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Ferns and Lycophytes as new challenges

Richness of ferns and lycophytes from Tijuca National Park, an urban forest

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Abstract
Tijuca National Park (TNP) covers an area corresponding to 3.5% of the city of Rio de Janeiro. It is an Atlantic Rainforest fragment with peaks and watersheds that make this protected area a mosaic of habitats. It is composed of four subunits: Serra da Carioca, Pedra Bonita and Pedra da Gávea Inselbergs, Tijuca Forest, and the Pretos Forros/ Covanca Considering the importance of conserving biodiversity in rainforest fragments, such as those found in Tijuca National Park and its subunits, we analyzed the spatial distribution of species in relation to climatic factors that could impact species richness. In addition to floristic analysis, we provide details of endemism, conservation status, substrate and habitat preferences, as well as data on geographic distribution patterns for each species. Precipitation during the wettest month was shown to be one of the most important climatic features in the study area and may be related to floristic richness and composition. The TNP holds about 38.5% of known species in the state of Rio de Janeiro with 254 taxa distributed in 26 families and 83 genera. Floristic richness can be impacted by environmental variables, including climatic factors. Our results show that relating floristic richness to environmental variables can be a way to understand biodiversity.
Key words: Atlantic Forest, climatic factors, endemic and endangered species, environmental variables, floristic composition.

Resumo
O Parque Nacional da Tijuca ocupa uma área correspondente a 3,5% da cidade do Rio de Janeiro. É um fragmento de Mata Atlântica com picos e bacias hidrográficas que fazem desta área protegida um mosaico de habitats. É composto por quatro subunidades: Serra da Carioca, Pedra Bonita e Pedra da Gávea Inselbergs, Tijuca Forest, e Pretos Forros/ Covanca. As espécies foram analisadas quanto à sua distribuição espacial, relacionando-as com os fatores climáticos que poderiam afetar a riqueza. Além disso, fornecemos comentários sobre o endemismo, estado de conservação das espécies, uma análise florística e dados sobre os padrões de distribuição geográfica. A precipitação do mês mais chuvoso foi uma das características ambientais mais importantes para essas áreas e pode estar relacionada à similaridade florística entre elas. O Parque Nacional da Tijuca detém cerca de 38,5% das espécies conhecidas para o estado do Rio de Janeiro, com 254 taxa, distribuídos em 26 famílias e 83 gêneros. Os nossos resultados mostram que, relacionar a riqueza florística às variáveis ambientais, pode ser uma caminho para o entendimento da biodiversidade..
Palavras-chave: Mata Atlântica, fatores climáticos, espécies endêmicas e ameaçadas, variáveis ambientais, composição florística.

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Introduction

Several authors have highlighted the importance of mountains in maintaining the diversity of tropical ferns (*e.g.*, Barrington 1993; Weigand *et al.* 2020), and mountain hotspots harbor a wide range of environmental niches (Suissa & Sundue 2020). On a global scale, plant diversity hotspots are well established. However, identifying them in smaller localities is critical to the effective conservation of plants, both globally and locally (Murray-Smith *et al.* 2009). Climate is known to determine the distribution pattern of species on a global scale, but on a local scale, different factors can also act on floristic composition (Tuomisto *et al.* 2019). For example, studies show that fern richness along the elevational gradient is driven by temperature- and precipitation-related parameters combined, and for low elevations, seasonal precipitation variability is the strongest determinant of fern species richness (Qian *et al.* 2022). The Brazilian Atlantic Rainforest is a hotspot with high endemism compared to the total number of endemic plants worldwide; accordingly, it is included as priority area for conservation (Myers *et al.* 2000). In Brazil, 1,467 taxa of ferns and lycophytes are known, and 37.1 % of these are endemic ("Ferns and Lycophytes" in Flora e Funga do Brasil 2023, continuously updated). The Atlantic Rainforest is the richest phytogeographic domain with 945 species; of these, 643 occur in the state of Rio de Janeiro ("Ferns and Lycophytes" Flora e Funga do Brasil 2023, continuously updated).

Studies reporting on flora from the state of Rio de Janeiro began in the 18th century. For example, Raddi made numerous collections in Rio de Janeiro and published the first results on ferns for Brazil, including *Synopsis Filicum Brasiliensium* (1819) and *Plantarum Brasiliensium Nova Genera et Species Novae* (1825), collections that were later revised by Pichi-Sermolli & Bizzarri (2005). Other historical records were *Flora Fluminensis* (Vellozo 1825, 1827, 1881) and *Flora brasiliensis*, by Martius (1840–1906). Since then, different approaches, such as checklists or taxonomic and floristic studies have been done (*e.g.*, Rizzini CT & Bartram-Wunn E (1954); Brade 1956; Sylvestre 1997a, b; Mynssen & Windisch 2004; Coelho *et al.* 2017). In Tijuca National Park, Bicalho & Mynssen (2020) prepared a script and photographic guide for a didactic activity with species of ferns and lycophytes along the Student Trail, but the richness of ferns has not yet been studied. Furthermore, studies correlating the floristic richness of ferns with environmental variables are lacking in the state of Rio de Janeiro.

The city of Rio de Janeiro has the largest and oldest protected urban forest area within its perimeter known as Tijuca National Park (CNUC 2020). In the 18th century, part of this forested area was used for agricultural activities, causing problems in the city's water supply. For this reason, a restoration project was started in some areas that are currently within Tijuca National Park (Drummond 1988). This restoration project has been successful in using native and exotic species and promoting the natural regeneration of the forest (Freitas *et al.* 2006). The relief, with steep walls, peaks, and tables, interspersed by forest remnants and watersheds, makes this area a mosaic of habitats directly correlated with the high endemism observed there. Tijuca National Park is composed of four subunits: Serra da Carioca, Pedra Bonita and Pedra da Gávea Inselbergs, Tijuca Forest, and Pretos Forros/Covanca. Their geomorphological characteristics, humidity, and waterfalls are distinct (Siqueira *et al.* 2013; ICMBio 2008). Previous works have considered these subunits to be contiguous; indeed, physical proximity of the TNP's subunits cannot be disputed. Nonetheless, we hypothesize that the areas are different in climatic and topographic terms and that this is reflected in the composition and richness of fern and lycophyte species. In this study, we explored the relationships between species richness and environmental factors in each subunit and concluded that some environmental variables influence species richness and composition. We also provide a checklist of ferns and lycophytes, highlighting endemic, endangered, or rare species.

Material and Methods

Study sites

Tijuca National Park (TNP), created in 1961, covers an area of 39.51 km^2 and is inserted within the urban perimeter that encompasses the city of Rio de Janeiro (22°55'–23°00'S and 43°12'–43°19'W) where elevations vary from 80–1,021 m (ICMBio 2008). The TNP belongs to the Tijuca Massif, which is located in the eastern part of the city, which is situated in the state of Rio de Janeiro on the Atlantic coast. It includes more than 60 springs and 36 hydrographic basins (Siqueira *et al.* 2013). According to Köppen's Cf-type, the climate is humid and tropical in the upper mountainous ranges, whereas the climate in the mid-to-lower portions meets the criteria of Köppen's Am-type with total precipitation ranging from 1,300–3,000 mm annually (Coelho-Netto *et al.* 2007). Rocky substrate dating from the Precambrian age is constituted predominantly by different gneisses (microcline, biotite, and granitoid) and some granite intrusions (Fernandes *et al.* 2006). The vegetation is characterized as Dense Ombrophilous Forest in an advanced stage of regeneration, forming fragments of the original biome of the Atlantic Forest.

Currently, this protected area is composed of four subunits: Serra da Carioca - 17.28 km^2 (SC), Pedra Bonita and Pedra da Gávea Inselbergs - 2.5 km^2 (BG), Tijuca Forest - 14.73 km^2 (TF), Pretos Forros/Covanca - 5 km^2 (FC) (Fig. 1). Serra da Carioca is a continuous area formed by an alignment of peaks with the Dona Marta and Corcovado hills to the east end and the Pedra Bonita and Gávea Inselbergs to the west end of the mountain range. The Tijuca Forest area has several waterfalls, caves, and the two highest peaks of TNP, Pico da Tijuca (1,021 m) and Bico do Papagaio (989 m). The subunits Pretos Forros (483 m) and Covanca (267 m) are foothills on the north face of Tijuca Massif. Having less studied flora, these foothills, which are surrounded by local communities and slums, represent the most disturbed sectors of the TNP.

Experimental design

Around 2,150 specimens were consulted and verified from the following virtual herbaria: INCT - Virtual Herbarium of Flora and Fungi (speciesLink Network - Herbário Virtual da Flora e dos Fungos - specieslink.net) and Reflora - Virtual Herbarium (<http://reflora.jbrj.gov.br/reflora/herbarioVirtual>). Through these databases, we consulted the following collections: ALCB, ASU, B, BHCB, CESJ, FCAB, FLOR, GUA, HB, HUCS, HUEFS, IAC, ICN, IPA, K, MBM, MO, NY, P, PACA, R, RB, RBR, RFA, SJRP, SPF, UB, UEC, UFP, UPCB, US, and W (acronyms according to Thiers, continuously updated). Additionally, all collections of GUA, HB, R, RB, RFA, and RBR herbaria were analyzed. Field trips were carried out to complement the sampling, and all specimens with localities were georeferenced for accuracy by point or collection site. A total of 1,366 records of specimens were georeferenced (Fig. 1). Specimens whose identification could not be verified were excluded from the list. We followed Fiaschi & Pirani (2009) for geographical distribution patterns. For endemism and conservation status of species, we followed Martinelli & Moraes (2013), Martinelli *et al.* (2018), and "Ferns and Lycophytes" in Flora e Funga do Brasil 2023 (continuously updated). Substrate and habitat preferences were verified for each species considering terrestrial (including scandent), rupicolous, epiphytes, facultative epiphytes, and hemiepiphytes.

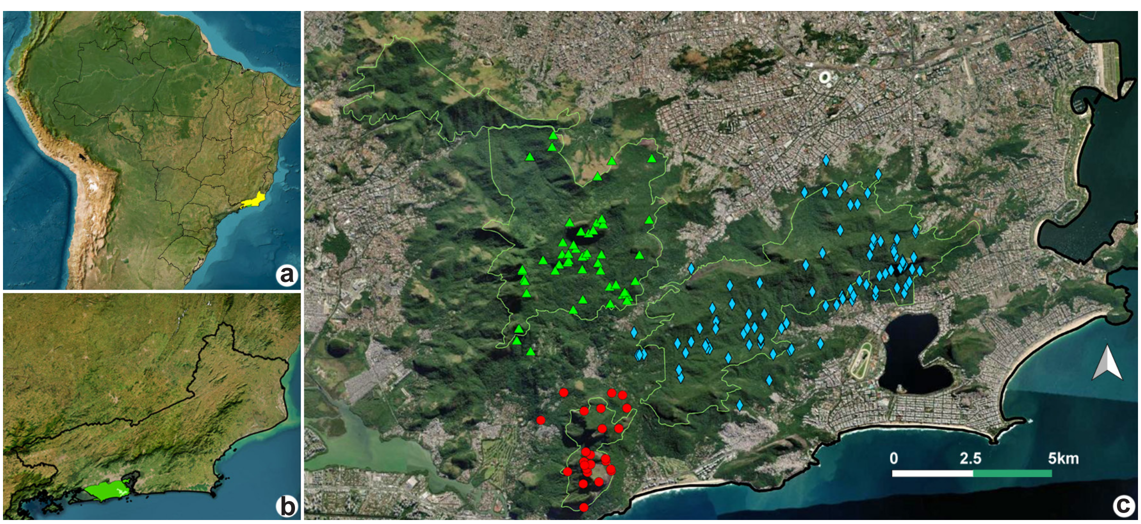

Figure 1 – a-c. Map of the study area of TNP – a. showing Brazil; b. showing the state and city of Rio de Janeiro; c. the city of Rio de Janeiro showing TNP sectors by solid green line and plots with the sampling units for each sector: red dots for Pedra Bonita and Gávea (BG), green triangles for Tijuca Forest (TF), blue diamonds for Serra da Carioca (SC), and Preto Forros/Covanca without dots (FC).

Environmental analyses

We chose to spatialize the data using a 1 km^2 resolution grid to capture at least one record per pixel since we did not have the exact precision of the individual collection point of the total samples. Therefore, we used 57 pixels with species records to extract values of environmental factors from 19 climatic variables from Worldclim 1.4 (Hijmans *et al.* 2005) and three topographic variables (altitude, drainage density, and exposure). A PCA (Principal Component Analysis) was used to summarize the main characteristics of the dataset to analyze the variance or internal structure of the total observed distribution, considering the total area of Pedra Bonita and Pedra da Gávea, Tijuca, and Serra Carioca. Then we reduced the dimensions by selecting the variables with the highest scores within the main dimensions and those with the lowest collinearity values among them to compare the areas in terms of these variables through a boxplot graph. Pretos Forros and Covanca were excluded since they had no representative collections. These analyses were performed using the factoextra R package v. 1.0.6 (Kassambara & Mundt 2017) and R Base Graphs v. 4.2 (R Core Team 2021) for box plots in the RStudio environment.

Results

Tijuca National Park has a total of 254 taxa recorded among ferns and lycophytes, and they are distributed in 26 families and 83 genera (Tab. S1, available on supplementary material <https://doi.org/10.6084/m9.figshare.24459877.v1>; Figs. 2-4). This corresponds to 38.5 % of the total number of species recorded in the state of Rio de Janeiro. Three families were richest in the number of genera and species: Dryopteridaceae (11 genera and 36 spp.), Pteridaceae (9 genera and 36 spp.), and Polypodiaceae (9 genera and 29 spp.). These three families, plus Aspleniaceae (24 spp.) and Hymenophyllaceae (19 spp.), represent more than 56% of all species found in the TNP (Fig. 2). The following genera had the greatest richness: *Asplenium* (24 spp.), *Anemia* (15 spp.), *Pteris* (12 spp.), *Cyathea* (11 spp.), *Elaphoglossum* (9 spp.), and *Selaginella* (10 spp.). Analyzing each protected subunit, Serra da Carioca was the richest (80.9%), followed by Tijuca Forest (68.1%). Pteridaceae was the richest family for all areas, and Polypodiaceae was second in number of species, except in the Serra da Carioca where Dryopteridaceae was the second richest. Pretos Forros and Covanca are represented by ten species most of which were collected between the 1960s and 1970s, and low sampling of this area is related to limited access to these areas for security reasons.

Geographic analysis revealed 92 distribution patterns exclusive to Brazil (36%), 81 exclusive to the neotropics (32%), 56 broadly distributed patterns in South America (22%), 18 with pantropical distribution (7%), and 5 endemics from the state of Rio de Janeiro (Tab. S1, available on supplementary material <https://doi.org/10.6084/m9.figshare.24459877.v1>). Substrate and habitat preferences were verified for each species and showed a predominance of terrestrial species (70–77%), followed by epiphytes (15–22%), facultative epiphytes (4–5%), hemiepiphytes (1–2%), and rupicolous (2–3%) (Fig. 3). Families with the greatest substrate variability and preferred habitats were Aspleniaceae, Hymenophyllaceae, and Polypodiaceae distributed among the three areas of TNP. Among species analyzed within TNP, a total of seven were identified as threatened, including three classified as vulnerable (VU), three as endangered (EN), and one as critically endangered (CR). *Anemia blechnoides* (VU), *Lytoneuron tijucanum* (EN) and *Pteris congesta* (EN) are found in Serra da Carioca, Tijuca Forest, and Pedra Bonita and Pedra da Gávea Inselbergs. *Anemia gardneri* (VU), *Asplenium cariocanum* (EN), and *Doryopteris rediviva* (VU) occur in Serra da Carioca and Tijuca Forest. *Lytoneuron quinquelobatum* (CR) is exclusively present in Tijuca Forest (Tab. S1, available on supplementary material <https://doi.org/10.6084/m9.figshare.24459877.v1>).

For all areas, environmental spatial analysis shows that climatic and topographic variables explain about 84% of environmental variation. Dimension 1 and 2 explain 67.7% and 16.4% of the variation, respectively (Fig. 5). An overlap of environmental conditions was observed among the areas, most strongly between Serra Carioca and Pedra Bonita and Gávea (Fig. 5). The following variables presented the highest contributions in dimension 1: minimum temperature of coldest month (bio6), mean temperature of coldest quarter (bio11), mean temperature of driest quarter (bio9), annual mean temperature (bio1), mean temperature of warmest quarter (bio10), precipitation of warmest quarter (bio18), precipitation of wettest quarter (bio16), maximum temperature of warmest month (bio5), annual precipitation (bio12), and seasonal temperature (bio4) (Fig. 5). For dimension 2, precipitation of driest quarter (bio17), precipitation of driest month (bio14), seasonal precipitation (bio15), and precipitation of coldest quarter (bio19) showed the highest contributions with bio17 and bio19 having less collinearity (Fig. 5).

A comparison of selected environmental variables among the three areas (Fig. 6) showed that Serra da Carioca has the lowest altitude (Fig. 6a) and the least drainage density (Fig. 6f). Tijuca Forest has the lowest average annual temperatures (Fig. 6b), the highest values of precipitation, precipitation of driest month, and drainage density (Fig. 6c-d,f). Pedra Bonita and Gávea are the only subunits with a difference in exposure (Fig. 6e).

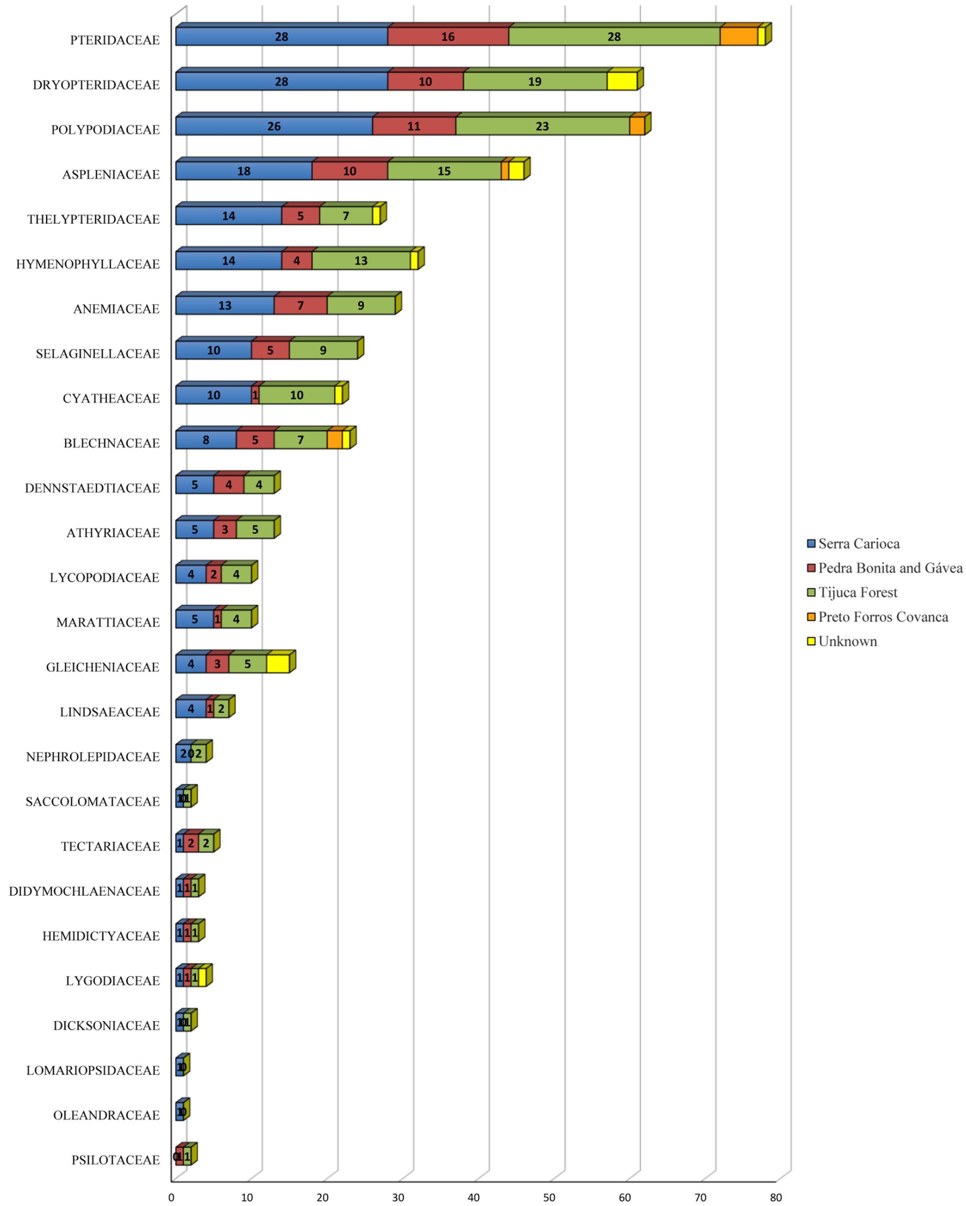

Figure 2 – Ferns and lycophytes in TNP, showing families with species number, where blue indicates Serra da Carioca, red indicates Pedra Bonita and Gavea, green indicates Tijuca Forest, orange indicates Preto Forros/Covanca, and yellow indicates unknown locality.

Discussion

Floristic analysis

The distribution and richness of species in the four TNP subunits are not homogeneous. Among the factors related to this difference, we include size of the areas, their fragmentation, the sampling effort, and the heterogeneity of habitats. This can be seen when comparing the list of species by TNP subunit. Serra da Carioca is the richest area in species (81.1%), and it also has the highest number of specimens collected. Tijuca Forest is second in species number (68.5%) and consists of a set of mountains towards the continent with waterfalls, caves, and the two highest peaks, Pico da Tijuca and Bico do Papagaio. Pedra Bonita and Gávea Inselbergs (94 spp.) are the smallest areas of the TNP, and their foothills are surrounded by slums and buildings that continuously expand towards the forest. The latter point is highlighted because human activity is recognized as one of the most important causes of habitat fragmentation. For example, studies in a Japanese urban forest showed that the diversity of ferns is dependent on patch area and the isolation distance (Murakami *et al.* 2005). Also, human alterations of the landscape cause a phenomenon known as "urban heat island", reducing species diversity by drying forest floors (Ohashi & Kida 2002). The subunits of TNP are considered contiguous areas of forest that preserve original forest fragments. However, both demographic growth and expanded urbanization are affecting some areas and can impact and reduce the diversity of fern flora.

Pteridaceae, Dryopteridaceae, and Polypodiaceae are always among the richest families in floristic surveys of dense rain forests (*e.g.*, Matos *et al.* 2010, 2020; Nóbrega *et al.* 2016; Mazziero *et al.* 2015; Coelho *et al.* 2017; Mynssen & Windisch 2004). A study on floristic diversity in the state of Rio de Janeiro shows that the municipality of Rio de Janeiro is third richest in the number of species of ferns and lycophytes (Coelho *et al.* 2017). Tijuca National Park holds 38.5 % of the species known in the state of Rio de Janeiro, which is considered the third largest state in richness and endemism of fern species (Tryon

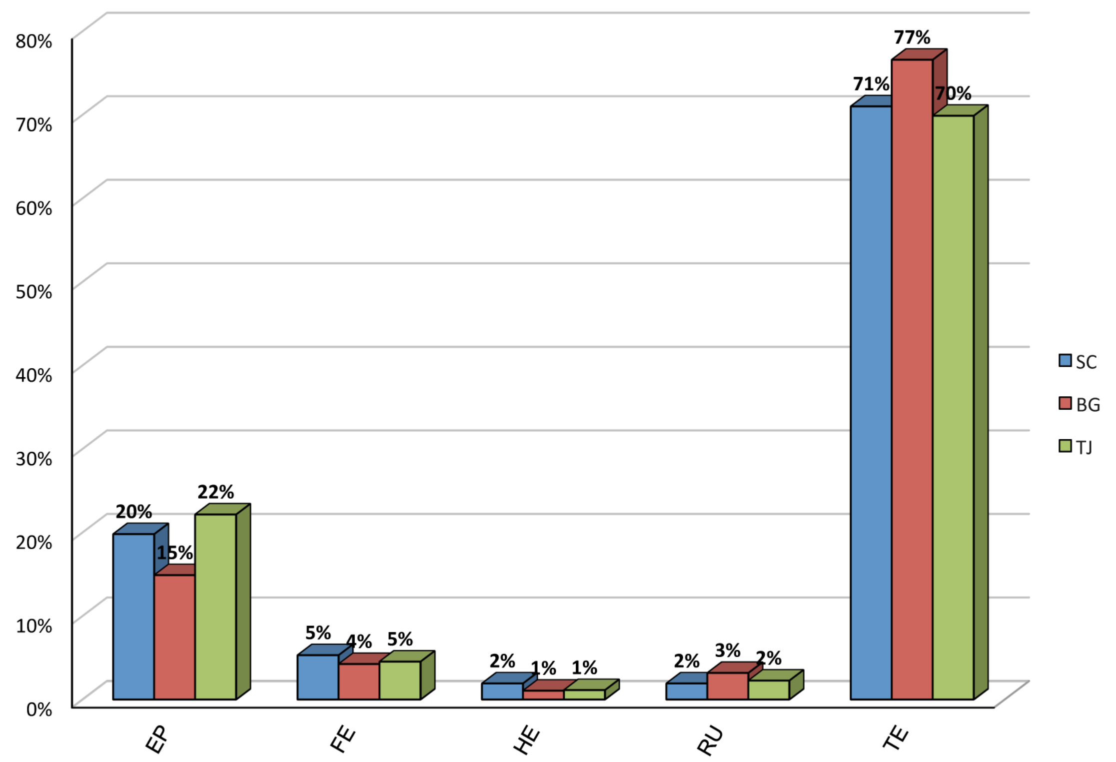

Figure 3 – Variation in substrate and habitat preference of species occurring in three areas of TNP, including Pedra Bonita and Gávea (BG), Tijuca Forest (TJ) and Serra Carioca (SC), along with corresponding substrate (SUB): epiphyte = EP; facultative epiphyte = FE; hemiepiphyte = HE; rupicolous = RU; terrestrial = TE.

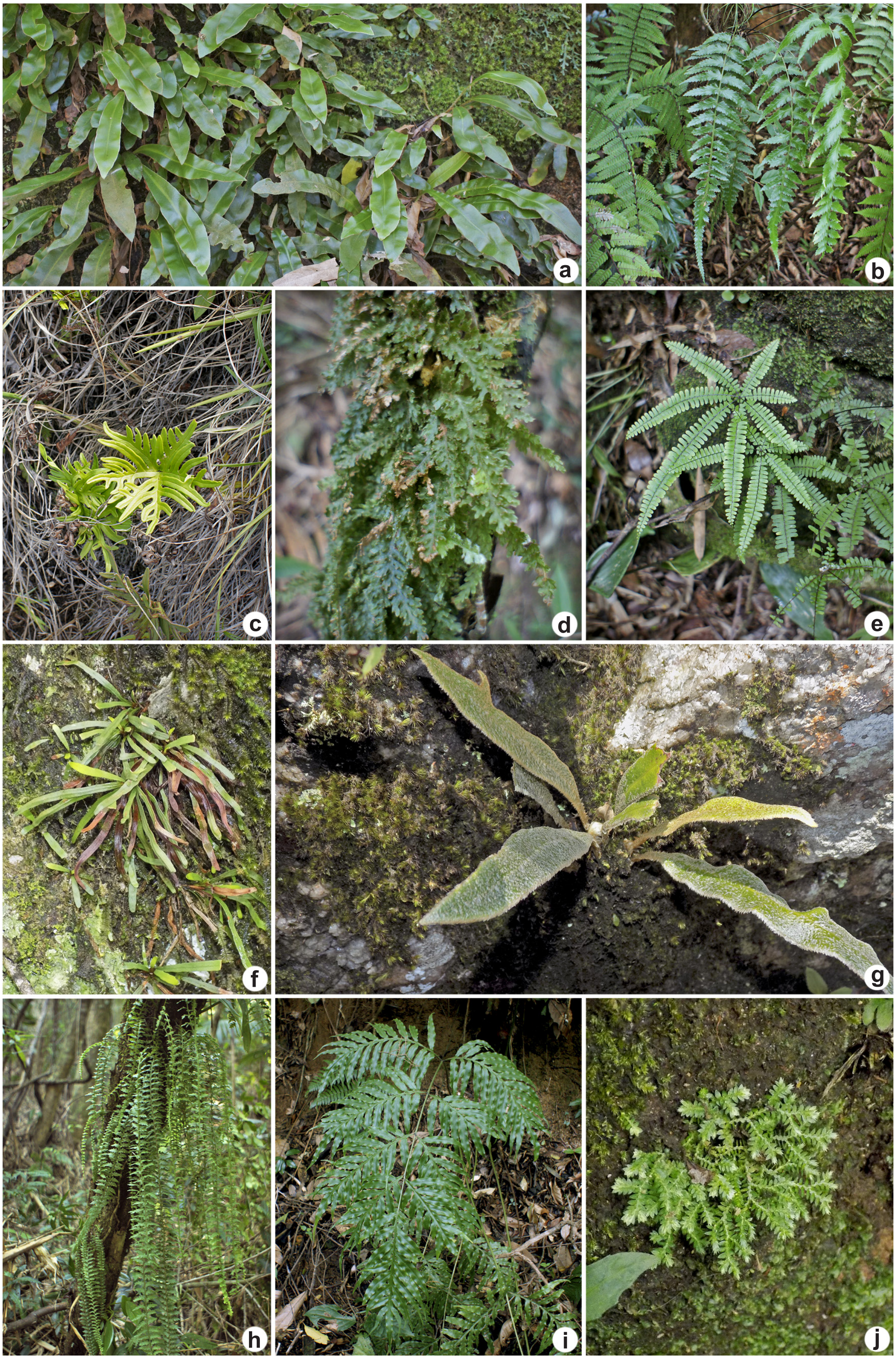

Figure 4 – a-j. Specimens of ferns and lycophytes recorded in TNP, RJ, Brazil – a. *Elaphoglossum glaziovii*; b. *Asplenium cariocanum*; c. *Lytoneuron tijucanum*; d. *Trichomanes polypodioides*; e. *Adiantopsis radiata*; f. *Cochlidium punctatum*; g. *Elaphoglossum plumosum*; h. *Asplenium mucronatum*; i. *Pteris angustata*; j. *Selaginella muscosa*.

1972; Suissa & Sundue 2020). The mountain range on the Atlantic coast within the boundaries of TNP includes more than 60 springs and 36 hydrographic basins forming varied microhabitats (Siqueira *et al.* 2013). Several authors have pointed out the importance of mountains in the diversity of tropical ferns. Indeed, recent data explain how the ability of species to grow and multiply within tropical mountains contributes to fern diversity and, hence, drives *in situ* speciation (Suissa & Sundue 2020).

Pteridaceae is the richest family in all areas of TNP: Serra da Carioca (28), Inselbergs Pedra Bonita and Pedra da Gávea (16), Tijuca Forest (28), and Pretos Forros and Covanca (five). The three genera that most contributed to this predominance are *Pteris* (12), *Adiantum* (8), and *Doryoteris* (7). This family is considered ecologically diverse with most species inhabiting open spaces and rocky outcrops. *Adiantum* and *Pteris* are the most frequent genera in forests (Prado *et al.* 2007). The Tijuca National Park has an altitudinal variation and wide variability of habitats with forest areas, rivers, and waterfalls formed by different gneisses (microcline, biotite, and granitoid). Some granite intrusions form niches exposed to sunlight, which, along with the influence of the sea, could favor the richness of this family (Fernandes *et al.* 2006).

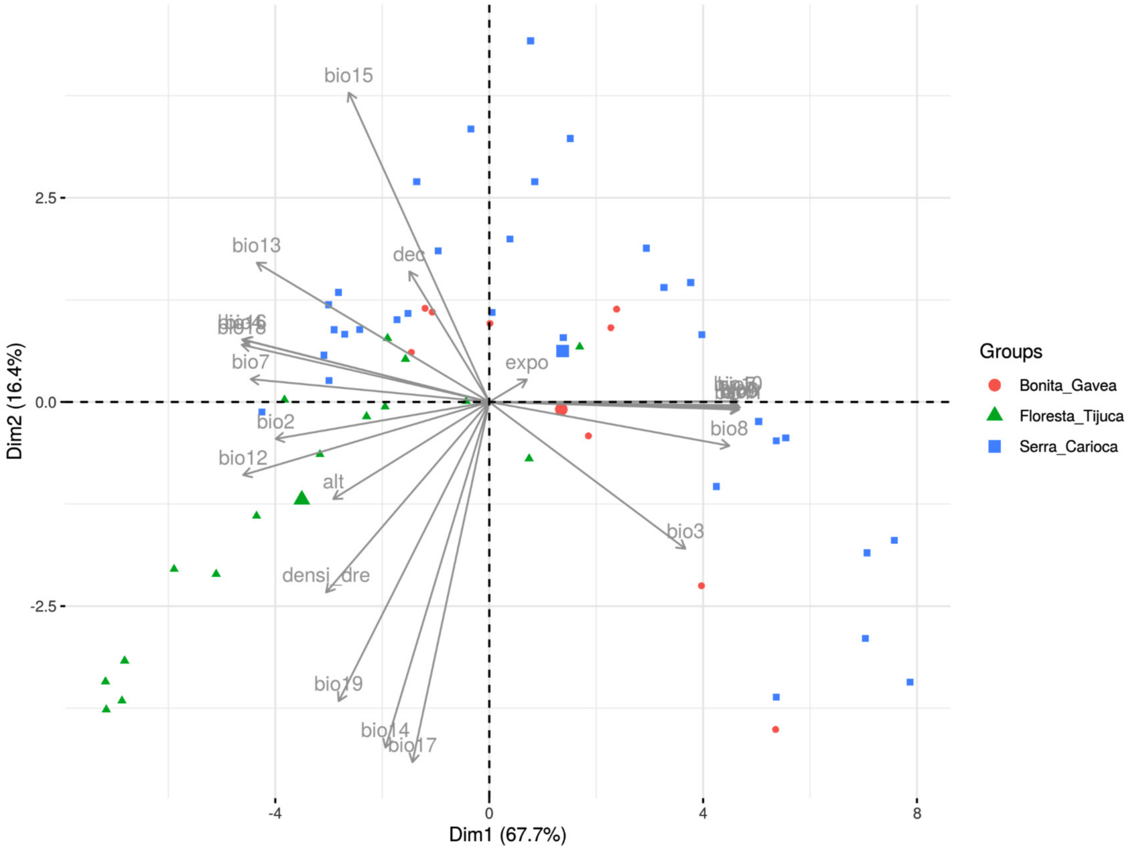

Figure 5 – Principal Component Analysis (PCA) showing environmental variables among three TNP subunits (Pedra Bonita and Gávea, Serra Carioca, and Tijuca Forest) – Temperature: annual mean temperature (bio1), mean diurnal temperature range (bio2), isothermality (bio3), seasonal temperature (bio4), maximum temperature of warmest month (bio5), minimum temperature of coldest month (bio6), temperature annual range (bio7), mean temperature of wettest quarter (bio8), mean temperature of driest quarter (bio9), mean temperature of warmest quarter (bio10), mean temperature of coldest quarter (bio11); Precipitation: annual precipitation (bio12), precipitation of wettest month (bio13), precipitation of driest month (bio14), seasonal precipitation (bio15), precipitation of wettest quarter (bio16), precipitation of driest quarter (bio17), precipitation of warmest quarter (bio18), precipitation of coldest quarter (bio19); Topology: altitude (alt), declivity (dec), drainage density (densi-dre), and exposure (expo).

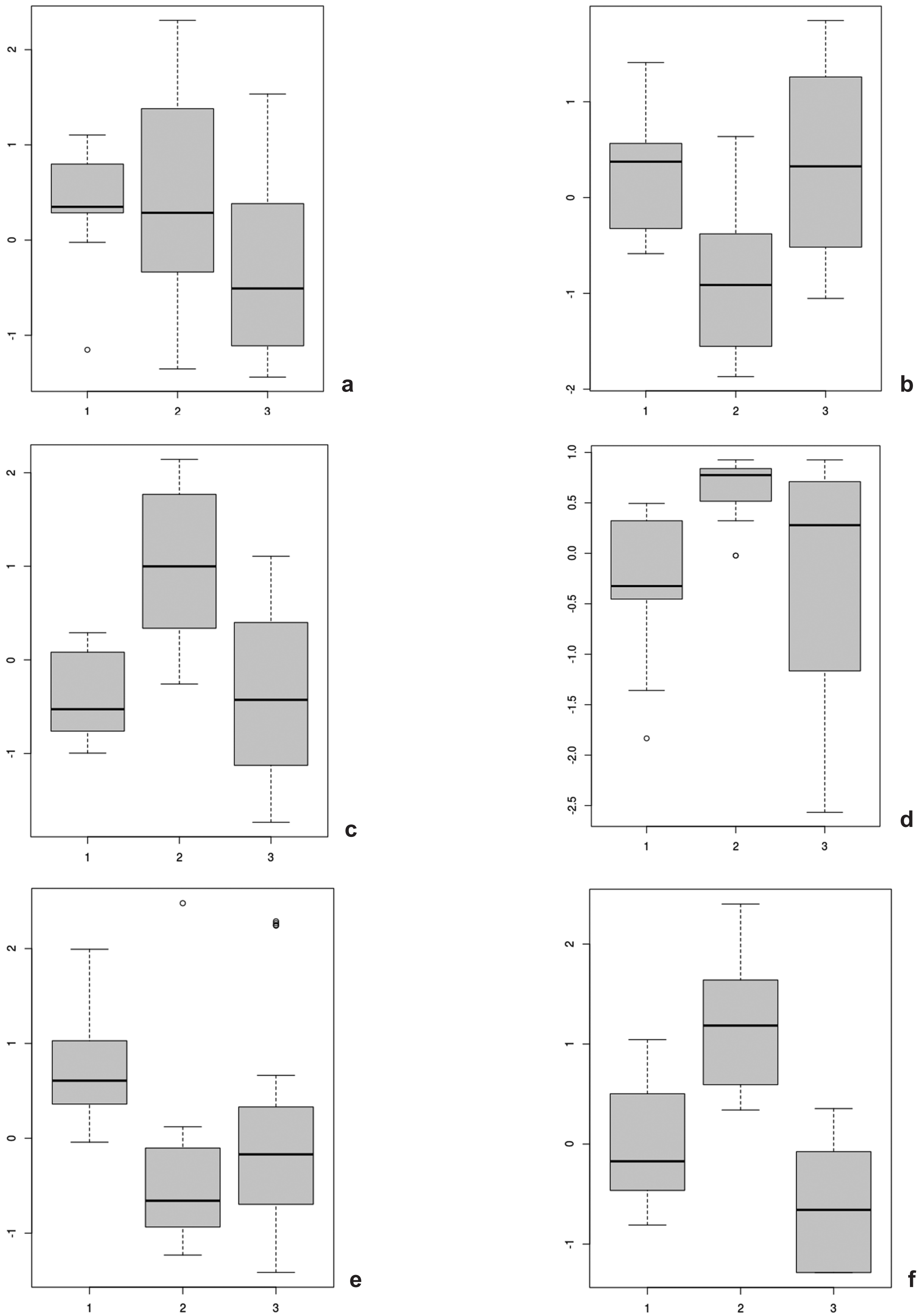

Figure 6 – a-f. Box plots showing three TNP subunits: Pedra Bonita and Gávea (1), Tijuca Forest (2), and Serra Carioca (3) with corresponding environmental variables – a. including elevation - alt; b. including annual mean temperature - bio1; c. including annual precipitation - bio12; d. including precipitation of driest month - bio14; e. including exposure - expo; f. including drainage density - densi-dre.

Dyopteridaceae is represented by terrestrial (including scandent), rupicolous, and epiphytic plants; all these forms are observed among the 36 species found in TNP (Tab. S1, available on supplementary material <https://doi.org/10.6084/m9.figshare.24459877.v1>). A comparative analysis among TNP subunits shows that the area with the highest richness of Dryopteridaceae is Serra da Carioca (27 spp.), followed by Tijuca Forest (19 spp.), and Pedra Bonita and Pedra da Gávea Inselbergs (10 spp.). This family is represented by 11 genera, and the richest are *Elaphoglossum* (10 spp.) and *Ctenitis* (7 spp.). The state of Rio de Janeiro has 48 species of *Elaphoglossum* (Matos 2023), 10 of which occur in TNP. *Elaphoglossum* is among the genera with the highest number of species in floristic lists of rainforests (Matos *et al.* 2010, 2020; Mazziero *et al.* 2015). *Elaphoglossum glaziovii* (Fig. 4a) is the species most frequently found in TNP since it occurs in all subunits. *Elaphoglossum vagans* is represented by a collection from 1929, but its location has not yet been identified. Other species occur in the Serra da Carioca. As observed in other families, some species just have very old records, such as *Polystichum platyphyllum*, which occurs in Corcovado and is represented by three collections in herbaria P and NY (P01489065, P01489062, and NY00808389) recorded in 1928.

Polypodiaceae is a cosmopolitan family, and its species are predominantly epiphytic (Tryon & Tryon 1982; PPG I 2016). The state of Rio de Janeiro has 89 species (Assis *et al.* 2023), and 29 of them are represented in TNP: Serra da Carioca (26), Pedra Bonita and Pedra da Gávea Inselbergs (11), Tijuca Forest (23), and Pretos Forros and Covanca (2). Among the 58 species endemic to Brazil (Assis *et al.* 2023), 7 occur in TNP. The distribution of Polypodiaceae species is not homogeneous among TNP subunits in that only 10 species occur in all areas. The three richest are *Microgramma* (6), *Campyloneurum* (5), and *Pecluma* (5).

Although many specimens had only the indication "Tijuca" on the label, the location of most species can be confirmed in at least one of TNP's subunits Exceptions are as follows: *Asplenium alatum*, *A. harpeodes*, *Cranfillia mucronata*, *Cyathea miersii*, *Elaphoglossum glabellum*, *E. hymenodiastrum*, *E. vagans*, *Dicranopteris rufinervis*, *Sticherus lanuginosus*, *S. pruinosus*, *Didymoglossum krausii*, *Lygodium venustum*, *Adiantum ornithopodum*, and *Amauropelta rivularioides*. *Cyathea miersii* occurs in the states of Rio de Janeiro, Minas Gerais, and São Paulo, frequently above 1,300 m in altitude (Lehnert & Weigand 2013). Two specimens collected in TNP were from historical collections (Glaziou 1702 and Schwacke 860) without a specific date and location. *Dicranopteris rufinervis*, *Sticherus lanuginosus*, and *S. pruinosus* are plants that occur on steep slopes in open areas and are exposed to the sun. Considering the high incidence of fire affecting most open places in TNP, these populations could be reduced by frequent fires. Although widely distributed in the state of Rio de Janeiro, *Lygodium venustum* in the state of Rio de Janeiro it is more frequently found in lowland forests. Finally, for the two *Elaphoglossum* species, belonging to one of the richest genera of ferns, only one record was found for TNP and none recent: *E. glabellum* (Guimarães 99, in 1966) and *E. vagans* (Brade NY00809705, in 1929).

Tijuca National Park is the type-locality of several fern species, and some epithets refer to this site, such as *Cyathea corcovadensis*, *Olfersia corcovadensis*, *Stigmatopteris tyucana*, and *Lytoneuron tijucanum* (Fig. 4c).

Endangered species

Rio de Janeiro, Minas Gerais, and Espírito Santo are Brazilian states that lead in both diversity of species and number of species threatened by extinction (Prado *et al.* 2015; Coelho *et al.* 2017). Tijuca National Park presents 20.2 % of species richness of Brazil and 40.8 % of species richness in the state of Rio de Janeiro (Prado *et al.* 2015). Five species are considered endemic to the state of Rio de Janeiro. They also occur in TNP and are considered endangered by their exposure to different threats. *Anemia blechnoides*, *A. gardneri* and *Doryopteris rediviva* are vulnerable (VU), while *Lytoneuron tijucanum* is endangered (EN), and *L. quinquelobatum* is critically endangered (CR) (Martinelli & Moraes 2013). Fragmentation and habitat loss are identified as the main threats affecting fern species (CNCFlora 2012). *Lytoneuron tijucanum*, an endemic and endangered species of Rio de Janeiro (Martinelli *et al.* 2018), occurs in several locations in TNP among grasses at the base of the Pico da Tijuca and Bico do Papagaio inselbergs. Recurrent fires have caused a predominance of grasses in some areas of the Tijuca Massif (Zaú 1994; Freitas 2001), and at least two species could be affected by this threat: *Lytoneuron tijucanum* and *L. quinquelobatum*. In addition, *L. quinquelobatum* is only known to grow in these areas, occurring between rocks. While *L. quinquelobatum* is labeled in the RB collection, it has not been recorded for over 80 years. Anemia aspera is another endangered species with restricted distribution. In TNP, it occurs in Morro Queimado, Corcovado, and Sumaré in clay cliffs along roads and trails. *Asplenium cariocanum* (Fig. 4b) is an epiphyte occurring on tree ferns along trails, and it is endemic to this location. *Polystichum pallidum* is another species known only in TNP, and its distribution is restricted to Corcovado and Paineiras. *Pteris congesta* is an endangered species (EN), which occurs in the state of Espirito Santo state and three sites in the state of Rio de Janeiro state, and we suspect that it may occur in other places. A study that successfully germinated spores of *P. congesta* from the soil spore bank may indicate new ways for conservation actions for this species (Bastos *et al.* 2023).

Going back a century, no collection records can be found for the following species in TNP: *Adiantum ornithopodum*, *Anemia hirsuta*, *A. rotundifolia*, *A. tomentosa* var. *anthriscifolia*, *Asplenium brasiliense*, *A. uniseriale*, *Cyathea miersii*, *Diphasiastrum thyoides*, *Elaphoglossum scolopendrifolium*, *E. tectum*, *Hypolepis repens*, *Parablechnum glaziovii*, and *Pityrogramma chaerophylla*. A historical survey of the fires that occurred in TNP between 1937 and 2008 showed 323 occurrences, mainly in the winter (dry) period (Aximoff & Rodrigues 2011). Fires damage the forest system by decreasing the supply of water and nutrients, causing microclimatic changes (Oliveira *et al.* 1985). A likely consequence of this is the loss of fern diversity, and many species have not been registered in recent years.

Environmental analysis

Studies on a global scale have indicated the strong relationship between species richness and climate to establish geographic patterns for vascular plants (*e.g.*, Kreft & Jetz 2007; Boucher-Lalonde *et al.* 2012). A study in tropical Africa on a continental scale showed that environmental variables can be used to predict floristically defined vegetation units and that water and temperature availability are strongly related to floristic turnover (Marshall *et al.* 2021). Moreover, environmental and spatial variations play a significant role in the composition of tree and shrub species in the subtropical rainforest in Brazil on the local scale (Maçaneiro *et al.* 2016). Nevertheless, our floristic and spatial analysis allowed cross-referencing of environmental information. To interpret the effects of these variables on the composition of this flora, we compared the set of species both present and absent between areas. On a local or regional scale, different factors can act on floristic composition. In the entire Amazon region, for example, soils explained the strongest floristic gradient of ferns and lycophytes, even though climatic variables were also important (Tuomisto *et al.* 2019). Our results show that both topographic and climatic variables explain 84% of variation in the total area (Fig. 5). The influence of environmental variables on the distribution of sample units among the three areas is shown in Figures 5 and 6. Variables with the greatest contribution are annual precipitation (bio12) and precipitation of wettest quarter (bio 16) (Fig. 5). Precipitation of warmest quarter was indicated as a main predictor of fern and lycophyte species richness with regional and local response (Weigand *et al.* 2020), and in our analysis, this variable was also important. A study in a rainforest in Panama shows that the distribution of ferns and trees is influenced by changes in precipitation, seasonality, and soil characteristics, as well as the interaction among these factors (Jones *et al.* 2013).

Species composition of Pedra Bonita and Pedra da Gávea (BG) is shared with Tijuca Forest (TF), except for one taxon, *Trichomanes lucens*, distributed in southeastern/southern Brazil. Pedra Bonita and Pedra da Gávea and TF are farther away from each other than the proximity of either one to Serra da Carioca (Fig. 1). Pedra Bonita and Pedra da Gávea are contiguous with Serra da Carioca, but they have eight unshared species: *Anemia organensis*, *A. phyllitidis* var. *fraxinifolia*, *Diplazium herbaceum*, *Histiopteris incisa*, *Megalastrum connexum*, *Trichomanes lucens*, *Psilotum nudum*, *Pteris altissima*, *P. multifida*, and *Tectaria pilosa*.

When we look at the floristic list of subunit SC in comparison to the other areas, we see that 64 species have an exclusive occurrence in this area. This is an area slightly larger than TF (ca. 2 km^2) and seems to have greater variability of niches that provided occurrence of 25% of the taxa in TNP. Also, the lowest altitude and least amount of drainage density are the main environmental variables for this area (Fig. 6a,f) as distinct from BG and TF.

In Tijuca Forest, the following variables best explain the total variation of the data: annual precipitation (bio12) and drainage density (Fig. 6c,f). However, the lowest average annual temperatures and precipitation of driest month (Fig. 6b,d) seem to differentiate TF from BG and SC.

In TF, we observed 24 exclusive species, and this could, for example, represent a greater homogeneity of niches in relation to SC. However, ecological abundance studies would gain more insight in this discussion.

Although Aspleniaceae, Hymenophyllaceae, and Polypodiaceae are families with the greatest diversity, substrate and preferred habitat verified for the species showed that 12 species are exclusive to Tijuca Forest and 20 are exclusive the Serra da Carioca, taking epiphytes and facultative epiphytes into consideration. These results should be investigated, including functional diversity in epiphytic communities. For example, the functional diversity of epiphytes is greater than that of terrestrial ferns at the community level. Such findings can describe how sets of species as a whole are adapted to their environment and also determine how they will react to changing conditions (Nitta *et al.* 2020; Aros-Mualin *et al.* 2021). Environmental variables affect both spatial distribution and species richness, while functional characteristics are indirectly correlated spatially through their relationship with the environment (Fortin & Dale 2005; Weigand *et al.* 2020). In addition, size of the species pool and environmental heterogeneity are relevant to the composition of the community (Karger *et al.* 2015). Our results show that the relationship between floristic richness and environmental variables can provide greater insight into biodiversity. However, it is necessary to study community composition since an increase in size of the species pool leads to an increase in competition for available environmental niches, leading, in turn, to a closer connection between environmental factors and community composition (Karger *et al.* 2015). Understanding factors related to species richness can provide insight into the processes that control and maintain local biodiversity.

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Data availability statement

In accordance with Open Science communication practices, the authors inform that all data are available within the manuscript.

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