Received: 14 January 2025 | Accepted: 12 March 2025

DOI: 10.1111/icad.12822

ORIGINAL ARTICLE

Insect Conservation and Diversity

Species traits may predict extinction risk of Azorean endemic arthropods

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Funding information
Portugal's Foundation for Science and Technology, Grant/Award Numbers: FCT-PTDC/BIA-CBI/0625/2021, UIDP/00329/2020, UI/BD/151406/202, UIDB/00329/2020–2024; cE3c - Centre for Ecology, Evolution and Environmental Changes, Grant/Award Number: 10.54499/UIDB/00329/2020; CHANGE - Global Change and Sustainability Institute, Grant/Award Number: 10.54499/LA/P/0121/202; Spanish Ramón y Cajal Fellowship, Grant/Award Numbers: RYC2020-029407-I, MICIN/AEI/10.13039/501100011033; ESF Investing

Abstract

1. Oceanic islands, recognised for their isolation, high endemic species richness and unique evolutionary paths compared with their continental counterparts, are extremely susceptible to anthropogenic activities.
2. The fragmentation of island habitats and disruption of native ecosystems has increased the risk of extinction for many endemic species, including arthropods. Extinction is not random, and some species traits may increase the probability of species entering an extinction trajectory.
3. Studying species traits alongside International Union for Conservation of Nature (IUCN) threat levels may offer valuable insights into their vulnerability and inform targeted conservation strategies. Here, we aim to test the predictability of IUCN threat categories and conservation status based on endemic Azorean arthropods' functional traits: body size, trophic group and vertical strata occupancy.
4. We demonstrate that species with limited vertical occupancy, particularly those restricted to ground level, are more vulnerable to extinction than those that inhabit the forest canopy. Contrary to our expectations, body size and trophic group did not appear to be direct predictors of the threat level. Overall, our findings

in Your Future; Regional Government of the Azores, Grant/Award Number: M3.1.a/F/012/2022; Azores DRCT Pluriannual Funding, Grant/Award Number: M1.1.A/FUNC.UI&D/010/2021–2024

Editor: Nick Littlewood and **Associate Editor:** Christie A Bahlai

underscore previous and ongoing effects of human activities in island ecosystems. Hence, we emphasise the need to look at species traits as predictors of future extinctions in endemic island arthropods.

KEYWORDS
conservation, habitat fragmentation, human impact, human threats, red listing, vulnerability

INTRODUCTION

Oceanic islands, characterised by their isolation, limited area and unique evolutionary histories, are increasingly vulnerable to the impacts of human activities in the Anthropocene (Russell & Kueffer, 2019; Triantis et al., 2010; Whittaker et al., 2017). Land-use change, including deforestation and urbanisation, has led to a significant habitat loss (including habitat reduction, destruction, fragmentation and degradation) and fragmentation of island native ecosystems worldwide (Fernández-Palacios et al., 2021; Gaspar et al., 2008; Nogué et al., 2021; Norder et al., 2020). These modifications disrupt ecological processes and threaten the survival of endemic species, particularly arthropods, which constitute a significant portion of island biodiversity (Russell & Kueffer, 2019). Arthropods include a wide variety of taxonomic and functional species, playing a significant and often underappreciated role in ecosystems due to their unique ecological characteristics (Noriega et al., 2018). Hence, island endemic arthropods, with their unique traits, might be more susceptible to decreases both in abundance and richness due to the loss of their natural habitats (Ferreira et al., 2016; Lhoumeau & Borges, 2023; Oyarzabal, Cardoso, Rigal, Boieiro, Santos, & Amorim, 2024; Whittaker et al., 2017).

The extinction risk of island endemics arises from a combination of their uniqueness, constant exposure to adverse effects of human-induced threats and their restricted spatial distribution (Gillespie & Will, 2018; Rodríguez et al., 2015; Terzopoulou et al., 2015). Therefore, the 'Criterion B – Restricted Geographical Range' of International Union for Conservation of Nature (IUCN) is commonly used to define species threat levels (IUCN, 2024). However, a species' ecological role is often overlooked, and focusing only on common threats may limit our understanding of human impacts, potentially delaying efforts to prevent species loss (Cardoso et al., 2011). In this way, previous works that include an array of different taxa, suggest that functional traits may help to effectively predict species vulnerability (Cardoso et al., 2011; Hanz et al., 2022). For instance, large-bodied arthropods, similar to other terrestrial taxa, may have elevated extinction risk due to smaller offspring numbers and the relative higher demand of energy intake (Chichorro et al., 2022; Gossner et al., 2015; Rigal et al., 2018). At the same time, those specialised in only one food source (only carnivore or only herbivore), may also face elevated threats and extinction risks as their native habitats are converted to human purposes (Chichorro et al., 2022; Gossner et al., 2015; Purvis et al., 2000; Rigal et al., 2018; Terzopoulou et al., 2015). Moreover, arthropods restricted in their distribution in the habitat, only living in the ground or the tree canopy, may struggle to adapt, disperse in or survive under altered environmental conditions, further exacerbating their vulnerability to human activities (Chichorro et al., 2022; Costa et al., 2023; Gaona et al., 2021; Gossner et al., 2015; Zhang et al., 2023).

Using traits to study and predict threatened species enhances our understanding of the complex interactions between organisms and their environment (Arslan et al., 2024; Chichorro et al., 2022). Moreover, it may help to prioritise conservation efforts that aim to diminish the negative impacts of land-use change and provide guidance for restoration projects that consider threatened species' specific needs. Therefore, we aim to assess if the functional traits of Azorean endemic arthropods can predict the threat level of previously assessed species following the IUCN criteria (Borges, Lamelas-Lopez, Andrade, et al., 2022; IUCN, 2024). We hypothesise that body size, trophic group and the preference for the ground or tree canopy level correlate with IUCN threat level, predicting that large-bodied species, predators and ground-dwellers are at a higher risk of extinction.

METHODS

Our research took place in the Azores archipelago, situated in the northern Atlantic Ocean between 37° and 40° N latitude and 24° and 31° W longitude. Comprising nine volcanic islands divided into three island groups—western (Corvo and Flores), central (Faial, Pico, São Jorge, Graciosa and Terceira) and eastern (São Miguel and Santa Maria)—the archipelago spans about 615 km from east to west. The region experiences a temperate oceanic climate with notably high atmospheric humidity, particularly in the elevated native semi-tropical evergreen laurel forest (Borges, Lamelas-Lopez, Andrade, et al., 2022; Borges, Lamelas-Lopez, & Schülke, 2022; Elias et al., 2016). Human activities, dating back to the 15th century, have significantly altered the landscape, with the original native forest now occupying only around 5% of the total archipelago area (Borges, Lamelas-Lopez, Stüben, et al., 2022; Elias et al., 2016; Gaspar et al., 2008; Triantis et al., 2010).

We compiled a list of Azorean endemic terrestrial arthropod species, pooling together arachnids and insects, from previously published works (Borges et al., 2005; Lobo & Borges, 2010) and from the data of two long-term monitoring projects, the 'Biodiversity of Arthropods from the Laurisilva of the Azores' (BALA project) (Borges et al., 2006, 2016; Pozsgai et al., 2024) and the 'Long Term Ecological Study of the Impacts of Climate Change in the Natural Forest of Azores' (SLAM project) (Borges, Lamelas-Lopez, Stüben, et al., 2022; Costa & Borges, 2021; Lhoumeau & Borges, 2023). Species threat level were obtained through the IUCN Red List (IUCN, 2024) and species traits were compiled from publicly available databases: (i) the Azorean Biodiversity Portal (ABP, 2025) and IUCN Mid Atlantic Islands Portal (ABP, 2025; AIISG, 2025); (ii) previously published data and papers on Azorean arthropods (Borges et al., 2006, 2016; Borges, Lamelas-Lopez, Stüben, et al., 2022; Costa & Borges, 2021; Lhoumeau & Borges, 2023; Oyarzabal, Cardoso, Rigal, Boieiro, Santos, Amorim, et al., 2024; Pozsgai et al., 2024); and (iii) personal knowledge on the species' natural history by PAVB. We selected traits that are expected to respond to anthropogenic disturbance while being comparable between the different arthropod groups and their threat level (Chichorro et al., 2022; Gossner et al., 2015; Rigal et al., 2018; Simons et al., 2016). These traits were also previously proven to be significant in predicting species abundance trends in Azores (Oyarzabal, Cardoso, Rigal, Boieiro, Santos, & Amorim, 2024). Thus, we selected three traits: (i) body size, standardised by the z-score within each order (average size of the order minus the size of the species divided by the standard deviation of size in the order), following Oyarzabal, Cardoso, Rigal, Boieiro, Santos, and Amorim (2024); (ii) average of the vertical stratum that species occupy in the vegetation (henceforth verticality), following Costa et al. (2023), where species that occupy only the ground level were assigned a verticality value of 0 and species that occupy only the tree canopy a verticality value of 1 and; (iii) trophic group, expressed in three categories of predators, herbivorous (herbivorous and fungivorous species) and omnivorous. Our dataset included 77 Azorean endemic arthropods for which we were able to compile the IUCN threat level and trait data. To simplify the analysis, we transformed their classification into binary values, where zero (0) represented non-threatened species and one (1) for threatened species.

We fitted a binomial Bayesian framework, which allows estimating probabilities for parameters rather than relying on frequentist *p*-values, to assess how species' threat level could be predicted from their traits (explanatory variables). As a random effect, we used arthropod orders, accounting for variability and intrinsic differences within orders. We have built the Bayesian frameworks with the help of the *jagsUI* package (Kellner & Meredith, 2021), with 1 million interactions (total number of steps the MCMC algorithm runs to estimate posterior distributions), 500,000 burn-in (the first 500,000 iterations were discarded to allow the model to converge and remove the influence of initial parameter values), in five simultaneous chains (MCMC was run five times in parallel to ensure robust estimates and check for convergence) and five thins (Every fifth iteration was retained to reduce autocorrelation in the samples). Traits were considered to significantly predict the threat levels when 97.5% of their credible intervals (CRI) were either positive or negative, not passing through zero (Hespanhol et al., 2019). Finally, we evaluated the individual contribution of each predictor through hierarchical partitioning using R^2 of a generalised linear mixed-effects model (GLMM) with the same data. The GLMM was performed using the *lme4* package (Bates & Mächler, 2015) and the hierarchical partitioning was obtained using the *glmm.hp* package, as its functions consider both the unique and shared variance that sum to the overall marginal R^2, evaluating the relative importance of each fixed effect (Lai et al., 2022). All analyses were performed within the R environment (R Core Team, 2025).

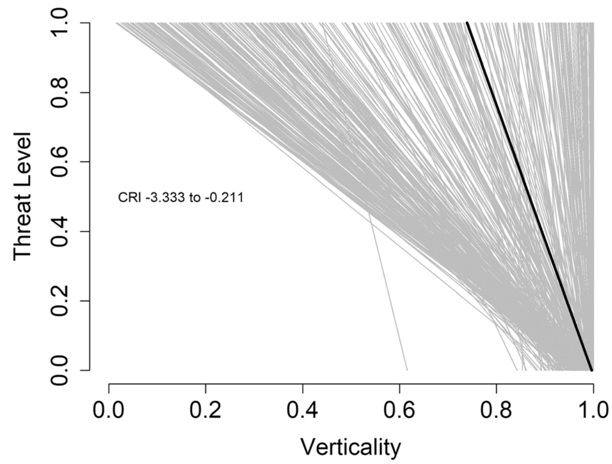

FIGURE 1 Relationship between species threat level prediction and verticality. Black line shows the posterior means and grey lines show estimation uncertainty, based on 400 random posterior distributions of the Bayesian predictions, as a way to depict the prediction uncertainty. Species threat level predicted by species verticality, where 0 means ground-dwellers and 1 indicates canopy dwellers. CRI indicates the credible intervals of 97.5% estimated by the Bayesian framework.

RESULTS

The 77 species compiled included 30 Coleoptera (beetles), 21 Araneae (spiders), 11 Hemiptera (true bugs), 10 Lepidoptera (butterflies and moths), 2 Plecoptera (Stoneflies), 1 Archaeognatha (jumping bristletails), 1 Neuroptera (lacewings) and 1 Trichoptera (caddisflies) species. Our response variable was the IUCN Red List classification of the Azorean endemic species. Regarding the IUCN threat level, 26 of these species are non-threatened (16 Least Concern and 10 Near Threatened) and 51 are threatened (10 Vulnerable, 24 Endangered and 17 Critically Endangered). The data regarding the functional traits are publicly available through the Dryad database (Oyarzabal, Cardoso, Rigal, Boieiro, Santos, & Amorim, 2024; Oyarzabal, Cardoso, Rigal, Boieiro, Santos, Amorim, et al., 2024).

Verticality was the most important trait to predict species threat level, where ground-dwelling species, those with verticality closer to 0, were more threatened than canopy-dwelling species (verticality closer to 1) ($\beta_{\text{Verticality}}$: −3.33 to −0.211 CRI, Figure 1). Verticality also presented the highest unique R^2 (0.157, individual contribution of 74%). This value was much higher than that for the other two variables, body size (R^2 0.006, individual contribution of 2%) and trophic group (R^2 0.053, individual contribution of 23%), which were not found to be significant predictors of species threat level. Finally, the GLMM fixed effects explained 20% of data variance (R^2m) while the fixed/random effect explained 47% (R^2c) of the variance.

DISCUSSION

Our study explored to what extent species traits like body size, trophic group and vertical stratum occupancy can predict the threat level of a selected group of Azorean endemic arthropods. Overall, we found that species that exclusively occupy the ground level face a greater risk of extinction compared with species that inhabit the forest canopy.

Previous findings suggest that the Azorean arthropod composition is strongly segregated along the vertical stratum, with negligible overlay between ground- and canopy-dweller species (Gaspar et al., 2008), except in the case of spiders (Costa et al., 2023). In line with this, our results showing that ground-dwelling species are more threatened than canopy dwellers corroborate with previous findings from the Azores that highlight the impact on ground species diversity caused by land-use changes and exotic invasive plants (Florencio et al., 2013, 2015; Gaspar et al., 2008; Meijer et al., 2011; Oyarzabal, Cardoso, Rigal, Boieiro, Santos, & Amorim, 2024). The ongoing spread of invasive plant species is dramatically altering large patches of native forest in most Azores Islands (Hortal et al., 2010; Kueffer et al., 2010; Lourenço et al., 2011). Although the impacts of invasive plants are still largely unknown, there is some evidence of local extirpation of endemic plant species, like bryophytes and ferns, in some disturbed sites (Sousa et al., 2024). In terms of canopy species, it is important to note that the verticality trait was obtained through the sampling of isolated remains of the Azorean native forest (Borges et al., 2016; Costa & Borges, 2021; Lhoumeau & Borges, 2023; Pozsgai et al., 2024; Whittaker et al., 2017). Those forest remains, although protected, are far from being the same area size as they were before humans had settled in the Azores and most likely do not encompass the diversity and abundance once present, since more than 95% of all original forest has been converted to human use (Amorim et al., 2012; Gaspar et al., 2008; Rego et al., 2015; Triantis et al., 2010). Therefore, while canopy species may appear less threatened, they could still face extinction, struggling to persist in isolated patches of protected forest surrounded by a matrix of human-modified environment (Raupp et al., 2010; Swart et al., 2020), especially in the smallest and most degraded forest fragments of the archipelago (e.g. Santa Maria Island small 4-ha forest fragment). Ultimately then, despite some evidence that canopy species have greater resilience to climatic change and variability as compared with ground-dwelling species (Scheffers & Williams, 2018), the advance of invasive plants and climatic changes may threaten these species at some point in the near future (Borges et al., 2006; Ferreira et al., 2016; Oyarzabal, Cardoso, Rigal, Boieiro, Santos, & Amorim, 2024; Queiroz et al., 2014; Ribeiro et al., 2005). The restoration, management and protection of natural habitats may mitigate future biodiversity losses, from the ground to the canopy level, while supporting the long-term survival of endemic species in the face of accelerating environmental changes.

Contrary to our hypothesis, body size and trophic group did not seem to be able to predict the threat level of endemic arthropods in the Azores. Body size is generally a predictor of arthropod abundance trends in many ecosystems, including the Azores (Oyarzabal, Cardoso, Rigal, Boieiro, Santos, & Amorim, 2024; Parmakelis et al., 2015; Rigal et al., 2018; Terzopoulou et al., 2015). Typically, larger-bodied species are more vulnerable due to lower population densities, greater resource needs and slower reproduction rates, which may correlate with higher extinction risk (Chichorro et al., 2022; Martins et al., 2023; Terzopoulou et al., 2015). In fact, it was recently found that Azorean endemic herbivorous arthropods, with large body sizes, indeed show negative population trends (Oyarzabal, Cardoso, Rigal, Boieiro, Santos, & Amorim, 2024). However, our lack of association between body size and threat level may actually represent that the larger-bodied species are already extinct (see e.g. Terzopoulou et al., 2015), which is the case for large-bodied beetle species in Azores (IUCN, 2024). Hence, our sample may represent only the survivors of the previously mentioned human-induced conversion of the original forest, which likely has led to the extinction of many unknown endemic arthropods (Triantis et al., 2010; Whittaker et al., 2014). Similar patterns have been reported for birds (Alcover et al., 2015; Illera et al., 2012; Rando et al., 2013). On the other hand, although the aforementioned relation with herbivorous body size and the loss of abundance, previous papers were not able to find a direct relationship between trophic group and abundance trends, which aligns with the results found here (Oyarzabal, Cardoso, Rigal, Boieiro, Santos, & Amorim, 2024). This underscores that, at least for Azorean endemic arthropods, the association between trophic group and threats is likely weak and may not be a good predictor of extinction risk.

In conclusion, our study highlights that the vertical stratum—specifically the occupancy of the ground level and the tree canopy—emerges as a critical factor in predicting extinction risk among Azorean endemic arthropods. Species restricted to the ground level face significantly higher threats than those inhabiting the canopy, likely due to greater exposure to habitat degradation (Oyarzabal, Cardoso, Rigal, Boieiro, Santos, & Amorim, 2024). The ongoing fragmentation of habitats and the introduction of invasive animal and plant species also suggest that both ground and canopy arthropods remain at significant risk. Our results underscore the importance of considering habitat loss and vertical stratum specialisation when assessing extinction risk. We also emphasise the urgent need for conservation strategies, such as the creation of ecological corridors connecting native forest fragments, which can further safeguard canopy-dwelling species by enhancing endemic species populations and their resources (food, habitat), also providing a buffer against climate change and the disturbance effects from neighbouring human-transformed habitats (Aparício et al., 2018). Several actions to restore and enhance habitat connectivity are already underway on three Azores islands through LIFE projects (LIFE BEETLES, LIFE AZORES NATURA and LIFE SNAIS), one of them focusing on the conservation of three endangered beetle species (LIFE BEETLES); however, the results are yet to be demonstrated (Tsafack et al., 2023). Finally, it is imperative to incorporate protective measures for threatened and less-threatened endemic species (Baker et al., 2019; Ceballos et al., 2020), since in an island context even widespread species may be declining. Therefore, sustainability (ecological and economic) in oceanic islands must involve the protection and restoration of fundamental natural habitats and hence, the uniqueness and rare ecosystem services provided by endemic arthropods (Baker et al., 2019; Ceballos et al., 2020; Gaston & Fuller, 2007, 2008; Oyarzabal, Cardoso, Rigal, Boieiro, Santos, & Amorim, 2024).

AUTHOR CONTRIBUTIONS

Guilherme Oyarzabal: Conceptualization; data curation; methodology; formal analysis; validation; visualization; writing – original draft; writing – review and editing. **Pedro Cardoso:** Methodology; validation; writing – review and editing. **François Rigal:** Methodology; validation; writing – review and editing. **Mário Boieiro:** Methodology; validation; writing – review and editing. **Ana M. C. Santos:** Methodology; validation; writing – review and editing. **Isabel R. Amorim:** Methodology; validation; writing – review and editing. **Jagoba Malumbres-Olarte:** Methodology; validation; writing – review and editing. **Ricardo Costa:** Methodology; validation; writing – review and editing. **Sébastien Lhoumeau:** Methodology; validation; writing – review and editing. **Gabor Pozsgai:** Methodology; validation; writing – review and editing. **Rosalina Gabriel:** Methodology; validation; writing – review and editing. **Paulo A. V. Borges:** Conceptualization; data curation; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; writing – review and editing.

ACKNOWLEDGEMENTS

We are grateful for the hard work of all colleagues that collaborated, for the past 25 years, in fieldwork preparation, trapping, assembling, sampling, sorting and species identification of BALA and SLAM projects.

FUNDING INFORMATION

We are thankful for the Portugal's Foundation for Science and Technology Foundation (FCT) for funding the MACRISK project – FCT-PTDC/BIA-CBI/0625/2021. PC is supported by cE3c - Centre for Ecology, Evolution and Environmental Changes (https://doi.org/10.54499/UIDB/00329/2020), and CHANGE - Global Change and Sustainability Institute (https://doi.org/10.54499/la/p/0121/2020). IRA and MB were supported by FCT under DOI 10.54499/DL57/2016/CP1375/CT0003 and /CT0001, respectively. GP was funded by the contract FCT UIDP/00329/2020. AMCS was supported by a Spanish Ramón y Cajal Fellowship RYC2020-029407-I, funded by MICIN/AEI/10.13039/501100011033 and by "ESF Investing in Your Future". SL is funded by the Regional Government of the Azores Ph.D. grant number M3.1.a/F/012/2022. RC is funded by FCT Grant number UI/BD/151406/2021. GO, MB, IRA, GP, RG and PAVB were also funded by the projects FCT UIDB/00329/2020–2024 DOI 10.54499/UIDB/00329/2020 (Thematic Line 1 – integrated ecological assessment of environmental change on biodiversity) and Azores DRCT Pluriannual Funding – M1.1.A/FUNC.UI&D/010/2021–2024.

CONFLICT OF INTEREST STATEMENT

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

DATA AVAILABILITY STATEMENT

The BALA and SLAM projects data that support the findings of this study are available in the published literature cited in the *Methods* sections of this manuscript and publicly available at the Dryad Digital Repository: https://doi.org/10.5061/dryad.qv9s4mwpf (Oyarzabal, Cardoso, Rigal, Boieiro, Santos, Amorim, et al., 2024).

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How to cite this article: Oyarzabal, G., Cardoso, P., Rigal, F., Boieiro, M., Santos, A.M.C., Amorim, I.R. et al. (2025) Species traits may predict extinction risk of Azorean endemic arthropods. *Insect Conservation and Diversity*, 18(4), 545–551. Available from: https://doi.org/10.1111/icad.12822