary mechanisms that underlie the formation of the South American odonatofauna.

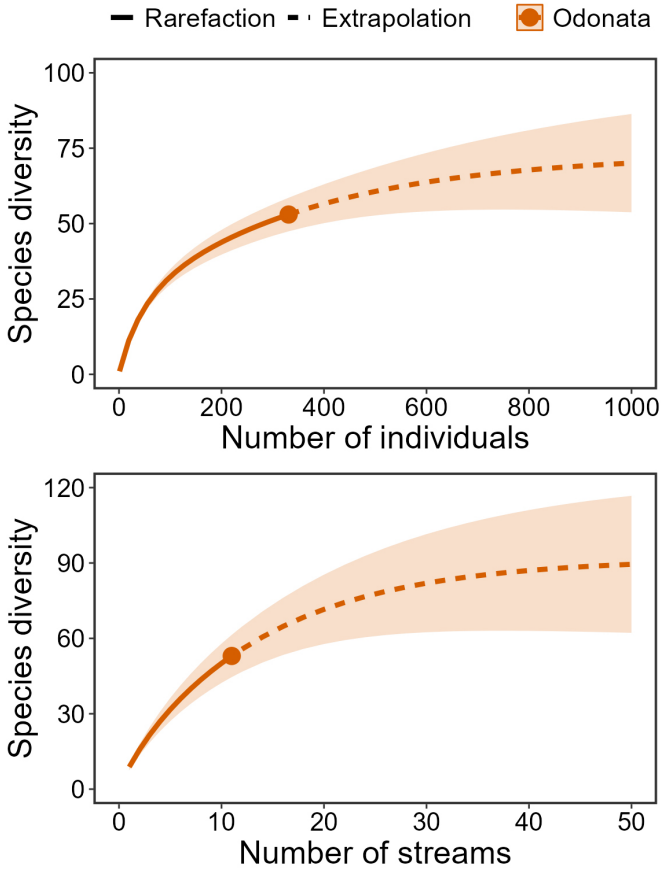

Figure 4. Rarefaction and extrapolation curve based on the number of individuals collected and the size of the sampled points, respectively, with 95% confidence intervals (shaded areas).

Taking into account our data collected at 11 sampling points, where eight new records were documented for Brazil, if we consider *P. jueni* and *D. baniwa*, the rate of new occurrence records per point is approximately 0.727, and that, on average, more than 72% of the surveyed locations revealed new country records for Brazil. Given the significance of environmental integrity and habitat complexity for the conservation of biodiversity, it is essential to prioritize the collection efforts in this area. These should provide data on the geographic distribution, ecology and biology of the local species, furthering a better understanding of their population dynamics and interactions with the environment (Hortal et al., 2015).

In this study, our priority was to focus on small streams, with a maximum of third order and a width of up to 5 meters. Only one of the collection points (P7) was situated in a still-water environment; thus, lentic environments like lakes and flooded areas were not considered to a more significant extent. It is important to note that areas known to host Odonata, such as macrophytes (Brito et al., 2021) and bromeliads (Haber et al., 2015; Ingley et al., 2012) were not checked by ourselves. Thus, Odonata diversity in this region may be even higher, and there is a distinct potential of this area harboring as yet unknown species.

Despite the progress in Odonata sampling over the past decade, our findings reveal that states with vast territories, such as Amazonas, still need to be sampled with greater intensity. We emphasize the significance of safeguarding protected areas in the Amazon region to ensure its biodiversity conservation, because this would aid in mitigating the adverse effects of biodiversity loss, as has been evidenced by Bota-Sierra et al. (2018). Furthermore, the impacts of climate change and water scarcity on the region have been growing, emphasizing the urgent need for investment into the protection of these ecosystems (Gatti et al., 2021). It is important to highlight that establishing new protected areas and improving the management of existing ones are crucial to preserving biodiversity and as a result preservating of the valuable services provided by these ecosystems.

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Supplementary Material

Supplementary Table S1. List of species recorded from the municipality of SGC.