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Policy analysis

Threats and conservation status of the endemic terrestrial arthropods of the Azores

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ABSTRACT

Insular ecosystems are disproportionately threatened by human activities, leading to an unprecedented decline in species diversity, particularly on remote archipelagos like the Azores. However, the impacts of humans on arthropods, which typically represent a big proportion of island biotas, remain poorly documented. We present an assessment of threats affecting different groups of species, examining the relationship between species occupancy, IUCN threat categories and trophic interactions for arthropods in the Azores (Macaronesia). We compiled data on endemic arthropods from published lists and IUCN assessments, including extinction risk, direct threats, and geographical ranges, to identify key pressures on species. Using network analyses, we examined the association between extinction risk and number of species, also estimating the IUCN Red List Index (RLI) for each island conservation status. We found that some of the Azorean endemic arthropod species have already gone extinct and more than half are classified as threatened by the IUCN Red List. Of these, predatory beetles (Coleoptera) and spiders (Araneae) have the highest numbers of threatened species, mainly due to habitat degradation, the spread of invasive plant species, and climate change. The RLI differs greatly among islands, being the lowest in Santa Maria, which concentrates a large number of critically endangered (CR) single-island endemic species, and higher in islands with larger and better-preserved native forest fragments, such as Terceira. A comprehensive approach integrating habitat protection, invasive species management and conservation measures is essential to ensure the long-term survival of Azorean arthropod endemic species in particular and island biota in general.

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1. Introduction

Oceanic volcanic islands rise from the seabed devoid of life, are limited in area, typically have high geological activity, and are often isolated from large land masses like continents (Arjona et al., 2018; Whittaker et al., 2023). Thus, remote oceanic islands are characterized by biotas that are highly filtered by dispersal limitations, with part of its diversity originating from in situ diversification (Kier et al., 2009; Warren et al., 2015; Whittaker et al., 2023, 2017). Consequently, islands are rich in endemic species, which collectively represent a unique taxonomic, functional and phylogenetic diversity, contributing immensely to the planet's biodiversity (Warren et al., 2015; Whittaker et al., 2023, 2017). Among animals, arthropods excel in the colonization of and diversification on isolated islands (Russell and Kueffer, 2019), being fundamental for ecosystem functioning due to their crucial roles in predation, herbivory, pollination, and nutrient cycling (Noriega et al., 2018).

The biodiversity crisis is impacting islands' arthropods disproportionately compared to their mainland counterparts (Fernández-Palacios et al., 2021; Kueffer and Kinney, 2017), with consequences at all levels of biodiversity and implications for human populations and economies (Russell and Kueffer, 2019). Through deforestation, urbanization, and agricultural expansion, humans have altered island landscapes, at the expense of native habitats (Fernández-Palacios et al., 2021; Triantis et al., 2010; Whittaker et al., 2023). These changes fragment and degrade habitats, leading to losses in diversity and the disruption of ecological processes, limiting the survival of populations and species to small fragments of suitable areas (Lhoumeau and Borges, 2023; Pozsgai et al., 2023). Additionally, the introduction of exotic/invasive species, of plants and animals, either intentionally or inadvertently, further exacerbates these effects because these newcomers often outcompete native ones (Pyšek et al., 2020). Climate change may also amplify these threats, leading to shifts in temperature and precipitation patterns, which can change the distribution and abundance of species (Betzold, 2015; Harter et al., 2015; Veron et al., 2019).

From a conservation perspective, the IUCN (International Union for Conservation of Nature) Red List of Threatened Species is one key tool to assess species extinction risk (IUCN, 2024). This list assigns species into different categories, which are based on criteria such as population size and trends, as well as distribution (IUCN, 2024). Moreover, the IUCN also provides valuable information on the direct and indirect threats to species, and which human activities or processes have affected, are affecting or might affect species in the future (IUCN, 2022). Among the criteria used to assess species conservation status, Criterion B of the IUCN Red List – Restricted Geographical Range (IUCN, 2024), is particularly useful for arthropod species, as population estimates and trends are rare and difficult to conduct in this animal group (Cardoso et al., 2011). Hence, the IUCN Criterion B has been used to assess the extinction risk of many arthropod species, including crickets/grasshoppers (Kadlečík, 2014), dragonflies (Kadlečík, 2014), saproxylic beetles (Carpaneto et al., 2015; García et al., 2018), dung beetles (Numa et al., 2020), spiders (Milano et al., 2021) and hoverflies (Vujić et al., 2022). Species ranges as defined in Criterion B are based on two main concepts, the Extent of Occurrence (EOO) and Area of Occupancy (AOO). The EOO represents the minimum convex polygon encompassing all known occurrences of a species, including areas deemed to be non-suitable such as the sea for terrestrial species (Rodríguez et al., 2015). The AOO measures the area within the EOO that is actually occupied by the species at a 2×2 km resolution (Rodríguez et al., 2015). Therefore, larger EOOs and AOOs suggest wider spatial distribution, potentially indicating lower vulnerability to threats, whereas smaller distributions may imply greater vulnerability (Rodríguez et al., 2015).

The Azores archipelago (Macaronesia) faces a combination of alarming factors linked with past and present anthropogenic activities that negatively affect its biodiversity, namely climatic changes, eventual natural disasters, an increasing influx of exotic species that are potentially invasive, along with fragmented populations of endemic arthropods (Borges et al., 2022a, 2020b; Lhoumeau and Borges, 2023; Norder et al., 2020; Triantis et al., 2010). Since the first confirmed Portuguese settlements 600 years ago, and especially after World War II (Gaspar et al., 2008; Triantis et al., 2010), a combination of deforestation and land-use alterations (predominantly livestock farming), have been changing the native forest, shrublands, subterranean habitats and the semi-natural grasslands in the Azores, causing the extinction and decline of endemic arthropods diversity (Borges et al., 2022a; Lhoumeau and Borges, 2023; Norder et al., 2020; Pozsgai et al., 2023; Rigal et al., 2018; Terzopoulou et al., 2015). As a result, the original native forest is now restricted to approximately 5 % of the archipelago's total land area, mostly in remote and elevated regions (Gaspar et al., 2008; Norder et al., 2020; Triantis et al., 2010). In addition, many endemic arthropod species are often extremely restricted (Borges et al., 2019, 2018, 2016a), ranging from single-island endemics (SIE) or species only found in a few caves (Borges et al., 2019), to those present in small fragments of the native pristine forest (Borges et al., 2018, 2016a; Oyarzabal et al., 2025).

The Azorean endemic arthropod species have been assessed during the last five years using the Criterion B of the IUCN Red List, creating the opportunity for a general evaluation of their conservation status (Borges et al., 2022a; IUCN, 2024). However, to date, no large data compilation and taxonomic analysis has been conducted on Azorean threatened species. In this study, we aim to summarize and understand the relative contribution of the most common threats to the conservation of Azorean arthropods. Specifically, we aim to: i) compile and present a comprehensive synthesis of dominant threats and extinction risks for the previous assessed arthropod groups; ii) investigate the IUCN Red List Index (RLI) for each Azorean islands; and iii) evaluate whether or not IUCN extinction risk change according to trophic strategies (e.g. carnivores, herbivores, omnivores or fungivores), predicting that species in high trophic levels (e.g. predators) would be more threatened (Chichorro et al., 2022). With this contribution we also aim to inspire future conservation efforts for Azorean arthropods and island invertebrates elsewhere, serving as a valuable groundwork for forthcoming research efforts.

2. Methods

2.1. Study area

We conducted this study in the Azorean Archipelago, which comprises nine main volcanic islands spread over 615 km in the northern Atlantic Ocean, located approximately between 37° and 40° N latitude and 24° and 31° W longitude (Fig. 1). The archipelago is divided into three island groups: the western group (Corvo and Flores), the central group (Faial, Pico, São Jorge, Graciosa and Terceira), and the eastern group (São Miguel and Santa Maria) (Fig. 1). The climate across all islands is temperate oceanic, characterized by high levels of atmospheric humidity, with a mean annual rainfall around 2800 mm - being particularly high in the elevated native subtropical evergreen laurel forest regions, and temperatures ranging from 6 °C in February (coldest month) to 25 °C in August (warmest month) (Borges et al., 2022a, 2022c; Henriques et al., 2016).

2.2. Species database and analyses

We compiled data of Azorean endemic arthropods from previously published species lists, particularly of those species with IUCN Red List assessments (Borges et al., 2022a, 2010; Oyarzabal et al., 2024). We systematically reviewed and screened each species list, extracting species information (species name and author) from these established sources, rather than conducting new assessments. Next, we searched for these species in the IUCN Red List (IUCN, 2024). For the species that were previous assessed in IUCN we gathered: their extinction risk assessment (EX – Extinct, EW – Extinct in the wild, CR – Critically

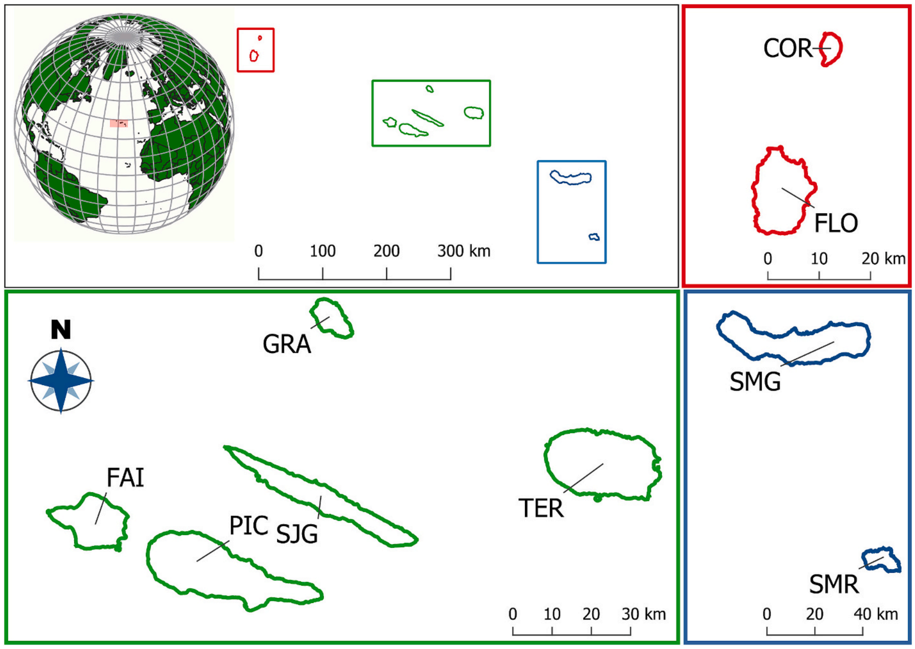

Fig. 1. Map of the Azores archipelago. Top left shows the position of the three island groups: Western group – red for Corvo (COR) and Flores (FLO); Central group – green for Faial (FAI), Pico (PIC), São Jorge (SJG), Graciosa (GRA), and Terceira (TER); and Eastern group – blue for São Miguel (SMG) and Santa Maria (SMR). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

endangered, EN – Endangered, VU – Vulnerable, NT – Near threatened, LC – Least concern and DD – Data deficient); geographical ranges (EOO and AOO); and assessed direct threats (12 Unified Classification of Direct Threats (IUCN, 2022). The 12 Unified Classification of Direct Threats refers to immediate human activities or processes that have influenced, are influencing or may influence the status of each assessed species (Supplementary Table 1). Hence, this classification can provide an overview of sources of stress and pressures, noting that each species can be exposed to more than one threat. Moreover, we compiled additional information regarding species trophic strategies from: (i) the Azorean Biodiversity Portal and the IUCN SSC Atlantic Islands Invertebrate Specialist Group Portal (ABP, 2025; AIISG, 2025), (ii) previous publications (Borges et al., 2019, 2018; Oyarzabal et al., 2024), (iii) from two projects databases that are public available: the 'Biodiversity of Arthropods from the Laurisilva of the Azores' (BALA project) (Borges et al., 2016b, 2006; Gaspar et al., 2008; Pozsgai et al., 2023; Ribeiro et al., 2005) and the 'Long Term Ecological Study of the Impacts of Climate Change in the Natural Forest of Azores' (SLAM project) (Borges et al., 2020a, 2020b, 2022b; Borges et al., 2017a, 2017b; Costa and Borges, 2021; Lhoumeau and Borges, 2023), and (iv) the personal knowledge on the species' natural history by the senior author (PAVB). Then, we divided this compiled dataset into two subsets that we analyzed separately: i) grouping the data by arthropod classes (Arachnida, Collembola, Diplopoda, Insecta and Malacostraca); and ii) grouping the data for only the most representative arthropod orders, that together composed 88 % of all species (209 species), i.e. Araneae (spiders), Coleoptera (beetles), Diptera (flies and mosquitos), Hemiptera (true bugs), Lepidoptera (butterflies and moths) and Sarcoptiformes (moss mites). To evaluate the association between the extinction risk of the IUCN Red List and the number of species in each data subset, we used a chi-square test of independence. For a chi-square test to be reliable, each expected category should typically have at least five observations or data points. Since some groupings fell below this threshold, we calculated the *p*-value using a Monte Carlo simulation with 3000 iterations (Van Voorhis and Morgan, 2007). We also applied a network analysis to describe the association patterns between direct threats and the number of species within arthropod classes or most representative arthropod orders. Here, arthropod orders and the 12 Unified Classification of Direct Threats are considered as nodes, and the links between these entities quantify the most representative threats for Azorean endemic arthropods.

We estimated the IUCN Red List Index (RLI) for each of the Azores Islands using the '*red*' package (Cardoso, 2017; Cardoso and Branco, 2023). The RLI can summarize the conservation status of a species, region or ecosystem considering the extinction risk within IUCN Red List, from the most to the least threatened (EX, EW, CR, EN, VU, NT, LC and DD) (Butchart et al., 2007, 2004). An RLI score ranges from 0 to 1.0, where 0 indicates the extinction of all species and 1.0 indicates that all species are assessed as Least Concern. The confidence intervals of RLI can also be calculated by bootstrapping the data and considering the number of Data Deficient species (Cardoso, 2017). We also evaluated the association between threatened and non-threatened species on each island using a chi-square test of independence (Monte Carlo simulated p-value with 3000 replicates).

We explored the extinction risk of IUCN Red List patterns for each trophic strategy using the EOO and AOO. We divided arthropods in three different trophic strategies: herbivores (chewers, suckers, pollinators and fungivores; i.e. the collembola *Orthonychiurus azoricus* (Jacquemart, 1974); the true bug *Cixius azofloresi* Remane and Asche, 1979; the hoverfly *Sphaerophoria nigra* Frey, 1945; and the beetle *Atlantocis gillerforsi* Israelson, 1985), predators (carnivores and parasitoid: i.e. the spider *Gibbaranea occidentalis* Wunderlich, 1989; and the wasp *Meloboris insularis* Horstman, 1980) and omnivores (decomposers and species with broad diets; i.e. the moss mite *Parachipetria floresiana* (Perez-Iñigo, 1992); and the beetle *Cryptolestes azoricus* (Ratti, 1972) (Supplementary Table). We then evaluated the association between IUCN extinction risk and trophic strategies using a chi-square test of independence (Monte Carlo simulated p-value with 3000 replicates). We tested whether trophic strategies can predict species EOO and AOO using a Generalized Linear Mixed Model (GLMM) with a Negative Binomial distribution. We performed all analyses in R software (R Core Team, 2025).

3. Results

We obtained information for 235 endemic Azorean arthropod species, belonging to five classes, 18 orders and 93 families. These species are mainly insects (180 species, 76 %), followed by arachnids (49 species, 21 %). Six orders dominated our data, representing collectively 88 % (208 species) of all arthropods evaluated with IUCN criteria: Coleoptera (Insecta, 68 species, 29 %), Diptera (Insecta, 43 species, 18 %), Lepidoptera (Insecta, 36 species, 15 %), Araneae (Arachnida, 25 species, 11 %), Sarcoptiformes (Arachnida, 22 species, 9 %) and Hemiptera (Insecta, 14 species, 6 %). The least represented classes are Diplopoda (1 species), followed by Malacostraca (2 species) and Collembola (3 species).

3.1. *Threats for arthropod's classes*

A total of 26 % of the arthropod species are assessed as non-threatened (Least Concern (LC) or Near Threatened (NT)) while 50 % are assessed as threatened (Vulnerable (VU), Endangered (EN) or Critically Endangered (CR)). Five insect species, namely four beetles *Bradycellus chavesi* Alluaud, 1918, *Calathus extensicollis* Putzeys, 1873, *Calathus vicenteorum* Schatzmayr, 1937 and *Strophosoma occidentalis* (Crotch, 1867) and one fly species *Campsicnemus atlanticus* (Dyte, 1980), are assessed as Extinct (EX). Finally, 21 % are assessed as Data Deficient (DD) (Fig. 2A).

At the family level, Carabidae (ground beetles, Coleoptera) has the most threatened species and includes the three aforementioned extinct species. Moreover, nine species of this family belong to the usually cave-restricted genus *Trechus* (five CR, two EN and two VU). The second family with the highest number of threatened species is Linyphiidae (money spiders, Araneae), of which particularly the genus *Canariphantes* has the highest number of threatened species, with a total of three species. Zopheridae (ironclad beetles, Coleoptera) is the third most threatened family, with all species belonging to the genus *Tarphius*.

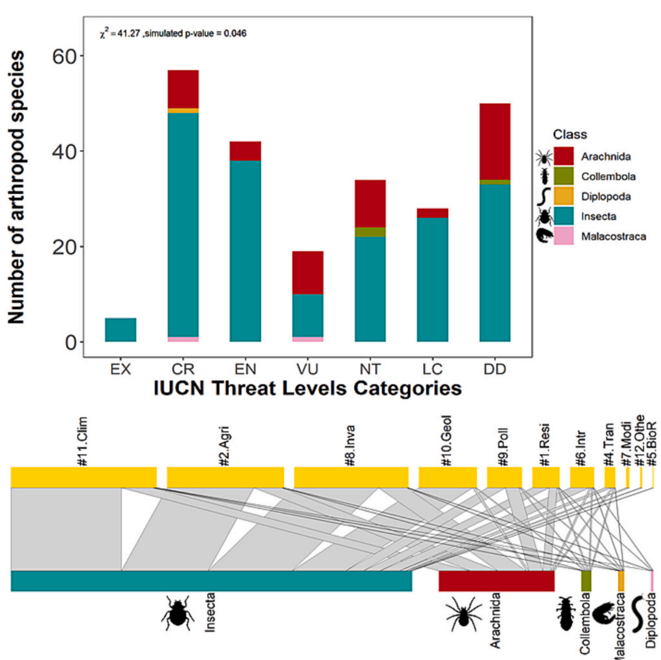

Fig. 2. – Number of arthropod species, by taxonomic class. A – Species in each of the IUCN extinction risk, assessed by the most to the least threatened. Extinct (EX), Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), Least Concern (LC) and Data Deficient (DD). Chi-squared indicates the association between the IUCN extinction risk and the number of species, with the simulated *p*-value indicating a significant association. B - Graphical representation of networks connecting the arthropod classes affected by Unified Classification of Direct Threats of IUCN. The width of links between classes and threats is the sum of species, in decreasing order, where vertical bars are proportional to the number of species in the taxa (bottom) and the species associated with the threat (top). #1 Residential & commercial development (#1.Resi), #2 Agriculture & aquaculture (#2.Agri), #4 Transportation & service corridors (#4.Tran), #5 Biological resource use (#5.BioR), #6 Human intrusions & disturbance (#6.Intr), #7 Natural system modifications (#7.Modi), #8 Invasive and other problematic species, genes & diseases (#8.Inva), #9. Pollution (#9.Poll), #10 Geological events (#10.Geol), #11 Climate change & severe weather(#11.Clim), #12 Other options (#12.Other).

Regarding the IUCN list of 'Direct Threats', Azorean arthropods are affected by all of them, except threat #3 *Energy production & mining* (IUCN, 2022). In total, 93 % of Azorean endemic arthropods are threatened by #11 *Climate change & severe weather* (Fig. 2B). Specifically, threat #11.1 *Habitat shifting & alteration* can affect 92 %, while threat #11.2 *Droughts* can affect 85 %. Threats #2 *Agriculture & aquaculture* and #8 *Invasive and other problematic species, genes & diseases* are the next most important threats, impacting 75 % and 73 % of species, respectively (Fig. 2B). When looking into specific effects, threat #8.1 Invasive non-native/alien species/diseases can affect more species (71 %) compared to threat #2.2 *Wood & pulp plantations* (55 %) (Fig. 2B). Also, threat #10.1 *Volcanoes* 36 % of Azorean arthropod species (Fig. 2B).

3.2. *Threats for the most representative arthropod's orders*

The most representative orders, i.e., Araneae (spiders), Coleoptera (beetles), Diptera (flies and mosquitos), Hemiptera (true bugs), Lepidoptera (butterflies and moths) and Sarcoptiformes (moss mites), include 23 % of the non-threatened species, of which 11 % are assessed as Least Concern (LC) and 12 % as Near Threatened (NT) (Fig. 4A). These same orders include 45 % of all threatened species, of which 7 % are assessed asVulnerable (VU), 16 % Endangered (EN) and 22 % Critically Endangered species (CR) (Fig. 4A). Four beetle species (*B. chavesi C. extensicollis*, *C. vicenteorum*, and *S. occidentalis*) and one fly species (*C. mirabilis*) are assessed as extinct (EX).

For the Unified Classification of Direct Threats, the most representative orders follow the same pattern found for all arthropods. The main threat is #11 Climate change & severe weather, which represents 83 % of all affected species, followed by #2 Agriculture & aquaculture (70 %), #8 Invasive and other problematic species, genes & diseases (65 %) and #10 Geological events (33 %) (Fig. 4B).

3.3. *RLI variation between Azorean islands*

The IUCN Red List Index (RLI) indicates that Corvo and Graciosa islands have the lowest proportion of threatened species (Fig. 3A). In fact, both islands have more species assessed as LC and NT than as VU, EN or CR (Fig. 3B). The RLI for Pico, São Miguel and Santa Maria are the lowest compared to other islands (Fig. 3A). Moreover, these three islands have very similar values of non-threatened and threatened species (Fig. 3B).

3.4. *Species trophic strategies and extinction risk*

Our arthropod data includes 42 % of predators, followed by 32 % of herbivores and 23 % of omnivores. <2 % of arthropod species had no information regarding their trophic strategy, thus we disregarded these from the subsequent analyses. Moreover, there are 25 omnivores, 19 predators and three herbivores among the Data Deficient species (DD) (Fig. 5A). Species within non-threatened extinction risk are mainly herbivores, with this trophic strategy predicting a significantly greater EOO (EOO Herbivores estimate = 9.266, $p < 0.0001$) and AOO (AOO Herbivores estimate = 4.534, $p < 0.0001$) (Fig. 5A). At the same time, although predators are mostly threatened (Fig. 5A), we did not find a significant prediction on their EOO (EOO Predators estimate = −0.661, $p = 0.070$) and AOO (AOO Predators estimate = −0.103, $p = 0.536$). For omnivores though, we are able to predict only that they have smaller AOOs (AOO Omnivores estimate = −0.925 $p < 0.0001$), with no significant effect on EOO (EOO Omnivores estimate = −0.512, $p = 0.094$)

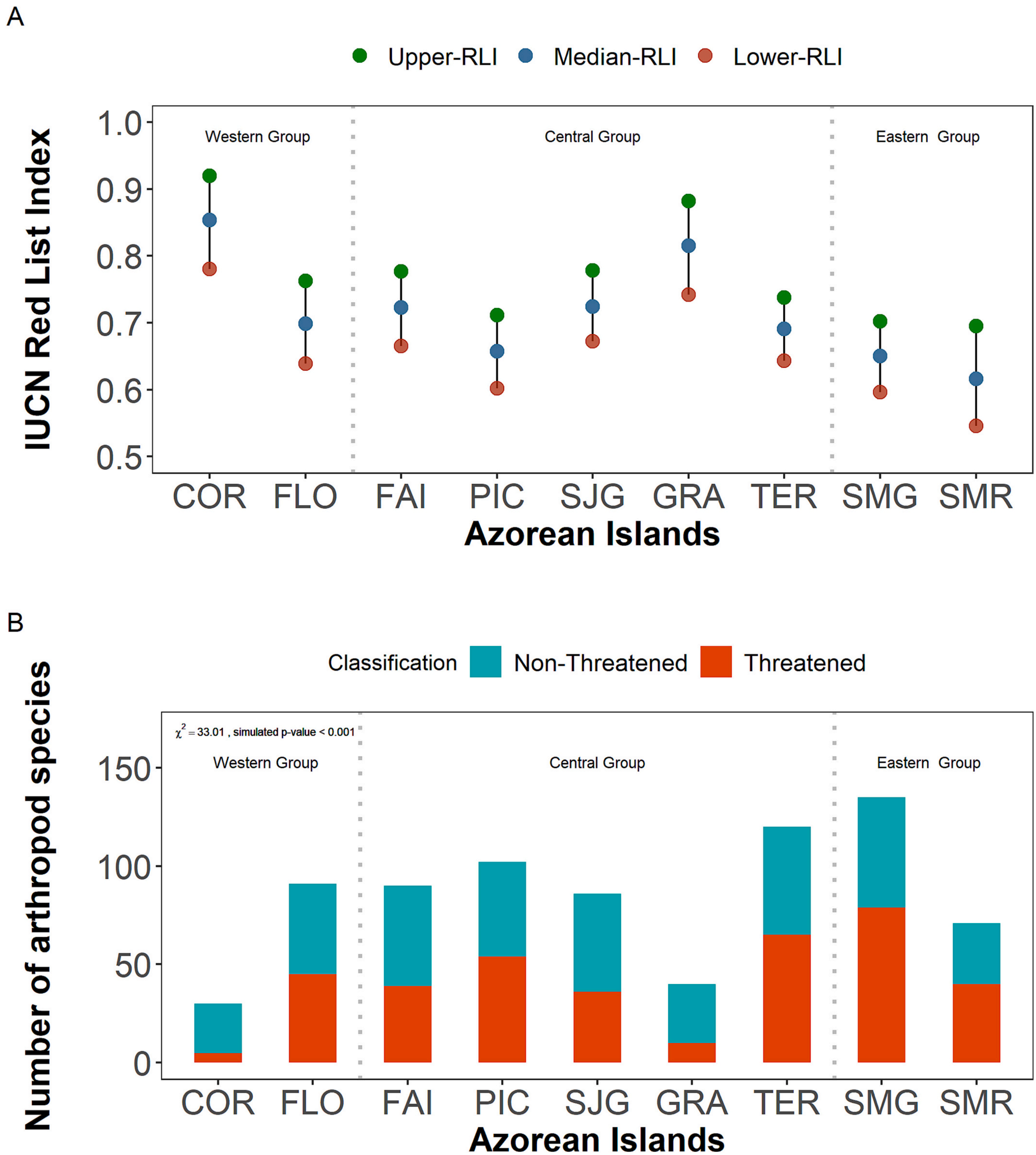

Fig. 3. – Number of arthropod species, by representative orders. A – Species in each of the IUCN extinction risk, assessed by the most to the least threatened: Extinct (EX), Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), Least Concern (LC) and Data Deficient (DD). Chi-squared indicates the association between the IUCN extinction risk and the number of species, with the simulated p-value indicating a significant association. Graphical representation of networks connecting the arthropod orders (number of species) affected by Unified Classification of Direct Threats of IUCN (nodes). The width of links between classes and threats is the sum of species, in decreasing order, where vertical bars are proportional to the number of species in the taxa (bottom) and the species associated with the threat (top). #1 Residential & commercial development (#1.Resi), #2 Agriculture & aquaculture (#2.Agri), #4 Transportation & service corridors (#4. Tran), #5 Biological resource use (#5.BioR), #6 Human intrusions & disturbance (#6.Intr), #7 Natural system modifications (#7.Modi), #8 Invasive and other problematic species, genes & diseases (#8.Inva), #9. Pollution (#9.Poll), #10 Geological events (#10.Geol), #11 Climate change & severe weather(#11.Clim), #12 Other options (#12.Other).

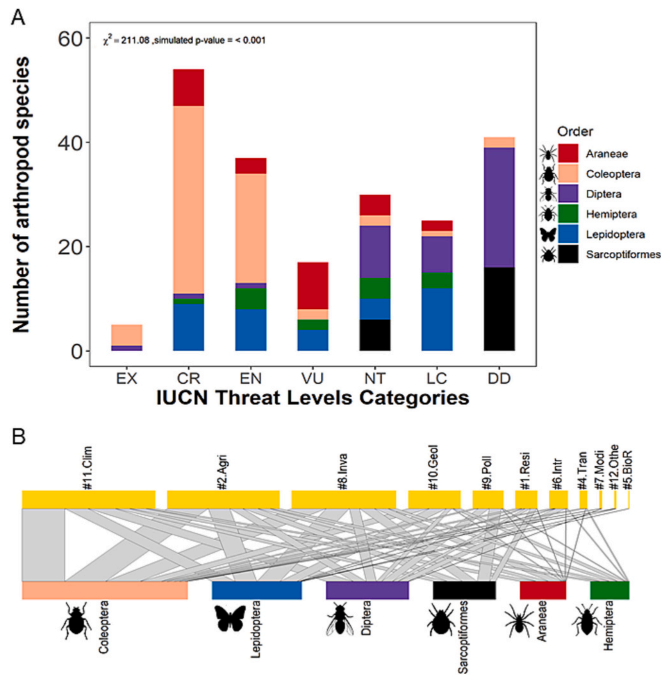

Fig. 4. – Assessment of non-threatened and threatened species in the Azores Islands. A) IUCN Red List Index (RLI) for each Azorean island. RLI scores close to 1.0 indicates species less threatened while RLI score close to 0 indicates species more threatened or extinct. Upper, median and Lower RLI indicates the bootstrapped confidence intervals. B) Number of non-threatened and threatened species in each of the Azores Islands. Islands are classified from left to right into the western group, Corvo (COR) and Flores (FLO), through the central group, Faial (FAI), Pico (PIC), São Jorge (SJG), Graciosa (GRA), and Terceira (TER), to the eastern group, São Miguel (SMG) and Santa Maria (SMR). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Fig. 5A).

Threatened herbivores and predators are spatially distributed through all values of AOO and EOO, covering species with very limited spatial ranges (25 % quantile at bottom left corner) to species with broader ranges (75 % quantile at top right corner) (Fig. 5B). Moreover, DD species show a spatial distribution pattern more similar to that of threatened species. In fact, the herbivore species assessed as DD are the only ones showing a similar spatial distribution pattern to those of non-threatened species, while the patterns of predatory and omnivore arthropods are more similar to the ones of threatened species (Fig. 5B).

4. Discussion

In this study we investigated the IUCN Red List status of endemic arthropod species across the Azorean Archipelago, spanning various taxonomic and trophic groups. Insects constituted the bulk of species evaluated by the IUCN, closely followed by arachnids. Granted, it is important to note that these are also the most studied arthropod groups. Our analyses revealed that more than half of the Azorean arthropod species evaluated by the IUCN are assessed as threatened. Notably, only insect species, four beetles (*Bradycellus chavesi* Alluaud, 1918, *Calathus extensicollis* Putzeys, 1873, *Calathus vicenteorum* Schatzmayr, 1939, and *Strophosoma occidentalis* (Crotch, 1867)) and one fly, have been declared extinct (*Campsicnemus atlanticus* Dyte, 1980). Moreover, the main threats for Azorean arthropod species are climate change, land use changes due to agricultural expansion/intensification, invasive vascular plant species and eventual geological events.

However, we are aware that the IUCN criteria, in their current form, are biased towards vertebrates, and multiple issues have been raised regarding how they are applied to invertebrates. These include the impact of threats in specific species being often determined indirectly, the subjectivity regarding the assignment of Data Deficient classification, and inadequate thresholds for invertebrate taxa (Cardoso et al., 2011). We recognize these limitations and implemented a rigorous approach that integrates long-term and trait-based datasets, aiming to enhance the reliability of our analyses. By doing so, we reduced further uncertainty and improve the applicability and understanding of the IUCN criteria to Azorean endemic arthropods. Moreover, we emphasize the urgent need for continued refinement of invertebrate-specific guidelines, which will allow for more accurate conservation status evaluations.

4.1. Human-driven threats and the rising impact of invasive arthropods

The IUCN direct threats to Azorean arthropods are mainly linked to human activities (Borges et al., 2020b; Spalding and Hull, 2021). Our findings suggest a high extinction debt, corroborating previous scenarios which indicate that, despite the challenges in predicting survivability, many Azorean endemic arthropods are at significant risk of extinction and may be on the brink of complete extirpation (Oyarzabal et al., 2024; Triantis et al., 2010; Whittaker et al., 2014). Furthermore, the continuous introduction of exotic and invasive arthropods is possibly causing negative direct and indirect effects on native non-endemic and endemic species (Boieiro et al., 2023; Borges et al., 2022a, 2013; Lhoumeau and Borges, 2023; Oyarzabal et al., 2024; Whittaker et al., 2014). These species are now common within the arthropod communities of Azorean native forests, having the same abundance-variance-occupancy as endemic ones (Gaston et al., 2006; Rigal et al., 2013). Despite the fact that the abundance of arthropod exotic species in native forest fragments is still lower than that of endemic and native non-endemic species, their abundance and diversity has steadily increased in the last decades (Borges et al., 2022a; Lhoumeau and Borges, 2023), taking up the endemic functional spaces and even adding new functional roles (Oyarzabal et al., 2024; Rigal et al., 2018; Whittaker et al., 2014). Hence, from a conservation perspective, the spread of exotic arthropod species and their negative impact will likely increase in the near future (Pozsgai et al., 2023).

Our results also show that climate change and eventual geological events on volcanic islands are current issues or may impose additional challenges in the near to long-term future. Climate change and its effects will be combined with those of land-use changes and exotic species spread, exacerbating human-driven species extinction in the Azores (Ferreira et al., 2016; Triantis et al., 2010). We corroborate recent studies that predict a continuous shift in species composition and extinctions of endemic species due to extreme weather events like rainfalls and droughts, that may shift the spatial and temporal availability of resources (Aparício et al., 2018; Carvalho et al., 2023; Ferreira et al., 2019; Wallon et al., 2023). Although volcanism may have played an important role in the evolutionary dynamics of Azorean arthropods (Amorim et al., 2012; Parmakelis et al., 2015) and it may be more easily predictable nowadays (Poland and Anderson, 2020), in the long-term, volcanic eruptions are hard to address in terms of biodiversity conservation due to the loss of area, lands slides and the extinction of populations and species (Nogales et al., 2022). For instance, after the 2021 eruption in the Canary Islands, 97 % of the invertebrate biomass was lost in the eruption area (Nogales et al., 2022). With the new landscape not being protected by any legislation, it was rapidly pressured for anthropogenic land-use alterations (Ferrer et al., 2023). Therefore, after a volcanic event, the main concern would be monitoring new habitats to avoid both the anthropogenic overexploitation and the re-colonization by exotic species rather than endemic ones (Gill et al., 2023).

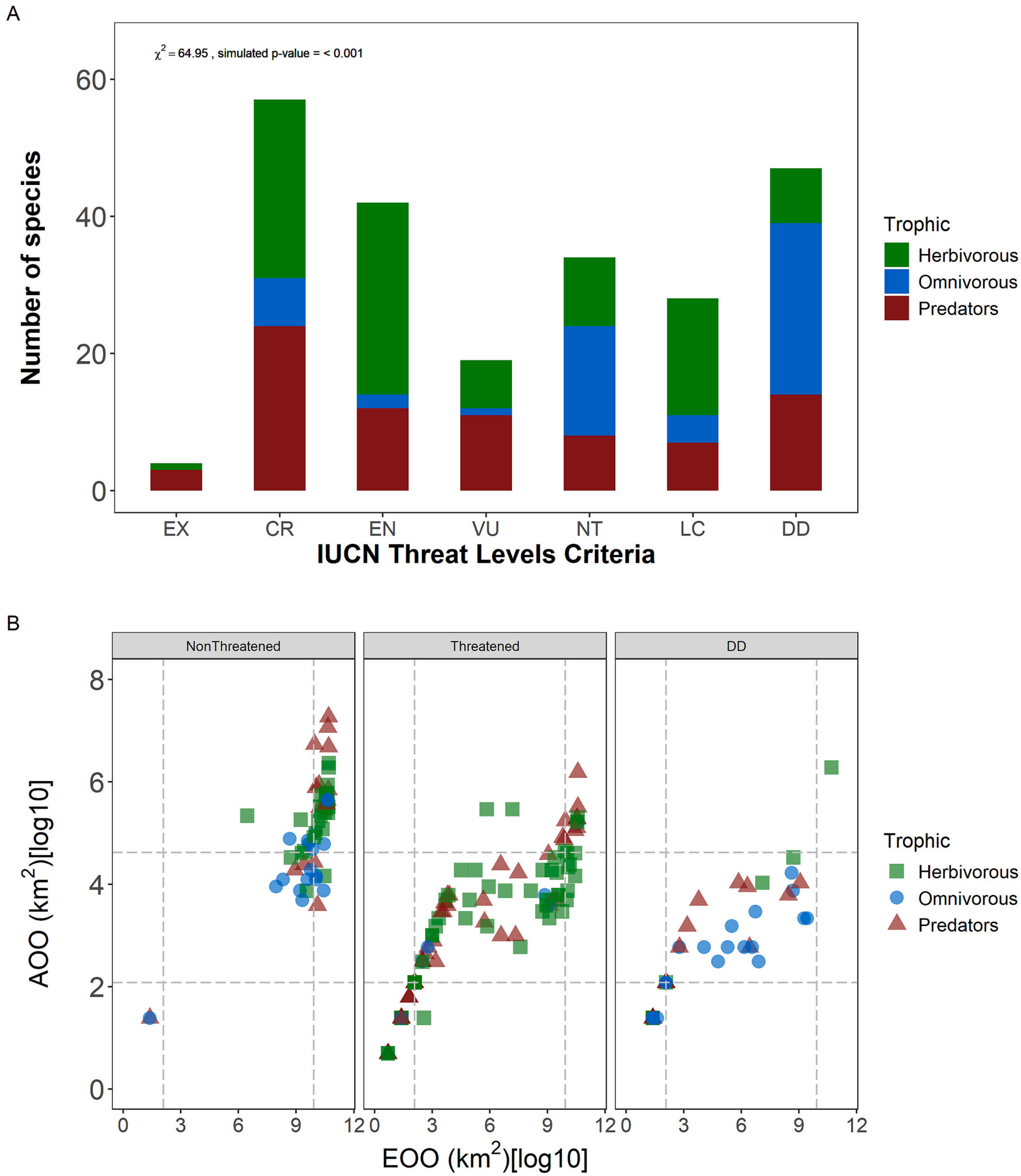

Fig. 5. – Endemic Azorean arthropods species classified by their trophic strategies. A – Number of arthropod species, by their trophic strategy. Colour indicates if a species is herbivores (chewers, suckers, pollinators and fungivores), omnivores (decomposers and species with broad diets) or predators (carnivores and parasitic). Data Deficient (DD), Least Concern (LC), Near Threatened (NT), Vulnerable (VU), Endangered (EN), Critically Endangered (CR) and Extinct (EX). Chi-squared indicates the association between the IUCN extinction risk and the number of species in each island, with the simulated *p*-value indicating a significant association. B – Spatial distribution of species by trophic and extinction risk in relation with their Area of Occupancy (AOO) and Extent of Occurrence (EOO). Dashed gray lines indicate the 25 % (AOO bottom and EOO left) and 75 % (AOO top and EOO right) quantiles cuts.

4.2. Interpreting IUCN red list index: Hidden extinctions and conservation measures

The low values of RLI associated with Santa Maria and São Miguel are in accordance with previous findings, since both islands are highly disturbed by invasive exotic plants, have a large number of single-island endemics (SIE) endemics and have small and highly disturbed remnants of native forest (Borges et al., 2024; Gaspar et al., 2011). For Terceira though, since this island has the largest and best-preserved fragments of native forest in the Azores (Borges et al., 2006; Gaspar et al., 2011), its RLI is higher than that of the other islands, which may indicate a successful implementation of conservation actions (Lhoumeau and Borges, 2023; Pozsgai et al., 2024a; Tsafack et al., 2023). On the other hand, we obtained a higher RLI for Corvo and Graciosa, despite being the most disturbed islands, with almost no remnants of native forest (Elias et al., 2016; Pozsgai et al., 2024b). This unusual finding, should be interpreted with caution because it may be the result of an early extirpation of rare and restricted endemic arthropods on Corvo and Graciosa, which happened before scientists had formally described these species. This loss is likely a consequence of the near-total destruction of native forests in these two islands closely following human colonization (Norder et al., 2020). Therefore, communities on these islands are now composed of only less threatened and often widespread endemic species, leading to a high RLI. These results call for special attention when applying the RLI to any particular region and habitat, highlighting that a high RLI does not necessarily imply a well-conserved biota, as in our examples with Corvo and Graciosa islands. Indeed, the presence of non-threatened species in a fragmented habitat on a small island may be an indicator of widespread species extirpations due to native forest clearing in historical times.

4.3. Threats on trophic levels, data deficiency, and cryptic species

Our data also reveal that spiders and predator beetles constitute the majority of threatened species. This corroborates previous works in the Azores (Cardoso et al., 2010; Borges et al., 2017a, 2017b; Costa and Borges, 2021; Lhoumeau and Borges, 2023) and in other oceanic archipelagos (Boieiro et al., 2013; Costa et al., 2023; Evans et al., 2011), and is linked to their restricted diets when compared to herbivores and omnivores species (Chichorro et al., 2019). Independently of trophic level though, threatened species are distributed throughout the whole range of species occupancy and occurrence. Data Deficient (DD) species, however, show similar distribution patterns to the threatened ones. This result may raise concerns regarding the actual extinction risk among DD Azorean arthropods. Most DD species belong to taxonomic groups still poorly studied in Azores (Diptera, Hymenoptera and Sarcoptiformes) (Lobo and Borges, 2010), clearly showing that the taxonomic impediment is impacting the knowledge on the conservation status of an important fraction of Azorean arthropods. Previous machine learning assessments have predicted that >60 % of DD species in the IUCN Red List may actually be at risk of extinction (Bachman et al., 2024; Bland et al., 2014). Moreover, widespread endemic species that occur on multiple islands may be structured into isolated island populations with no effective gene flow between them, which is especially likely for species with limited dispersal abilities (Suárez et al., 2022). Consequently, some Azorean endemic species currently assessed as Vulnerable (VU) might consist of cryptic species that are more threatened than previously thought. For instance, *Tarphius azoricus*, *T. tornvalli*, and *T. depressus* were initially described as Azorean endemics and recorded on several islands (Borges et al., 2010). However, a molecular study by Amorim et al. (2012) revealed that these were, in fact, composed of distinct cryptic species. Following a comprehensive taxonomic evaluation using an integrative approach, Borges et al. (2017a) reclassified these cryptic species as several single-island endemics (SIE). Subsequently, each Azorean *Tarphius* SIE underwent an island-level extinction risk assessment using the IUCN Red List criteria, with several being listed as Critically Endangered (Borges et al., 2017b) *T. relictus* (IUCN, 2024). Therefore, it is critical to properly assess these species and evaluate their true conservation status, providing a stronger baseline for conservation efforts in the Azores and elsewhere.

Oceanic islands are systems quite distinct from those in continental areas, not only in their geological history, dynamics, and isolation but also in how impacted they were in historical times by human activities (Fernández-Palacios et al., 2021). We expect that our work serves as a base example of how to synthesize IUCN species evaluation information for oceanic islands as more species from these systems are evaluated using the IUCN criteria.".

5. Conclusion

In this study we investigated the IUCN Red List status of Azorean endemic arthropod species across the Azores archipelago. Alarmingly, more than half of the species were assessed as threatened, with a few insect species declared extinct. The IUCN Red List Index (RLI) results highlight the conservation status of different islands within the archipelago, with Corvo and Graciosa displaying higher RLIs despite the complete absence of native forest. These findings suggest that rare species may have already gone extinct on these islands, with the survivors being the widespread and less threatened species. In contrast, Terceira island, with its larger and well-preserved native forest fragments, also displayed a high RLI, indicating the importance of larger areas of native forest and the success of conservation efforts through protected areas. Nevertheless, our analyses underscores the need to consider the particular historical human activities and conservation management of each Azorean islands when evaluating extinction risk of endemic arthropods, as certain species may face greater threats on specific islands.

The extinction risk for Azorean arthropods are predominantly driven by human activities. Land-use changes have drastically altered Azorean ecosystems, resulting in a significant reduction in native forest cover and isolating most endemic arthropods in small remnants of pristine forest. Moreover, the impacts of climate change pose an additional challenge to Azorean arthropods, exacerbating habitat loss and fragmentation, potentially accelerating species and population extinctions. Extinction debt looms large in island conservation biology, underscoring the critical need for conservation efforts and the protection of natural habitats to restore biodiversity, prevent future losses, and mitigate past declines. It is crucial to identify and preserve areas of high ecological value, such as refugia for endemic species, while implementing measures to enhance habitat connectivity and facilitate species movement and adaptation to changing environmental conditions (Aparício et al., 2018).

Given the urgency of natural habitats conservation in the Azores, a comprehensive strategy is needed—one that combines habitat protection, invasive species management, and the active involvement of stakeholders, including local communities and policymakers. Citizen science initiatives can play a crucial role in biodiversity monitoring, engaging the public in data collection and fostering awareness about the importance of preserving endemic species. By integrating scientific research with participatory conservation approaches, we can enhance the effectiveness of management actions and secure the long-term survival of Azorean arthropods, ensuring the protection of the archipelago's unique biodiversity (Elias et al., 2016; Mendes et al., 2023).

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CRediT authorship contribution statement

Guilherme Oyarzabal: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation. **Gabor Pozsgai:** Writing – review & editing, Visualization, Validation, Methodology. **Noelline Tsafack:** Writing – review & editing, Visualization, Validation, Methodology. **Pedro Cardoso:** Writing –

review & editing, Validation, Methodology. **François Rigal:** Writing – review & editing, Validation, Methodology. **Mário Boieiro:** Writing – review & editing, Validation, Methodology. **Ana M.C. Santos:** Writing – review & editing, Validation, Methodology. **Isabel R. Amorim:** Writing – review & editing, Validation, Methodology. **Jagoba Malumbres-Olarte:** Writing – review & editing, Validation, Methodology. **Ricardo Costa:** Writing – review & editing, Validation, Methodology. **Sébastien Lhoumeau:** Writing – review & editing, Validation, Methodology. **Rosalina Gabriel:** Writing – review & editing. **Paulo A.V. Borges:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the main author, GO, used ChatGPT 3.5 in order to improve legibility of some sentences into English. These sentences were then reviewed and rewritten by the same main author, GO.

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Declaration of competing interest

The authors declare that they have no known competing interests or personal relationships that could have influenced the work reported in this paper.

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Data availability

The BALA and SLAM projects data that support the findings of this study are available in the published literature cited in the Data sampling sections of this manuscript.

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