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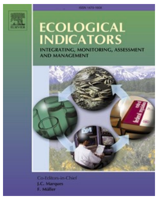

Arthropod-based biotic integrity indices: A novel tool for evaluating the ecological condition of native forests in the Azores archipelago

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ABSTRACT

Island ecosystems are experiencing a significant decline in biodiversity, with forest biodiversity being particularly affected by several biodiversity erosion drivers. This alarming situation highlights the urgent need for conservation managers to develop more accurate and efficient tools to assess and monitor the quality status of sites. To address this issue, our study focuses on the development of two biological integrity indices (IBI) that utilize arthropod communities as indicators to measure the quality of forest sites. In accordance with studies that showed stratification of species diversity, we developed an IBI for canopy stratum (IBI-Canopy) and an IBI for an intermediate stratum targeting the forest understory (IBI-SLAM). We calibrated both indices on seven parameters for comparison purpose with a previous developed epigean IBI. Percentages of endemic, native non-endemic and introduced species richness and abundance were included in both indices. Percentages of Diplopoda species richness and abundance were included in IBI-Canopy and percentages of Saprophagous species richness and abundance were included in IBI-SLAM. As expected species richness and abundance of endemic species were negatively related to disturbance and selected for both IBI. Surprisingly, species richness and abundance of native non-endemic species were positively related to disturbance. The study highlights the limitations of single measurements in detecting all types of pressure sources, and proposes a multi-measurement system to provide a more comprehensive understanding of the overall system conditions. Our efficient and accessible indices confirmed low preservation status in Flores Island compared to Terceira and Pico, consistent with prior empirical studies. Our analyses also showed that canopy detect disturbance earlier than intermediate understory stratum. Our methodology has successfully been developed and tailored to the unique arthropod communities found in the Azores forests. While it may not be suitable for random forest sites, it can serve as a valuable source of inspiration for the development of arthropod-based IBIs in other islands of the world for which standardized endemic and exotic species richness and abundance could be obtained. The study also showed that arthropod assemblages mimicked forest biodiversity stratification and this is reflected in differences expressed by the IBIs.

1. Introduction

Global forest loss and fragmentation are pressing issues that threaten the health and sustainability of the world's ecosystems (Haddad et al., 2015; Hansen et al., 2010). Forest loss refers to the decline in forest cover over time due to human activities such as deforestation, land use changes, and infrastructure development (Vuyiya et al., 2014). Fragmentation, on the other hand, refers to the breaking up of continuous forest landscapes into smaller and more isolated patches. This fragmentation can lead to habitat loss, decreased biodiversity, and altered ecosystem functions (Ciccarese et al., 2012; Da Ponte et al., 2017; Tadesse et al., 2014).

Forests in islands are experiencing a significant decline in biodiversity, being particularly affected by several biodiversity erosion drivers

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(Nogué et al., 2017). Azorean forests for instance have been deeply fragmented since human colonization. Up to 95% of forest area was clear in <600 years (Fernández-Palacios et al., 2011; Gaspar et al., 2011, 2008; Triantis et al., 2010). Since then, cleared spaces were filled with intensive and semi-natural pasturelands, forest plantations of exotic trees, agricultural parcels and urban constructions. The remaining forest is now composed of isolated fragments of native and exotic forests. Although some exotic forest fragments support some endemic arthropods species (Tsafack et al., 2021), they are considered unsuitable habitat for most indigenous species. Native forest fragments in the other hand have been indicated by several studies as the ideal habitat for indigenous arthropods species particularly endemic species (Borges et al., 2017, 2020; Ribeiro et al., 2005). Native forests harbour several native trees species to which endemic species are strongly associated (Nunes et al., 2015; Tsafack et al., 2022). Moreover, because most of primary characteristics have been saved, native forests act as physical barriers to colonization of exotic species (Florencio et al., 2016). Therefore, native forests support larger and richer communities of indigenous species (Borges et al., 2008, 2006; Lhoumeau and Borges, 2023a) than any other habitats including exotic forests, pasturelands or other agrosystems.

However, Azorean native forests do not escape the current biodiversity crisis (Boieiro et al., 2018; Cardinale et al., 2012; Terzopoulou et al., 2015; Triantis et al., 2010). Models predicted that 91 % of Azorean indigenous arthropod species will lose their climate space by the year 2100 (Ferreira et al., 2016). In addition, recent studies pointed changes in arthropods species community structure characterized by an increase in abundance and diversity of exotic species over time (Borges et al., 2020).

Ongoing conservation programs of the Ministry of Climate Changes and Environment in Azores Archipelago are taking actions to restore native forest fragments with the implementation of several LIFE projects (LIFE IP NATURA, LIFE BEETLES, LIFE SNAILS). Those actions include the uprooting of alien plants (such as *Hedychium gardnerianum*), and in some mixed forest fragments, the removing of invasive exotic trees (for example Eucalyptus trees). Such management actions from public stakeholders rely on biological indicators that evaluate the biological integrity, conservation state and also the effectiveness of ongoing conservation strategies in ecosystems (Hockings et al., 2000; Nicholson et al., 2012; Stephenson et al., 2022). Biological indicators have been promoted to inform status and trends in biodiversity dynamics with the aim to guide future biodiversity management actions or to measure the impact of actions conducted in sites.

Common biological indicators are community structure estimators – species richness, diversity, dominance, evenness and rarity indexes – which have long been used to assess biodiversity dynamics (Fattorini et al., 2012; Hortal et al., 2006). Yet, those indicators present several disadvantages including their sensibility to sampling effort (Hortal et al., 2006). In addition, single biological indicators fail to capture the complexity of biological assemblages.

Multimetric indexes have been suggested as more accurate, efficient and simple to use indicators because they combine multiple parameters that individually capture different aspect of a system. They have proven their efficiency in several situations. For instance multivariate drought indices were developed in Varol et al. (2023) to monitor and assess the drought. Although most multimetric biological integrity indexes concern freshwater and marine environments (Zhu et al., 2021), few have been developed for terrestrial ecosystems including forested landscapes.

In the path of global biodiversity indicators such as Red List index and Living Planet Index (Nicholson et al., 2012), Cardoso et al. (2007) developed a multimetric biotic integrity index (IBI) to access the capability of Azorean forests in supporting stable epigean arthropod communities. Although Cardoso's index presents many advantages including that it allows the comparison of sites with different sampling efforts and different areas, the index focused on epigean species collected with pitfall traps. Yet, studies showed that insect biomass and richness are sensitive to the type of trap (Busse et al., 2022; Uhler et al., 2022; Work et al., 2002; Yi et al., 2012) and even to the type of preservative solution used in the traps (Kwon et al., 2022). In that sense, Cardoso's IBI might be biased because it ignores other taxa groups, been focused on dwelling species collected with pitfall traps. Moreover, studies showed that the repartition of species was highly stratified (Ali and Yan, 2017; Haack et al., 2022; Yoshida et al., 2021) and therefore unevenly distributed when we consider vertical space, mainly due to habitat structure and variability in plant species composition (Ulyshen, 2011).

In Azorean long-term forest arthropods monitoring programs (Borges et al., 2018; Lhoumeau et al., 2022; Stephenson et al., 2022), three main types of sampling are used – Pitfall traps, canopy beating and SLAM traps – to collect respectively epigean, canopy and large spectrum arthropod communities. These programs aimed at capturing the most complete arthropod assemblages' picture. The three types of samplings allow to incorporate the vertical variability of arthropod species community.

Our primary objective was to create a robust biological index for evaluating forest biotic integrity in both the intermediate stratum (i.e. understory) and canopy stratum, utilizing Cardoso's approach (Cardoso et al., 2007). We employed a combination of parameters related to species biogeographical categories and trophic groups, and identified key ecological parameters that were most affected by site disturbance through principal component analysis. Subsequently, we utilized a binomial generalized linear model to refine and extract the most influential parameters to incorporate into the index. We intend to develop indices of biotic integrity that will be easily handled by forest managers as well as by scientists and easily used as a monitoring tool.

In addition, we investigated how biological integrity in native forest varies along vertical stratification. For this second goal, we used IBI adapted to epigean, canopy and large spectrum arthropod community collected respectively with pitfall traps, canopy beating and SLAM traps. Finally, we compared the biotic integrity indices in native forest fragments of three Azorean islands (Flores, Pico and Terceira). With this approach we aim to demonstrate the utility of a multimetric index to monitor the habitat quality of island arthropod communities based on standardize sampling techniques. This type of indices and their application in monitoring programs are important, considering the current biodiversity crisis and the European Union (EU) Biodiversity Strategy for 2030. Moreover, the ongoing financial investments of the LIFE program for invertebrate conservation also need concrete monitoring tools for species in supporting the recovery of several threatened species and habitats.

The study is innovative and important for three main reasons of general interest: (1) The study highlights the importance of arthropod species community to assess biotic integrity of forest sites filling the gap on forested lands (most multimetric indexes are developed for marine and freshwaters ecosystems) in the literature. (2) The indexes are easy to use and will serve conservation managers to assess biological integrity of forest sites in order to guide biodiversity management strategies in Azorean forest fragments. (3) The methodology can serve as a valuable source of inspiration for the development of arthropod-based IBIs in other islands of the world.

2. Research areas and methods

2.1. Study areas

The Azores is an oceanic archipelago of nine volcanic islands located on the North Atlantic between 37°–40° N latitude and 25°–31° W longitude (Borges et al., 2010). The nine islands are dispersed on a WNW-ESE line extended for about 615 Km. This geographic dispersion divides the nine islands into three groups: the western group with Corvo and Flores, the central group with Faial, Pico, São Jorge, Graciosa and

Terceira and the eastern group with São Miguel and Santa Maria. The archipelago is characterized by a temperate humid oceanic climate with high levels of humidity, up to 95% at high altitudes native forests. The Azores have mild temperature all year around with small fluctuations due to ocean influence. Maximum mean temperature is reached in August, minimum in February and the mean annual temperature is 17 °C (Nunes et al., 2015; Santos et al., 2004).

Landcover is currently dominated by intensively managed pastures and exotic forest fragments. Exotic forests are represented by plantations of *Cryptomeria japonica* D. Don (Cupressaceae) used for forestry, and patches of the invasive *Pittosporum undulatum* Vent. (Pittosporaceae). Native forests are evergreen forests dominated by endemic trees species and shrubs including *Juniperus brevifolia*, *Laurus azorica* and *Erica azorica* – trees and *Vaccinium cylindraceum* – shrub (Nunes et al., 2015; Tsafack et al., 2022). Currently, the past likely most dominant forest type Laurisilva (lowland and sub montane forests, with tall trees) is restricted to some patches at 500–700 m elevation (Elias et al., 2016). The current dominant forest occupies<5% of the original area and is dominated by the *Juniperus*–*Ilex* forests and *Juniperus* woodlands (Elias et al., 2016).

Azores is part of the Mediterranean biodiversity hotspots and as such is monitored through several projects including projects by the Azorean Biodiversity Group on native and exotic forests arthropods. Under long-term monitoring studies (BALA I, II, III, SLAM projects) up to 25 years, arthropods are surveyed using different types of traps and therefore a massive among of data are made available to the public (Borges et al., 2018; Lhoumeau et al., 2022). We used datasets from these databases to build the biotic integrity indices.

2.2. A previous IBI: Epigeal arthropod community

More than a decade ago, in an attempt to measure biological integrity of Azorean native forests for epigean arthropod communities, Cardoso et al., 2007 developed an index of biotic integrity. They built a robust multimetric index with seven taxonomical and ecological parameters of arthropod communities selected among sixteen candidate parameters correlated to environment disturbance. The seven parameters include percentages of (1) endemic species richness; (2) predator abundance; (3) predator species richness; (4) native non-endemic species richness; (5) saprophagous species richness; (6) introduced abundance and (7) herbivore abundance. In addition to their strong relation with disturbance, these parameters were retained due to both, “desirable scalability properties and relatively low correlation between them” (Cardoso et al., 2007). Taking these attributes into account, the IBI is reliable and is not influence by sampling effort. Moreover, the index allows to map the contribution of each metric to the total value of the multimetric integrity index.

Despite the numerous characteristics that made this IBI robust and reliable to assess biological integrity of forests sites, one major limit is that the IBI is restricted for epigean arthropods community, and therefore for ground-dwelling species. Consequently, the IBI will be biased if species communities included other species than ground-dwelling species such as highly mobile species or canopy adapted species.

2.3. Construction of IBI-SLAM and IBI-Canopy

2.3.1. Selecting data sets

To construct the IBI, we used datasets from arthropods surveyed in native and disturbed forests. Arthropods were surveyed using two methods to collect different arthropod communities: a passive flight interception SLAM traps (Sea, Land and Air Malaise traps) for a mixed community species (Borges et al., 2022a; Borges et al., 2022b; Lhoumeau et al., 2022; Tsafack et al., 2021) and beating technique to collect canopy arthropod species (see Borges et al., 2016; Tsafack et al., 2022). Hereafter, we named these communities respectively SLAM-species community and Canopy-species community.

Fourteen sites in native forest fragments and nineteen sites in disturbed forests were selected for the SLAM-species community (see also Tsafack et al., 2021), and twenty-four sites in native forest fragments and fourteen sites in disturbed forests for Canopy-species community. Nomenclature and colonization status of species (endemic, native non-endemic and introduced) are based on the most recent checklist of Azorean arthropods (Borges et al., 2022c).

We used data of arthropods sampled in summer 2019 for consistency with previous IBI calculations (Cardoso et al., 2007). SLAM samples were collected every three months in native forest and six months in disturbed forest. See companion papers (Borges et al., 2018; Tsafack et al., 2021; Lhoumeau et al., 2022) for more details on arthropods sampling and laboratory work for species sorting and identification.

For direct access to the original Terceira Island SLAM data, consult Borges et al. (2022b) for exotic and native forests; Borges and Lhoumeau (2023) for arthropods (excluding spiders); and Borges and Lhoumeau (2023) for spiders. Canopy data can be consulted in Borges et al. (2016).

2.3.2. Determining reference sites

Among sites presented above, we selected those which were representative of each type of forest (i.e. native (preserved) versus exotic (disturbed) forests). The selection was based on Principal Component Analysis (PCA) of arthropod abundances in the different sites. For SLAM-species community, the two first PCA components explained 55.39% of the total variability and the biplot PCA showed five outlier sites (two native and three disturbed forest sites, Fig. 1A) which were excluded. For Canopy-species community, the two first PCA components explained 49.76% of the total variability and the biplot PCA showed seven outlier sites (four native and three disturbed forest sites, Fig. 1B) that we excluded.

2.3.3. Determining candidate parameters

Referring to previous studies in Azores arthropod communities (Borges et al., 2020, 2018, 2006; Florencio et al., 2016; Rigal et al., 2013), we selected in each species community (SLAM and Canopy) the parameters which were sensitive to environmental disturbance. In this study, sensitivity to environmental disturbance is measured with the strength and significance of the candidate parameter response to environmental change, it is the ability of the parameter to discriminate native (preserved) from exotic (disturbed) forest sites. Overall, 16 parameters were retained as candidate parameters for the IBI-SLAM (Table 1) and 14 parameters for the IBI-Canopy (Table 1). For analysis, we used values of parameters as percentages to obtain comparable values between sites.

2.3.4. Testing and screening candidate parameters

We proceeded with a screening using generalized linear modelling (GLM). We computed a GLM for each of the previous candidate parameters (Table 1: 16 for IBI-SLAM and 14 for IBI-Canopy) to test the significance to discriminate native forests from disturbed forests. The forest type range follows binomial distribution with native forest set as 1 and disturbed forest set as 0. GLMs were therefore ran with logit link function following the formula *Type of forest* = *f (parameter)*.

2.3.5. Standardizing and scoring the selected parameters

Among several methods to standardize and score parameters of multimetric indexes, we adopted Cardoso et al. (2007)’s method where parameter values are ranked and the ranges divided in three, corresponding to three discrete scores of 0, 1, 2.

The attribution of scores is based on the sign of the parameter estimates obtained in GLM models during the screening of candidate parameters (Table 2).

When the parameter estimate is positive, score 0 is attributed to the third of the parameter range that most represents disturbed forest sites, score 2 to the third that most represent native forest sites and score 1 to the third in between the previous two thirds. The inverse was done for parameters with negative GLM estimates (Table 2 and 3).

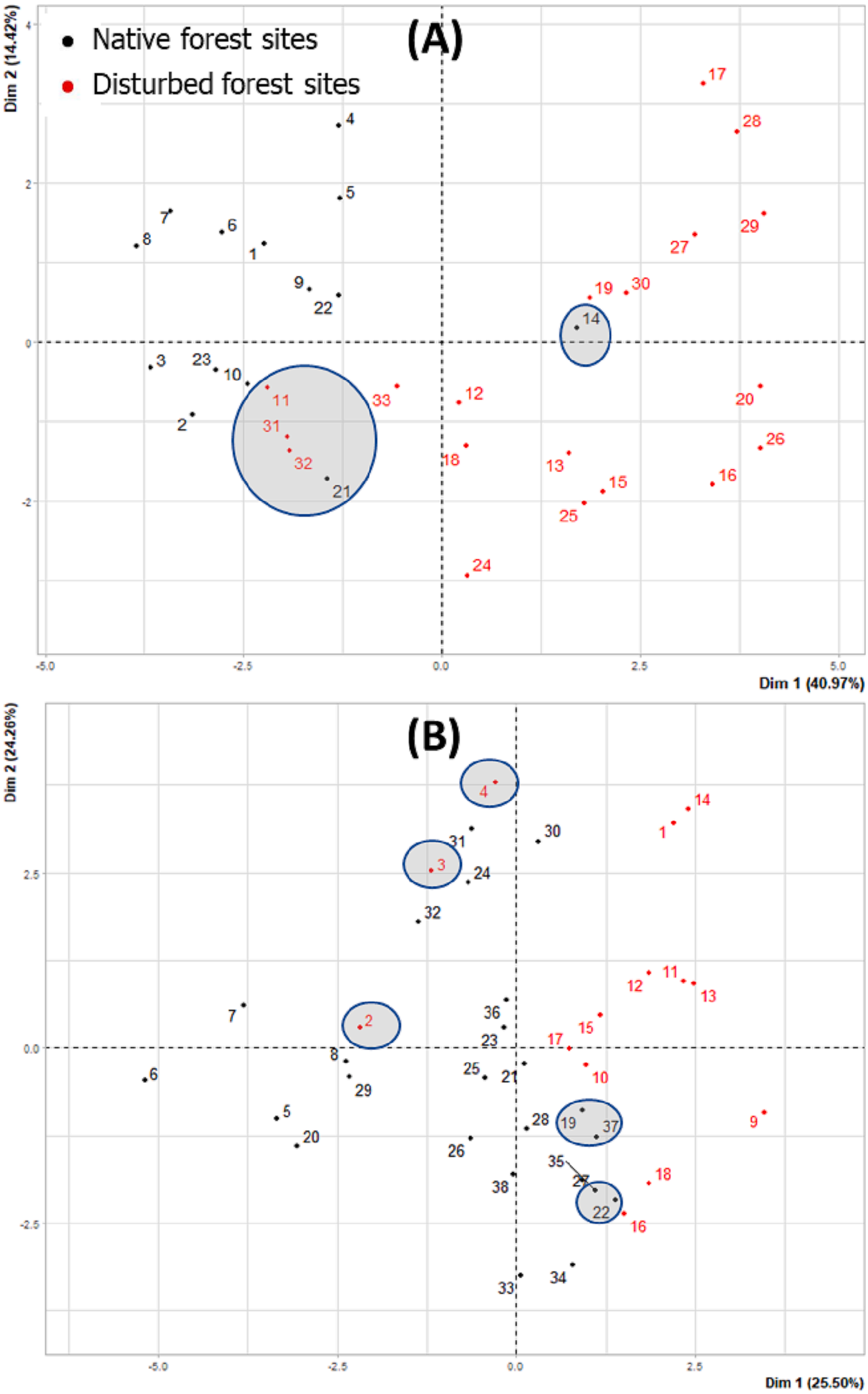

Fig. 1. PCA ordination plots with reference sites for IBI-SLAM (A) and for IBI-Canopy (B). Sites circled in blue were considered outliers and excluded from the reference sites dataset. Five outlier sites in SLAM-species community and seven outlier sites in Canopy-species community. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Candidate parameters sensitive to disturbance used to construct IBI-SLAM (16 parameters) and IBI-Canopy (14 parameters).

Candidate parameters		IBI-SLAM	IBI-Canopy
nFong	Fungivores individuals	x	
sFong	Fungivores species	x	
nHerb	Herbivorous individuals	x	x
sHerb	Herbivorous species	x	x
nPred	Predator individuals	x	x
sPred	Predator species	x	x
nPred/Herb	Generalist individuals	x	
sPred/Herb	Generalist species	x	
nSap	Saprophagous individuals	x	x
sSap	Saprophagous species	x	x
nInt	Introduced individuals	x	x
sInt	Introduced species	x	x
nEnd	Endemic individuals	x	x
sEnd	Endemic species	x	x
nNat	Native non-endemic individuals	x	x
sNat	Native non-endemic species	x	x
nDipl	Diplopoda individuals		x
sDipl	Diplopoda species		x

Table 2
GLM Estimates values of candidate parameters after testing their ability to discriminate preserved from disturbed forests sites. Selected parameters are highlighted in bold for IBI-SLAM and IBI-Canopy.

Parameters	Estimate	St.dev	Z-stat	P-value	Residual Deviance
IBI-SLAM					
sEnd	14.73	5.06	2.91	0.003	19.58
sSap	−58.86	21.87	−2.69	0.007	18.78
nSap	−21.20	8.02	−2.64	0.008	16.87
sNat	22.88	8.81	2.60	0.009	28.63
nEnd	10.97	4.24	2.59	0.009	18.18
nInt	−35.90	14.10	−2.55	0.010	11.62
nNat	−8.28	3.39	−2.45	0.014	29.69
sPred	25.14	10.64	2.36	0.018	29.23
sPred/Herb	−79.30	34.80	−2.28	0.022	31.47
sFong	55.39	26.23	2.11	0.034	32.97
sInt	−29.03	14.06	−2.07	0.038	10.40
nPred	−14.37	8.09	−1.78	0.075	31.47
nPred/Herb	−9.79	6.67	−1.47	0.141	35.39
nHerb	49.21	36.06	1.36	0.172	4.72
nFong	−7.06	12.55	−0.56	0.573	37.90
sHerb	3.72	7.13	0.52	0.602	37.97
IBI-Canopy					
sEnd	0.38	0.14	2.77	0.006	16.85
sNat	−0.24	0.09	−2.62	0.009	28.90
nEnd	0.12	0.05	2.57	0.010	28.04
sInt	−0.32	0.13	−2.56	0.010	28.32
nNat	−0.10	0.04	−2.49	0.013	29.82
nPred	0.04	0.02	1.91	0.056	36.02
sSap	−0.16	0.09	−1.83	0.067	36.16
sPred	0.08	0.05	1.60	0.110	36.89
nDipl	−1.58	1.02	−1.54	0.123	37.80
nSap	−0.08	0.05	−1.50	0.133	37.86
sDipl	−0.30	0.24	−1.27	0.204	38.59
nHerb	−0.02	0.02	−1.15	0.251	38.96
sHerb	−0.04	0.05	−0.80	0.421	39.66
nInt	−0.03	0.06	−0.51	0.608	40.06

The final IBI value is the sum of all parameters scores and ranges from 0 to 14 (Table 3). Sites of poor biological integrity will show an IBI value lower than 5; sites of moderate status, an IBI value between 5 and 10 and sites of good biological integrity will show an IBI value higher than 10 (See Fig. 1S, 2S and 3S for examples).

2.4. *Evaluating IBIs: Case study in three islands*

To test the performance of IBI-SLAM and IBI-Canopy, we investigated the biotic integrity of native forest sites on three islands: Flores, Pico and Terceira (Fig. 2). We aimed at evaluating how accurate were IBI-SLAM and IBI-Canopy and how closer they were to the previous IBI-Epigean. Thus, in order to provide recommendations for forest managers on the choice of vertical compartment (soil, intermediate, canopy) to focus on when assessing the biological integrity of a forest site. To that aim, we compared the vertical variability of IBI on the same site and IBI values between the different islands.

Table 3
Quantitative values for each metric and scores for the IBI-SLAM and for the IBI-Canopy.

Parameters	Score 0	Score 1	Score 2
IBI-SLAM			
%sEnd	<18	18–30	>30
%sSap	>25	20–25	<20
%nSap	>33	14–33	<14
%sNat	<38	38–46	>46
%nEnd	<35	35–63	>63
%nInt	>19	5–19	<5
%nNat	>47	33–47	> 33
IBI-Canopy			
%sEnd	<39	39–49	>49
%sNat	>33	28–33	<28
%nEnd	<53	53–62	>62
%sInt	>24	19–24	<24
%nNat	>40	30–40	<30
%nDipl	>1	0–1	<0.1
%sDipl	>3	2–3	<2

We selected datasets of arthropods surveyed in 2019 using methods (pitfall traps, SLAM traps and canopy-beating) that focus on three vertical strata representing respectively ground-dwelling, mixed, and canopy arthropod species community.

Overall, 12 sites were selected (four in each island, Fig. 2). Pitfall and canopy data for this purpose were obtained during the project BALA III and are part of a large dataset that will be published soon elsewhere (for equivalent BALA 1 and BALA II methodology see Borges et al., 2016). SLAM data can be assessed in Borges and Lhoumeau (2023) for spiders in Flores Island and other arthropods in all the three islands and also in Lhoumeau and Borges (2023b) for spiders in Pico and Terceira islands.

2.5. *Data analysis*

All analysis were performed within R environment (R Core Team, 2022). The principal components analysis (PCA) was performed with FactoMineR package (Lê et al., 2008) to select the sites which were the most representative of a type of forest (preserved versus disturbed). Candidate parameters were analyzed using GLM with MuMIn R package to select parameters which most discriminated preserved forest sites from disturbed forest sites. Boxplots were used to compared IBI values (between islands and between monitoring methods). The significance of differences was assessed using analysis of variances.

3. Results

3.1. *Screening of candidate parameters*

Of the 16 candidates' parameters tested for their discriminatory ability in the SLAM data set, eleven parameters showed significant ($p < 0.05$) responses. For comparison purpose with the previous epigean IBI (Cardoso et al., 2007), we selected the seven parameters which were the most discriminant ($p < 0.02$) to include in the IBI-SLAM. Therefore, the IBI-SLAM was composed of percentages of endemic species (%sEnd), native species (%sNat) and saprophylic species (%sSap), and percentages of endemic individuals (%nEnd), introduced individuals (%nInt), saprophylic individuals (%nSap) and native individuals (%n Nat) (Table 2 IBI-SLAM).

Of the 14 candidates' parameters tested for their discriminatory ability in the Canopy data set, five parameters showed significant (p <

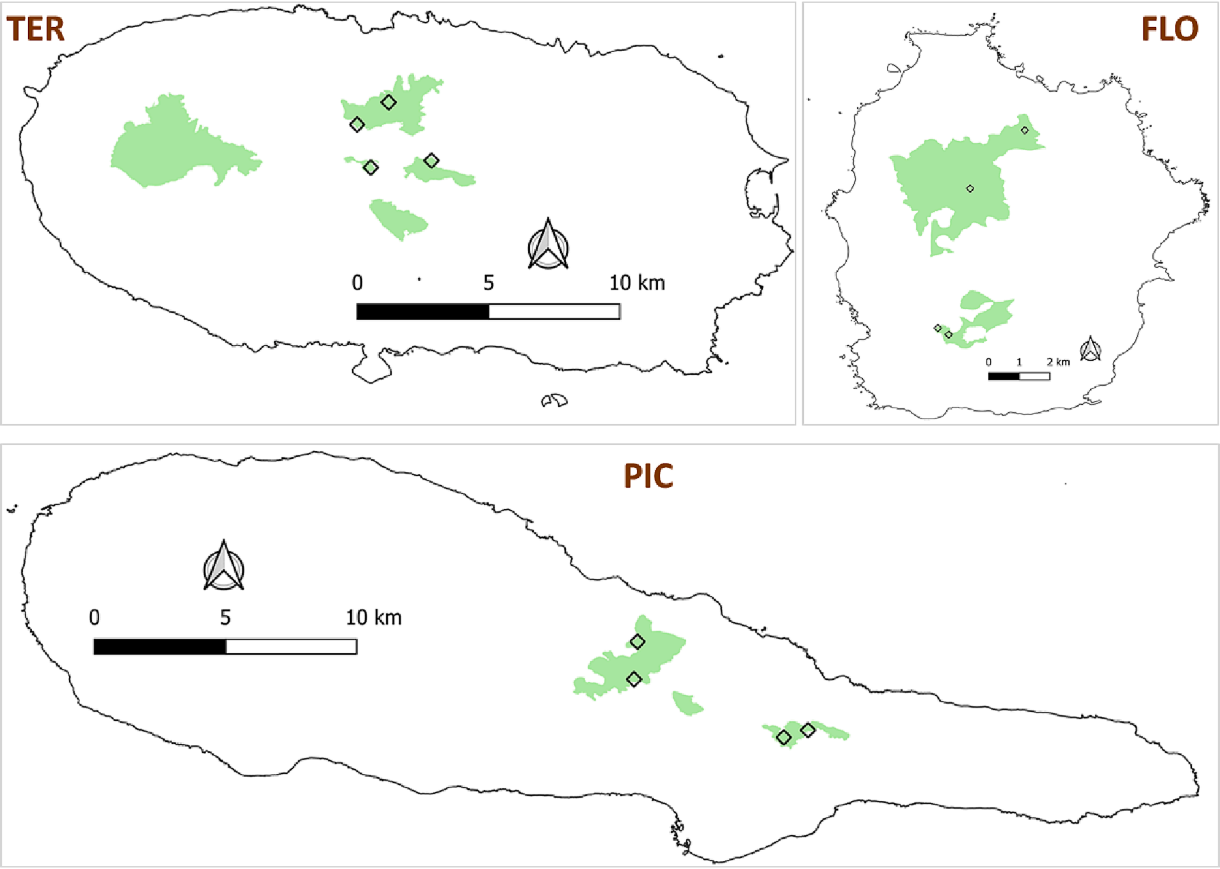

Fig. 2. Location of Islands and sites of the case study testing the use of IBI-SLAM and IBI-Canopy (FLO- Flores, PIC- Pico and TER- Terceira).

0.05) responses. To have the same number of parameters (7) as for the epigean IBI (Cardoso et al., 2007), we selected the five most discriminant ($p < 0.05$) parameters and added the percentage of species richness and abundance of the Diplopoda species (mostly composed by the invasive species *Ommatoiulus moreleti* (Lucas, 1860)) because of their surprising presence in canopy while they are ground-dwelling species (Silva et al., 2008). As a consequence of invasion of native forest, they are equally present in native and disturbed forests. Therefore, the IBI-Canopy was composed of percentages of endemic species (%sEnd), native species (%sNat), introduced species (%sInt) and Diplopoda species (%sDipl), and percentages of endemic individuals (%nEnd), native individuals (%n Nat) and Diplopoda individuals (%nDipl) (Table 2 IBI-Canopy).

3.2. Calculating parameters standards

For IBI-SLAM, resulting from the GLMs, three parameters showed positive estimates (%sEnd, %sNat, %nEnd) and four showed negative estimates (%sSap, %nSap, %nInt, %nNat). Standards for the first parameter were as follows: %sEnd < 18, score 0; $18 >$%sEnd > 30, score 1 and %sEnd > 30, score 2. Standards of the remaining parameters are presented in Table 3 IBI-SLAM.

For IBI-Canopy, two parameters showed positive estimates (%sEnd, %nEnd) and five showed negative estimates (%sInt, %sNat, %nNat, % sDipl, %nDipl). Standards for the first parameter were as follows: %sEnd < 39, score 0; $39 >$%sEnd > 49, score 1 and %sEnd > 49, score 2. Standards of the remaining parameters are presented in Table 3 IBI-Canopy.

3.3. Evaluating biological integrity indices using data matrices from three Azorean islands

IBI between islands were not different whatever the index (Fig. 3A). However, mean values of IBI varied in order Flores < Pico < Terceira and the variance was greater in Flores followed by Pico and Terceira showed the lowest variance (Fig. 3A). Then, considering all islands together, IBI-SLAM showed significant higher values than IBI-Canopy and IBI-Epigeal (Fig. 3B). IBI values at epigeal stratum were lower than Canopy's but the difference was not significant (Fig. 3B).

When we compared the three forest strata for each island, no significant difference was observed (Fig. 4) except in Pico island (Fig. 4 PIC) where IBI-SLAM was significantly higher than IBI-Canopy and IBI-Epigeal indicating that understory stratum is better preserved than ground or canopy strata in Pico island whereas the three strata seem to be similarly preserved in Flores and Terceira (Fig. 4 FLO and TER).

No difference was observed when we compared different islands for the same IBI (Fig. 5), but variance was clearly greater in Flores.

4. Discussion

We developed arthropod based multimetric indices to assess biological integrity (IBI) of Azorean native forests. Knowing that species composition of communities varies with forest strata, we developed two IBI, one describing forest canopy stratum (IBI-Canopy) and the other describing the intermediate stratum (IBI-SLAM) to complement a previous IBI developed for epigeal stratum (IBI-Epigeal) (Cardoso et al., 2007). Biogeographic colonization status origin (Endemic, Native non-endemic and introduced species), trophic group (Predators, Herbivores, Saprophagous), taxonomic richness and abundance were included as parameters to build the multimetric indices. We selected

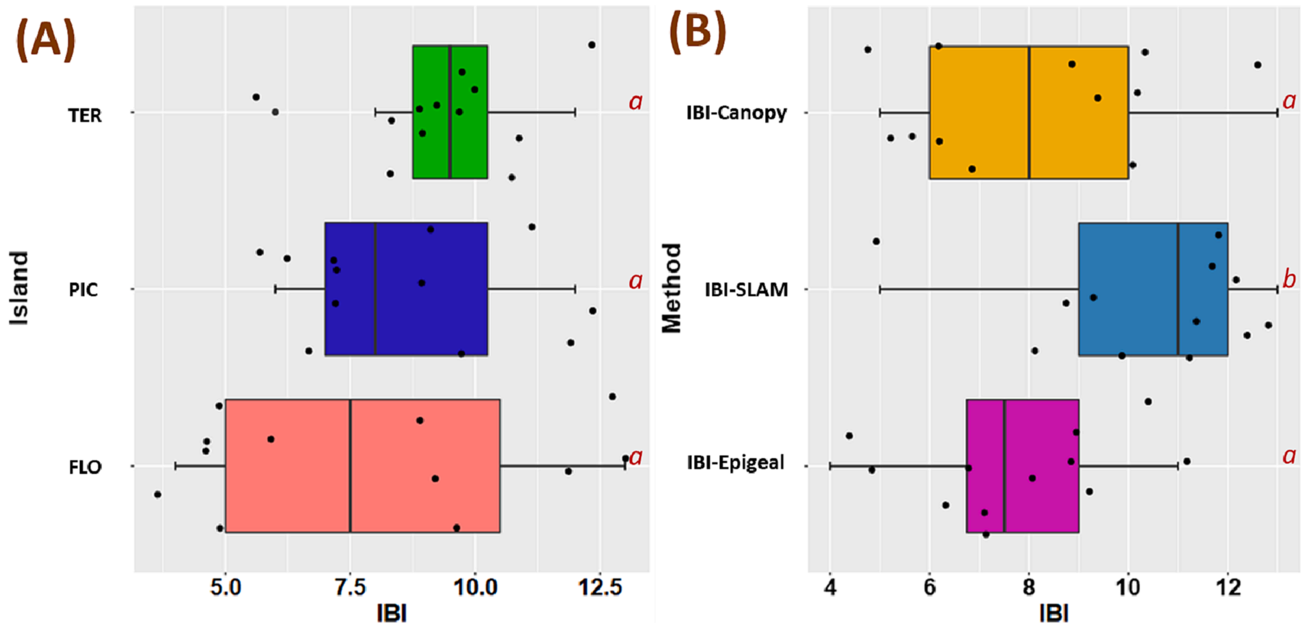

Fig. 3. IBI values for all samples: Comparison between islands ((A) Flo-Flores, PIC-Pico and TER-Terceira)) and between the three forest strata ((B) ground-understory and Canopy strata) for all samples. Different letters above the boxplots indicate significant differences based on the Tukey test ($p < 0.05$). No significant difference was observed between islands (A) but overall IBI-SLAM values were significantly higher than IBI-Epigeal ($P = 0.019$) and IBI-Canopy ($P = 0.045$) (B).

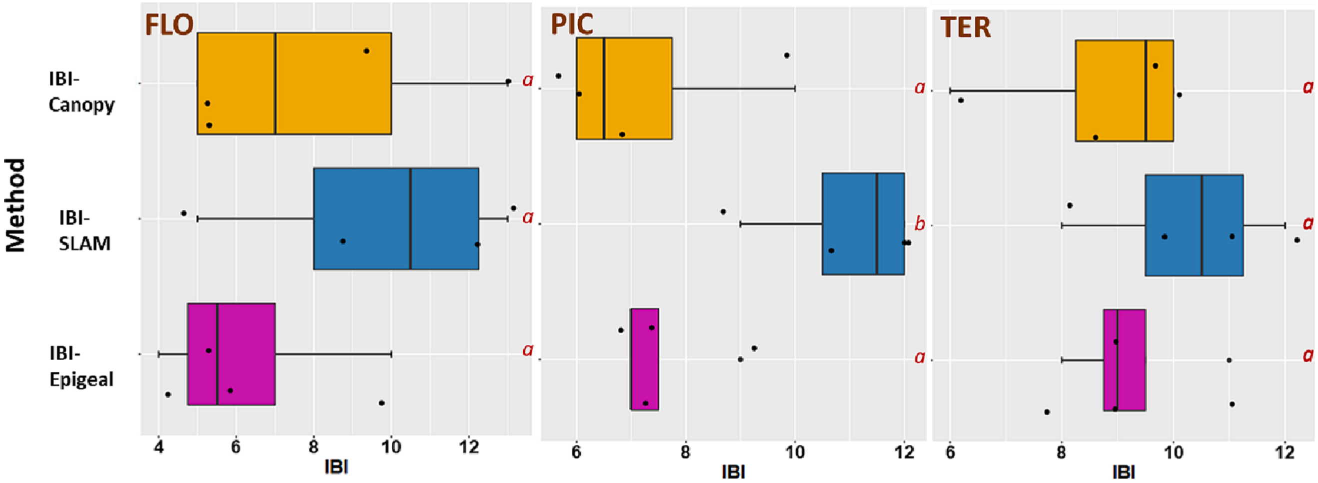

Fig. 4. IBI values in the three islands: Comparison of the three forest strata (methods) in each island (FLO- Flores, PIC- Pico and TER- Terceira). Different letters above the boxplots indicate significant differences based on the Tukey test ($p < 0.05$). No significant difference was observed except in Pico where IBI-SLAM was significantly higher than IBI-Epigeal ($P = 0.02$) and IBI-Canopy ($P = 0.01$).

seven parameters for each index, over 16 candidate parameters for IBI-SLAM and over 14 candidate parameters for IBI-Canopy.

4.1. Construction of IBI-SLAM and IBI-Canopy

Combining previous knowledge on Azorean forests and an ordination analysis, we extracted reference sites which for one group represented near pristine forest sites and for the other disturbed forest sites. For most studies that constructed IBIs (Kane et al., 2009; Wilson et al., 2013; Zhu et al., 2021), reference sites referred to the most preserved sites but, in our study, we found important to represent both preserved and disturbed sites (see also Cardoso et al., 2007). Therefore, all candidate parameters were parameters able to discriminate near pristine forest sites from disturbed forest sites. The final multimetric IBIs included parameters expressing biogeographic colonization status origin, trophic group and taxonomical richness and abundance of species in communities.

Within biogeographic colonization status origin-factors, endemic richness (sEnd) and abundance (nEnd) were selected for both IBIs (IBI-SLAM and IBI-Canopy) and were negatively related to disturbance. The negative relation observed is possibly a consequence of the ecological preferences of endemic species for a complex combination of habitat conditions that are disrupted in disturbed forests: a complete dominance of endemic tree species; a complex cover of ferns in the understory; a dominance of bryophytes covering all strata of the forest including parts of the soil (Gaspar et al., 2008). In disturbed forests invaded by some exotic plants, both the cover of ferns and bryophytes decrease and habitat structure changes dramatically compared to pristine forests. Our finding supports the previous multimetric epigeal IBI which similarly included sEnd (Cardoso et al., 2007) with a negative relation to disturbance. This means that island forest sites with high species richness and abundance of endemic species are efficiently indicative of well-

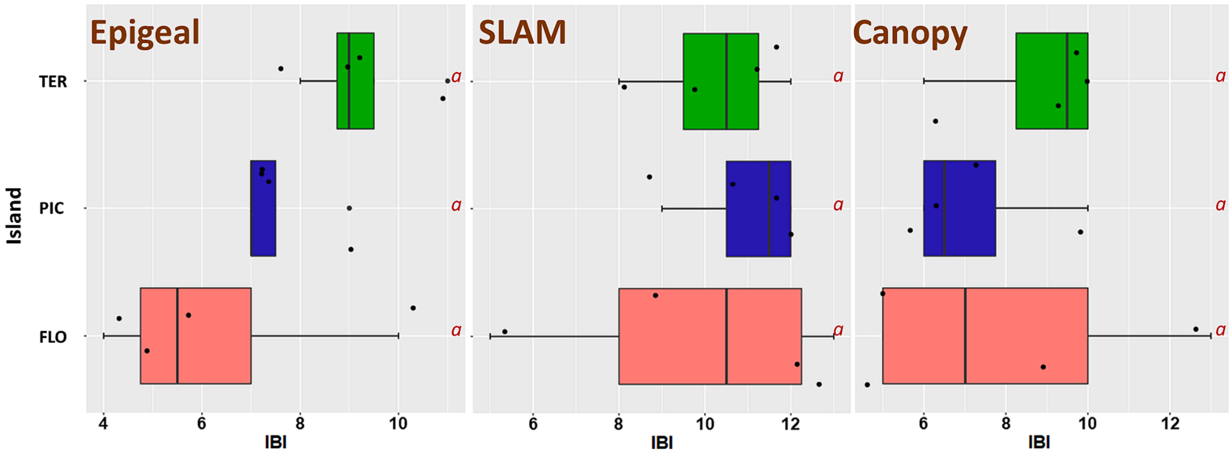

Fig. 5. IBI values at the three forest strata: Comparison of islands (FLO- Flores, PIC- Pico and TER- Terceira) at each forest stratum. Different letters above the boxplots indicate significant differences based on the Tukey test ($p < 0.05$). No significant difference was observed.

preserved forest sites.

Native non-endemic species richness (sNat) and abundance (nNat) were significantly related to disturbance in both strata (canopy and intermediate strata) and were therefore included in the multimetric IBIs. However, the sign of the relation with disturbance varies with the strata considered. In canopy stratum (IBI-Canopy) we found that sNat and nNat increased with disturbance. This is surprising because native non-endemic arthropod species are usually related to naturalness of sites (Cardoso et al., 2009; Florencio et al., 2016; Florencio et al., 2013) and showed high fidelity to sites of least disturbed native forest (Florencio et al., 2016). However, it has been suggested that some generalist native non-endemic species are well installed in disturbed forest sites (Tsafack et al., 2021) contrary to specialist species which are less tolerant to environmental changes. For the IBI-SLAM, parameter nNat was also positively related to disturbance whilst sNat was negatively related to disturbance. Regarding the response of abundance of native non-endemic species (nNat), the same explanation as at canopy stratum may be applied at this intermediate stratum. But regarding sNat, the hypothesis that native non-endemic arthropod species are strongly imbedded to native plant species present in preserved sites is validated.

As expected, parameters related to introduced species (sInt and nInt) were positively related to disturbance. Unlike indigenous species, introduced species were more abundant and richer in exotic forest because they are more tolerant to environmental changes (Cardoso et al., 2007, 2009; Meijer et al., 2011; Tsafack et al., 2021). Indeed, sInt was included in IBI-Canopy and nInt was included in IBI-SLAM.

Within factors related to trophic group, species richness (sSap) and abundance (nSap) of saprophagous were positively related to disturbance and included in IBI-SLAM. This finding is also similar to previous epigeal IBI (Cardoso et al., 2007) in which saprophagous species richness was also positively related to disturbance. Although studies showed that saprophagous species communities tend to flourish in stable systems characterized with stable abiotic factors, saprophagous species communities in Azorean forest are mostly introduced species with high capacity of invasion which ease their access in native as well as in exotic forest fragments. Species richness of predators and fungivores in SLAM community were negatively related to disturbance but they were not included in the index because they were ranked after the seven parameters included in the multimetric index. Trophic group variables seem to be less important than biogeographical colonization status indicators at canopy stratum and were not included in the IBI-Canopy.

Although parameters Diplopoda species richness (sDipl) and abundance (nDipl) did not significantly discriminate near pristine sites from disturbed, we added them in IBI-Canopy because of their surprising presence in canopy while they are ground-dwelling species. In addition, we found that the invasive saprophagous Diplopoda species *O. moreleti* which is characteristic of disturbed habitats dominated canopy samples. For these reasons, we added sDipl and nDipl in IBI-Canopy index with a negative sign to correlate their ecological feature. The invasive species *O. moreleti* is also currently spreading in native Laurel forests of Canary Islands (Pedro Oromí, pers. Com.) and can be used as an early indicator of disturbance within arthropod communities in Macaronesian archipelagoes.

4.2. Case study: Comparing islands and strata using IBI-Canopy and IBI-SLAM

We used a database of arthropods species sampled in different strata in three islands with different forest conservation status to test the reliability of biotic integrity indices. We investigated and compared biological integrity between strata (canopy, intermediate and epigeal strata) and between islands.

Our results indicate that biological integrity was better in canopy and ground strata, suggesting that canopy and ground-dwelling species communities may have detected habitat degradation earlier than those at the intermediate stratum (SLAM-community). Therefore, among the three strata, intermediate stratum seems to be the last compartment to reflect disturbances, or alternatively, exotic species are less efficiently sampled with SLAM traps (see also below). We may consider that forest vertical stratification of species diversity (de Souza Amorim et al., 2022; Haack et al., 2022; Ulyshen, 2011) explain this difference of sensitivity to disturbance. Insect communities at ground level can be richer than upper level communities (Preisser et al., 1998), but this does not hold for Azorean arthropod forest communities (Borges et al., unpublished data). In a mainland German forest, Haack et al. (2022) observed that ground stratum might be richer than upper stratum for common species but when considering rare species group the inverse occurs. In the current study, intermediate stratum which was sampled using SLAM (sea-land-air malaise trap) is composed of a unique mixed of upper and low stratum species communities and it is possible that species composing this intermediate community are not uniformly sensitive to disturbance, therefore blurring potential response of individual species. SLAM trap catches both high dispersive Azorean endemics adapted to canopy native forests, epigean species crawling up the trap and understory adapted species. Possibly, introduced species are not dominating the combination of these three sources of fauna sampled with SLAM traps.

The vertical stratification of IBI values was particularly highlighted in Pico Island whereas the three strata were similar in Flores and Terceira Islands. When the three strata where pooled, no significant difference was observed between islands. This shows that pooling strata communities hide stratum specific signal, which produce inaccurate evaluation of site biological integrity, stressing the singularity of strata within the same forest site. However, although not statistically significant, IBI values in Flores sites were the lowest with the highest variance between sites. This observation supports conclusions of previous studies that placed Flores forest fragments as the least preserved forest in the Azorean archipelago (Borges et al., 2011).

4.3. IBI-SLAM and IBI-Canopy in the path of multimetric indices

Attempts to assess the quality of ecosystems rely on multimetric indices such as index of biotic integrity (IBI). The popularity of IBI started in freshwaters and marine ecosystems with the need to assess waters quality (Karr, 1981; Karr et al., 1986) after multiple episodes of pollution. IBIs present numerous virtues such as capturing the complexity of sites by including many parameters that considered individually fail to present the complexity of ecosystem functioning.

The IBIs developed in this study are interesting in many ways. First, they exposed the fact that some parameters if considered individually might mislead the comprehension of ecosystems. For instance, abundance of native non-endemic species which was surprisingly positively related to disturbance. Second, our study reveals the need to adapt the IBI to the forest vertical compartment supporting studies that showed a stratification of community assemblages (Haack et al., 2022; Ulyshen, 2011; Yoshida et al., 2021). Third, our methodology has successfully been developed and tailored to the unique arthropod communities found in the Azores forests. While it may not be suitable for random forest sites, it can serve as a valuable source of inspiration for the development of arthropod-based IBIs in other islands of the world. For island systems for which it is possible to categorize species in the colonization status endemic versus introduced species, we demonstrate that these two indicators can be highly reliable as part of a conservation based multimetric index.

5. Conclusion

The main goal of EU-wide biodiversity strategy is to establish protected areas for at least 30% of land in Europe. The objective is unreachable without efficient assessment tools. Moreover, it is critical to monitor island forest biota (Borges et al. 2018). We developed IBIs for conservation managers to assess biological integrity of forest sites in order to guide biodiversity management strategies in Azorean forest fragments. IBIs are based on arthropods and consider the stratification of species assemblages for more accurate decisions.

CRediT authorship contribution statement

Noelline Tsafack: Conceptualization, Formal analysis, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **Sébastien Lhoumeau:** Data curation, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. **Alejandra Ros-Prieto:** Data curation, Writing – review & editing. **Loic Navarro:** Writing – review & editing. **Timea Kocsis:** Writing – review & editing. **Sónia Manso:** Writing – review & editing. **Telma Figueiredo:** Writing – review & editing. **Maria Teresa Ferreira:** Funding acquisition, Investigation, Writing – review & editing. **Paulo A.V. Borges:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.110592.

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