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Short Communication

New record after 200 years of *Prochilodus vimboides* Kner 1859 in its type locality, Rio Ipanema, Ipanema National Forest

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Abstract: In this manuscript, we provide a record of a captured specimen of Prochilodus vimboides in its type locality (Ipanema River, a tributary of the Sorocaba River, São Paulo state, Brazil), after more than 150 years. Despite extensive collection efforts over 30 years to find the species, only one specimen was sampled in 2020. Here we provide information (including a photograph) of the captured specimen. This record raises an alert regarding the species, which is increasingly rare in its range.
Keywords*: *Fish; conservation; Johann Natterer; threatened species; Prochilodontidae.

Novo registro após 200 anos de *Prochilodus vimboides* Kner 1859 em sua localidade tipo, Rio Ipanema, Floresta Nacional de Ipanema

Resumo: Neste manuscrito, fornecemos o registro de um exemplar capturado de *Prochilodus vimboides* em sua localidade tipo (Rio Ipanema, afluente do Rio Sorocaba, estado de São Paulo, Brasil), após mais de 150 anos. Apesar dos extensos esforços de coleta ao longo de 30 anos para encontrar a espécie, apenas um exemplar foi amostrado em 2020. Aqui disponibilizamos informações (incluindo fotografia) do exemplar capturado. Este registro levanta um alerta em relação a espécie, que tem seus registros cada vez mais raros em suas áreas de ocorrência.
Palavras-chave: *Peixe; conservação; Johann* Natterer; espécie ameaçada; Prochilodontidae.

Introduction

The Prochilodontidae family (Teleostei: Ostariophysi: Characiformes), currently with 21 valid species (Frable et al. 2022; Fricke et al. 2024), occurs in all major basins of South America (Castro and Vari 2004). Among the species of this family is *Prochilodus vimboides*, endemic of Brazil, described by Rudolf Kner in 1859 from specimens collected by Johann Von Natterer between 1819 and 1822, in the Ipanema River, in Iperó, currently a conservation unit (Ipanema National Forest) and sent to the Naturhistorisches Museum in Vienna (Ihering 1902, Vanzolini 1996, Smith 2003). *P. vimboides* occurs in the coastal basins of the country, from the Jucuruçu River, in the south of the state of Bahia, to the Paraíba do Sul River, in the state of Rio de Janeiro, also including the Doce River, in the states of Minas Gerais and Espírito Santo; in the headwaters of tributaries of the eastern portion of the upper Paraná River basin, in the state of São Paulo; and also in the tributaries of the São Francisco River, near Três Marias, in the state of Minas Gerais (Castro and Vari 2004; Langeani et al., 2007; Oyakawa & Menezes, 2011; SALVE, 2024).

Although information on the biology of this species is scarce, it can be considered a migratory species (Oliveira 2015). Like other species belonging to the same genus, it inhabits large bodies of water, and despite its migratory habits, it prefers lentic environments (Burbano et al. 2024). It probably reproduces in late spring and during the summer (November to March) (Honji et al. 2017). This species has iliophagous (detritivorous) and benthophagous feeding habits (Castro and Vari 2004).

P. vimboides is considered vulnerable according to the Biodiversity Extinction Risk Assessment System – Salve (ICMBio 2024) and the

Red List of Threatened Species (IUCN 2024). Some states such as São Paulo and Espirito Santo also classify this species as threatened. The basins where this species occurs suffer from the loss of water quality due to domestic and industrial effluents, in addition to dams and the degradation of floodplains and marginal lagoons, such impacts being major obstacles to the conservation of the species (Burbano et al. 2024). Thus, in this brief communication, we present a new record of *P. vimboides* in its type locality after more than 200 years since the collection of the first specimens and discuss the possible causes of its rarity and its relationship with *Prochilodus lineatus*, a very abundant species in the Ipanema River, Sorocaba River basin, SP, Brazil.

Material and Methods

Sampling was carried out in the Ipanema National Forest, throughout its drainage basin, composed of the Ipanema River, an important tributary of the Sorocaba River (Smith et al. 2013, Smith et al. 2021), Rio Verde and Ribeirão do Ferro (Figure 1). The Ipanema National Forest is located in the Metropolitan Region of Sorocaba, in the state of São Paulo, in an area of 5,180 ha, covering the municipalities of Iperó, Araçoiaba da Serra and Capela do Alto (Smith et al. 2021). Collections were carried out between 2018 and 2020, using the following capture methods: cast net, seine and gill nets. Collection was carried out under ICMBio/SISBIO authorizations no. 24151-1, 75101-1 and 85747-1. The specimen was captured with a gillnet (6 cm between opposite nodes), euthanized with benzocaine, fixed in 10% formalin and preserved in 70% alcohol. The specimen was identified and later confirmed by Francisco Langeani, Ricardo Macedo Correa e Castro and Osvaldo Takeshi Oyakawa and deposited in the fish collection of the Museu de Zoologia da USP, MZUSP 127803. In the studied river sections, measurements of environmental variables were taken through the application of the Rapid Assessment Protocol, adapted from Callisto et al. (2001). The chemical parameters of the water (temperature, pH, electrical conductivity and total dissolved solids) were also obtained using the OAKTON PCD650 multiparameter probe.

Results and Discussion

The specimen of *P. vimboides* (Figure 2) was collected in the Ipanema River (23°26′27.25″S 47°35′26.60″W), the main river of the Ipanema National Forest (Figure 3), in a stretch belonging to the municipality of Iperó, SP, Brazil, in November 2020. The stretch of the Ipanema River where the specimen was captured had temperatures between 23º and 27ºC, with pH values close to 7. The minimum width was 2.5 meters and the maximum was 5.6 meters, while the depth was between 0.9 m and 1.7 m. Throughout its length, a predominance

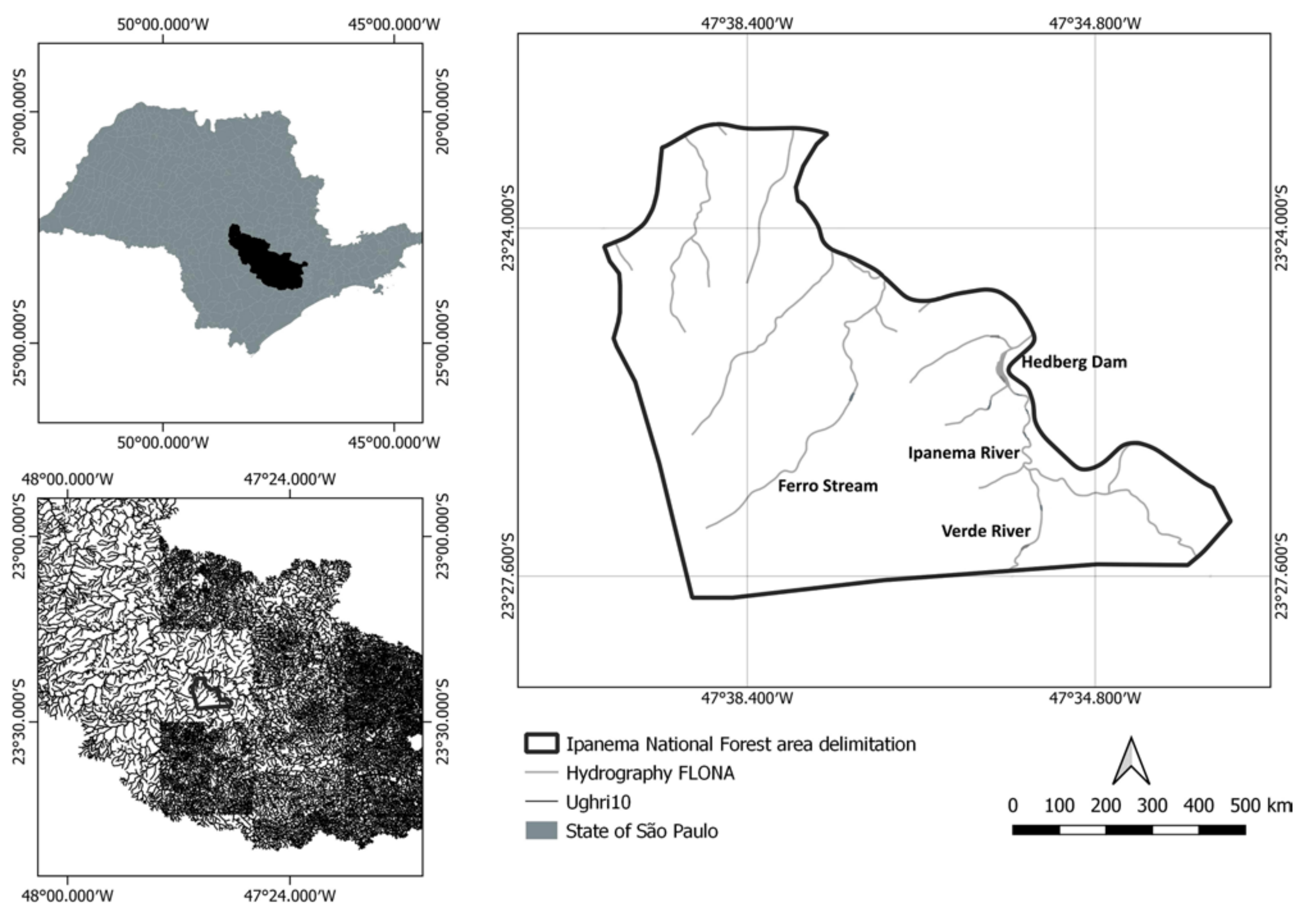

Figure 1. Hydrographic system of the Ipanema National Forest and sites sampled.

of rocky, stony and sandy substrates was observed, in addition to the presence of a large amount of plant material, such as branches and trunks. There were no human interventions such as deforestation, sewage or other impacts in the studied stretch (Table 1 and Figure 4).

The environmental characteristics obtained in the Ipanema River are relatively constant over the years, e.g. cited authors and Table 1, which reinforces the similarity and good conditions of the river presented by Smith et al (2013), Oliveira et al. (2013), Smith et al. (2021) and Smith et al. (2024). The importance of the CU in maintaining the ecological integrity of the species' type locality should be highlighted. Since this is a migratory species and depends on specific sites for feeding and reproduction, which are located in the buffer zone of the CU, efforts to maintain these conditions are extremely urgent.

Figure 2. *Prochilodus vimboides,* MUZUSP 127803, 220 mm SLW, 254.18 g, 34 scales on the lateral line; collected in the Ipanema River, Sorocaba River basin, Iperó municipality (SP- Brazil); 23°26′27.25″S 47°35′26.60″W (Carvalho et al. 2023). Photo: Welber Senteio Smith.

In addition to the species targeted by this manuscript, the Ipanema River contains relatively rare species such as *Tatia neivai* and *Microglanis garavelloi*, in addition to endangered species (*Bunocephalus larai* and *Pseudopimelodus mangurus*) considered vulnerable in the state of São Paulo by Oyakawa et al. (2009). Another relevant information is that there are numerous species that have their type locality in nearby rivers belonging to the same hydrographic basin as the Sorocaba River, such as *Hypostomus ancistroides*, *Hisonotus depressicauda* and *Steindachnerina insculpta*, reinforcing that the Ipanema River is a river that must be preserved and protected, including by law, preventing the occupation of its banks, the release of effluents and damming. It is suggested to decommission an unused and poorly maintained dam downstream of the Ipanema National Forest, at coordinate's 23°23′55.40″ S 47°35′28.27″W, belonging to the Brazilian Navy (Figure 5), which would benefit *P. vimboides* and other migratory species including *Salminus hilarii.*

The specimen collected measured 220 mm SL, weighed 254.18 g, and had 34 scales on the lateral line (Figure 2). This species differs from

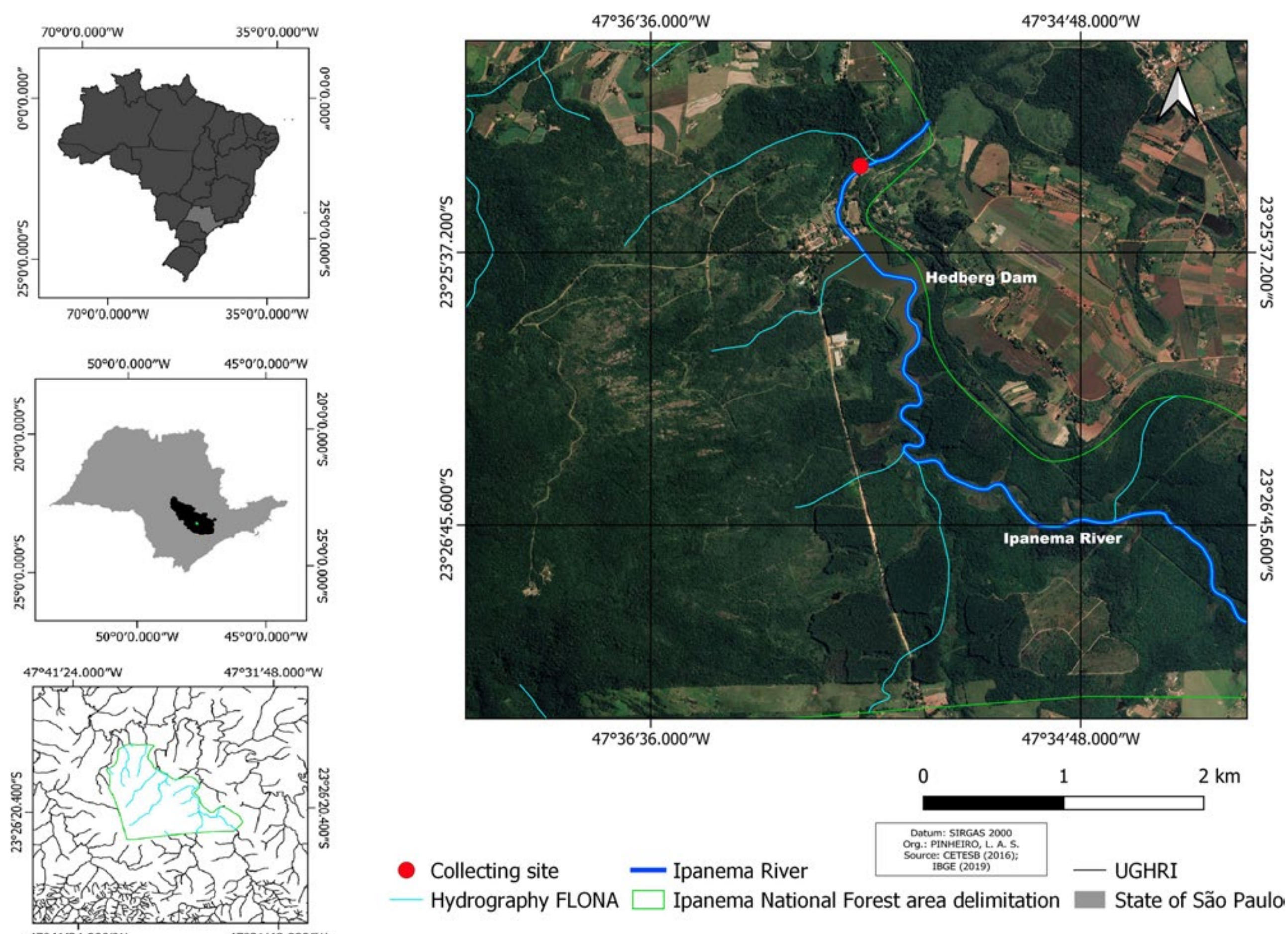

Figure 3. Place of collection of specimen in Ipanema River, Ipanema National Forest, São Paulo State, Brazil.

Table 1. Structural and physicochemical variables of environment where *Prochilodus vimboides* individual was found. Presence = 1; absence = 0.

Environmental variables	
pH	6.9 ± 0.14
Total dissolved solids (ppm)	76.44 ± 3.88
Condonductivity (µs/cm)	132.82 ± 18.82
Temperature (ºC)	24.42 ± 3.96
Average width	4.4 ± 0.54
Average depth	1.5 ± 0.38
Herbaceous vegetation %	0.2 ± 0.07
Large debris	1
Width Gully	1.15 ± 0
Fine substrate %	0.15 ± 0
Wood %	0 ± 0
Riverine vegetation %	0.75 ± 0
Muddy substrate	0
Sandy substrate	1
Rocky substrate	1
Loamy substrate	1
Organic matter %	1
Roots %	0.15 ± 0
Presence of wells	1
Flow	moderate
Presence of rapids	1
Presence of slow Flow and pools	1
Canopy density %	0.25 ± 0
Human influence	absent

other species of the Prochilodontidae family, including *P. lineatus*, which is very common in the Ipanema River, by the number of scales along the lateral line, which can vary from 34 to 39 (in other congeners they vary from 40 to 64); the number of scales around the caudal peduncle, which is 13 to 15; and the number of vertebrae, which is 36 to 39. It has larger scales compared to *P. lineatus* and no dark pigmentation on the dorsal and ventral margins of the body, in addition to a tall and laterally compressed body (Castro and Vari 2004).

The capture of this species has become increasingly rare. In the last 30 years, according to a systematic review carried out by the present author, only 31 specimens have been cited in articles published in the state of São Paulo, of which 3 have been confirmed: two in the Mogi-Guaçu River (Pauls and Bertollo 1990) and the specimen in the present study (Carvalho et al., 2023). In addition, it is important to record a specimen captured by C.S. Gonçalves in Lagoa da Pedra in Mogi Guaçu in 2006, which specimen is deposited in the fish collection of Unesp São José do Rio Preto (DZSJRP 12382).

Most captures occurred in the basins of the Doce River in Minas Gerais (Giacomini et al. 2011, Salvador et al. 2018, Ferreira et al. 2020), São Francisco, in the states of Minas Gerais and Bahia, acias norte do Espírito Santo (Sarmento-Soares et al. 2012) e rio Barra Seca no estado de Espírito Santo (Sarmento-Soares and Martins-Pinheiro 2014), Paraíba do Sul, in the states of Minas Gerais and Rio de Janeiro (Teixeira et al. 2005; Freitas et al. 2017) and Macaé River in the state of Rio de Janeiro (Catelani et al. 2017). With the exception of a large number of captures reported in the Mucuri River by Pompeu and Martinez (2006), a little over 300 individuals were captured in the basins mentioned above, reinforcing their rarity. It is worth mentioning the capture of larvae in the Paraiba do Sul River in 2017 (Souza et al. 2017), which may be evidence that the species is present and reproducing in this river. Reinforcing the rarity of the species, there are few specimens deposited in collections, as highlighted by Polaz et al. (2011).

Figure 4. Ipanema River stretch where *Prochilodus vimboides* individual was sampled.

Figure 5. Dam located on the Ipanema River, in the buffer zone of the Ipanema National Forest, downstream of the type locality.

The similarity in biological and ecological characteristics with *P. lineatus* (Castro and Vari 2004) is an aspect that has been considered as an explanation for the reduction of its populations, reinforced by Bizerril (1999) who stated 25 years ago that *P. vimboides* was becoming increasingly rare, attributing this to the increase in *P. lineatus*, introduced into the Paraíba do Sul River. Considering this information, we can infer that this is due, in part, to its lower biotic potential, which deserves attention and future research to elucidate. The specimen recorded in our study was sampled together with specimens of *P. lineatus*, which despite being two species native to the basin, in recent decades the dominance of *Prochilodus lineatus* in the rivers of the Sorocaba River basin has become evident, which reinforces the suspicions above. Furthermore, we must associate this with the environmental changes suffered in the basins where they occur, most of them located in the southeastern region of Brazil, favoring *P. lineatus* and potentially contributing to explaining this process.

Although this is an interpretation based on phylogeny, we can include in this discussion what Frable et al. (2022) stated, that the populations of *P. vimboides* became extinct in Paraguay and in the upper central-western Paraná, possibly due to ecological competition with *P. lineatus*, which colonized the upper Paraná during the Miocene-Pliocene, with this replacement having begun 2 million years ago. It is clear that what we present here requires further in-depth studies, and the purpose of these statements is to provoke such discussions so that the answers to these questions can be obtained.

The rediscovery of the species in its type locality is very relevant, as it confirms Natterer's findings and reinforces the importance of the Ipanema National Forest in its conservation since the CU reduces the deforestation and urbanization processes could increase the risk of extinction of the species. In addition, long-term research is necessary to attempt to obtain new records in the basin, not only in the watercourses but also in adjacent environments such as marginal lagoons and floodplains. Furthermore, although *P. vimboides* is not yet classified as "Endangered" or "Critically Endangered", records of captures of this species as described above are increasingly scarce and have become rarer over time, which would require a more careful analysis for reclassification of the species. The conservation status of the species should be reassessed, as well as the discussion of conservation actions through investment in research to better assess the populations of the species in the areas where it occurs. Repopulation actions should be evaluated with criteria, based on the research suggested above.

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Author Contributions

Welber Senteio Smith: conceptualization; data collection; manuscript preparation and revision.

Conflicts of Interest

The author declare that they have no conflict of interest.

Ethics

Not applicable.

Data availability

All data are available in the paper.

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Article

Anthropogenic pressure and protected areas in the Brazilian Atlantic Forest: Serra da Tiririca State Park process and patterns

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Abstract: Protected areas are key to biodiversity conservation and essential to ecosystem services. However, anthropogenic pressures, such as human population growth, and environmental factors, such as temperature and precipitation changes, have caused intense modifications in these areas, especially in the Atlantic Forest, a biodiversity hotspot. This study aimed to describe changes in land use and land cover (LULC) over 38 years in a protected area of the Atlantic Forest and assess the effects of anthropogenic and environmental factors on LULC cover dynamics. We explored mapping data from the MapBiomas, for the period between 1985 and 2022, and correlated these data to variables of human population density, temperature and precipitation by using generalized linear models. We observed that forest formations and *restingas* increased their coverage by 2.99% and 20.68%, respectively. In contrast, wetlands, rocky outcrops, farming, sandy areas, urban areas and water bodies decreased in coverage by around 28.11%. The increase in human population density outside the protected area is the main driver of changes in LULC in PESET. Predictions from the models showed that sandy areas are likely to disappear within ten years. Our study shows that even protected areas remain vulnerable to human actions and subject to significant changes in the future.
Keywords: *Rio de Janeiro; Land Use and Land Cover; Remote Sensing; Biodiversity Conservation; Population Density.*

Pressão antrópica e áreas protegidas na Mata Atlântica brasileira: processos e padrões do Parque Estadual da Serra da Tiririca

Resumo: As áreas protegidas são fundamentais para a conservação da biodiversidade e essenciais para os serviços ecossistêmicos. No entanto, as pressões antrópicas, como o crescimento da população humana, e os fatores ambientais, como as mudanças na temperatura e na precipitação, têm causado intensas alterações nesses locais, especialmente na Mata Atlântica, um *hotspot* de biodiversidade. Este estudo teve como objetivo descrever as mudanças no uso e cobertura da terra (LULC) ao longo de 38 anos em uma área protegida da Mata Atlântica e avaliar os efeitos de fatores antrópicos e ambientais sobre a dinâmica de LULC. Exploramos dados de mapeamento do MapBiomas, para o período entre 1985 e 2022, e correlacionamos esses dados com variáveis de densidade populacional humana, temperatura e precipitação por meio de modelos lineares generalizados. Observamos que as formações florestais e as restingas aumentaram sua cobertura em 2,99% e 20,68%, respectivamente. Em contrapartida, zonas húmidas, afloramentos rochosos, pastagens, zonas arenosas, zonas urbanas e corpos de água diminuíram a sua cobertura em cerca de 28,11%. O aumento da densidade populacional humana fora da área protegida é o principal fator das mudanças no uso e cobertura do solo no PESET. As previsões feitas a partir dos modelos mostraram que, dentro de dez anos, as áreas arenosas provavelmente estarão extintas. Nosso estudo

sugere que mesmo as áreas protegidas permanecem vulneráveis às ações humanas e estão sujeitas a mudanças significativas no futuro.
Palavras-chave: *Rio de Janeiro; Uso e Cobertura do Solo; Sensoriamento Remoto; Conservação da Biodiversidade; Densidade Populacional.*

Introduction

Protected areas (PA) are essential pillars in strategies for biodiversity conservation and management (Watson et al. 2014). These natural areas are important tools that protect historical and cultural resources, propel sustainable development, and provide crucial ecosystem services (Hummel et al. 2019). However, the decline of species richness, including both flora and fauna, in recent years, caused by increased anthropogenic activities and climate change, has drawn the attention of numerous researchers to an imminent biodiversity collapse (Laurance et al. 2012, Watson et al. 2014, Thomas & Gillingham 2015, Meng et al. 2023). Therefore, to conserve and protect the remaining species in these areas, it is necessary to understand the functioning and changes in their habitats over time and space (Lira et al. 2012).

The execution of international policies aimed at achieving conservation goals has led to a significant increase in PAs worldwide in the last decades (CBD 2021). It is estimated that around 24% of the Earth's land surface is covered by ca. 296,000 PAs (UNEP-WCMC & IUCN 2024). Of this total, ca. 2860 of them are in Brazil (MMA 2024), covering 18% of the country's continental area and 26% of its marine area. Pioneering in Latin America, Brazil hosts the largest species conservation network on the planet (UNEP-WCMC & IUCN 2024). Nevertheless, PAs remain the subject of considerable debate regarding their efficiency, protection, and locations (Geldmann et al. 2019, Silva et al. 2021a).

Considered one of the most emblematic tropical regions, the Atlantic Forest (AF) is home to ca. 145 million people (SOS Mata Atlântica 2022) which represents approximately two-thirds of the Brazilian population. Most of its original area is now dominated by agriculture, buildings, highways, and cities (Solórzano et al. 2021). The result of hundreds of years of interaction between human societies and the forest is marked by the devastation of the second-largest forest in South America, originally covering ca. 1,3 million square kilometers, of which less than 24% of its native coverage remains today (SOS Mata Atlântica 2022). Due to its high level of threat, the AF is protected by federal law 11,428/2006, which aims, among other objectives, to establish restrictions on forest use, biodiversity preservation, and promotion of sustainable development (Brasil 2006). Although the AF is considered a prioritized biodiversity hotspot for conservation (Myers et al. 2000), studies on changes in the patterns of land use and land cover (LULC) remain limited compared to the wealth of research on the Amazon biome (e.g. Aguiar et al. 2016, Armenteras et al. 2019, Göpel et al. 2018, Neves et al. 2020, Souza et al. 2020). Lira et al. (2012) examined LULC dynamics in three AF landscapes from the 1960s to the 2000s, finding variations in forest cover that alternated between regeneration and fragmentation, leading to isolated patches with mixed forest age classes and implications for biodiversity. Rezende et al. (2018) expanded on these findings using high-resolution mapping to identify a significant extent of native vegetation cover in the biome, highlighting the potential for restoration in degraded riparian areas to promote connectivity among fragments and achieve critical biodiversity thresholds. Silva et al. (2020) further contributed by analyzing mountain regions within the AF, which, despite pressures, maintain stable natural vegetation cover, highlighting these areas as critical biodiversity refuges within the biome. Consequently, ecological approaches that include temporal and spatial variations of LULC and their impact on landscape configuration are of great importance for the preservation of biodiversity and the functionality of altered areas (Mori et al. 2018).

Anthropogenic factors, such as population density, are elemental for understanding processes of human expansion. Certain LULC classes, such as farming and urban areas, which are inherently anthropogenic, are expected to be more affected by increasing human population density, as it drives higher land demand and habitat fragmentation (Freitas et al. 2010, Moraes et al. 2017). Conversely, forested areas within AF tend to experience reduced anthropogenic and climatic impacts (Silva et al. 2021b), compared to farming and urban areas, as they are less directly influenced by population-driven land conversion. However, the influence of anthropogenic factors is still rarely explored in studies on LULC in PAs (Côrtes & D'Antona 2014). On the other hand, variation on abiotic variables (environmental factors), such as temperature and precipitation, is extensively studied and considered a predictor of changes in biodiversity patterns at local, regional, and global scales (Thomas & Gillingham 2015, Klipel et al. 2022, Doughty et al. 2023). However, both anthropogenic and environmental factors are indispensable predictors that can directly impact the efficiency of preservation and landscape changes (Monzón et al. 2021). In this regard, a better understanding of LULC dynamics in the AF, which hosts over 50% of Brazil's PAs (MMA 2024), is relevant for environmental planning aimed at preserving its biodiversity. Thus, as it still poses a challenge, we aimed to describe changes in land use and land cover over 38 years in a protected area of the Atlantic Forest and assess the effects of anthropogenic factors, specifically human population density and environmental factors, such as temperature and precipitation, on these changes. The hypotheses tested were: i) areas characterized by predominantly herbaceous, sparse, or no vegetation, such as wetlands, rocky outcrops, farming, sandy areas, urban areas, and water bodies, despite being protected, are more vulnerable to the negative impacts of anthropogenic and environmental drivers, i.e., their coverage decreases as human population density increases, along with temperature and precipitation; ii) forested areas and wooded sandbanks (*restingas*) may potentially exhibit increased coverage, as they are less susceptible to the effects of increasing human population density, temperature, and precipitation; and iii) human population density exerts a stronger influence on LULC changes in the protected area compared to temperature and precipitation, as it is the primary driver of land conversion.

Material and Methods

1. Study area

This study focused on the Serra da Tiririca State Park (PESET), one of the main protected areas in the state of Rio de Janeiro. Established in 1991 by State Law No. 1901 (Rio de Janeiro 1991), this PA covers 3491.92 ha between the coordinates 22º48'–23º00'S and 42º57'–43º02'W, encompassing the municipalities of Niterói and Maricá. Notably, Niterói encompasses 2688 ha, while Maricá covers 803.92 ha of the PESET. The territorial division of the study area, which is not interconnected, is organized into the following sectors: Serra da Tiririca (1975.06 ha); Darcy Ribeiro (1155.35 ha); Lagoa de Itaipú (185.02 ha); Morro das Andorinhas (90.36 ha); Morro da Peça (37.82 ha); and the Insular sector (48.31 ha), the latter including Pai, Mãe and da Menina Islands (Figures 1 and 2). PESET is situated within the AF biome, with dense ombrophilous forest formations, rocky outcrops, *restingas*, and mangroves (INEA 2015). Floristically, the PESET is mostly composed of heterogeneous mosaics in different successional stages (Zuñe-da-Silva et al. 2023). The region experiences a contrasting climate (humid and hot), with heavy rainfall in the summer and a dry season in winter (Köppen's Aw) (Alvares et al. 2013), an average annual temperature of 23.7 °C, total annual precipitation of 1172 mm, annual relative humidity of 80%, and the soil is mainly formed by Argisols, Gleysols, Neosols and Cambisols (INEA 2015).

The history of LULC of PESET is characterized by a complex socio-environmental context (INEA 2015), sheds light on how past land-use practices and socio-economic factors have shaped the current environmental landscape. Remains found in archaeological sites within the Lagoa de Itaipú sector, indicate that at least 8000 years ago the area was inhabited by humans (Kneip 1995). Subsequently, the region was populated by the Tupi people, until the arrival of the Portuguese (Barros 2008). In the early colonial era, the vigorous Portuguese trade in 'Pau-Brasil' (*Paubrasilia echinata* (Lam.) Gagnon, H.C.Lima and G.P.Lewis) led to a disastrous devastation of the natural landscape along the coast (Dean 1996). Additionally, intense agricultural expansion, the establishment of mills, and the growth of charcoal extraction contributed to the destruction of large areas of native forests (Oliveira et al. 2020). However, with the decline of monocultures in the early 20th century, some natural areas were able to partially recover their original vegetation (Barros 2008). Furthermore, the increase in charcoal extraction during the 19th century and the first half of the 20th century played a significant role in shaping the floristic composition and landscape structure of PESET (Patzlaff 2016). Nevertheless, from the mid-20th century to the present day, large-scale land developments, real estate speculation, and land conflicts have continued to dictate the dynamics of landscape transformation in the region (Pimentel & Lindenkamp 2023).

2. Data acquisition and processing

The LULC data of PESET (response variable) were obtained from the MapBiomas platform's collection 8 database (https://brasil.mapbiomas.org/, accessed on: March 22, 2024), for the annual historical series from 1985 to 2022. MapBiomas products are regularly updated and generated from the pixel-by-pixel classification of images obtained by the satellites Landsat 5 TM, Landsat 7 ETM+, Landsat 8 OLI-TIRS, and Landsat 9 OLI-2-TIRS-2. The satellite image collections from Landsat, with a resolution of 30m, are made available by the United States Geological Survey (USGS) and extensively processed by machine

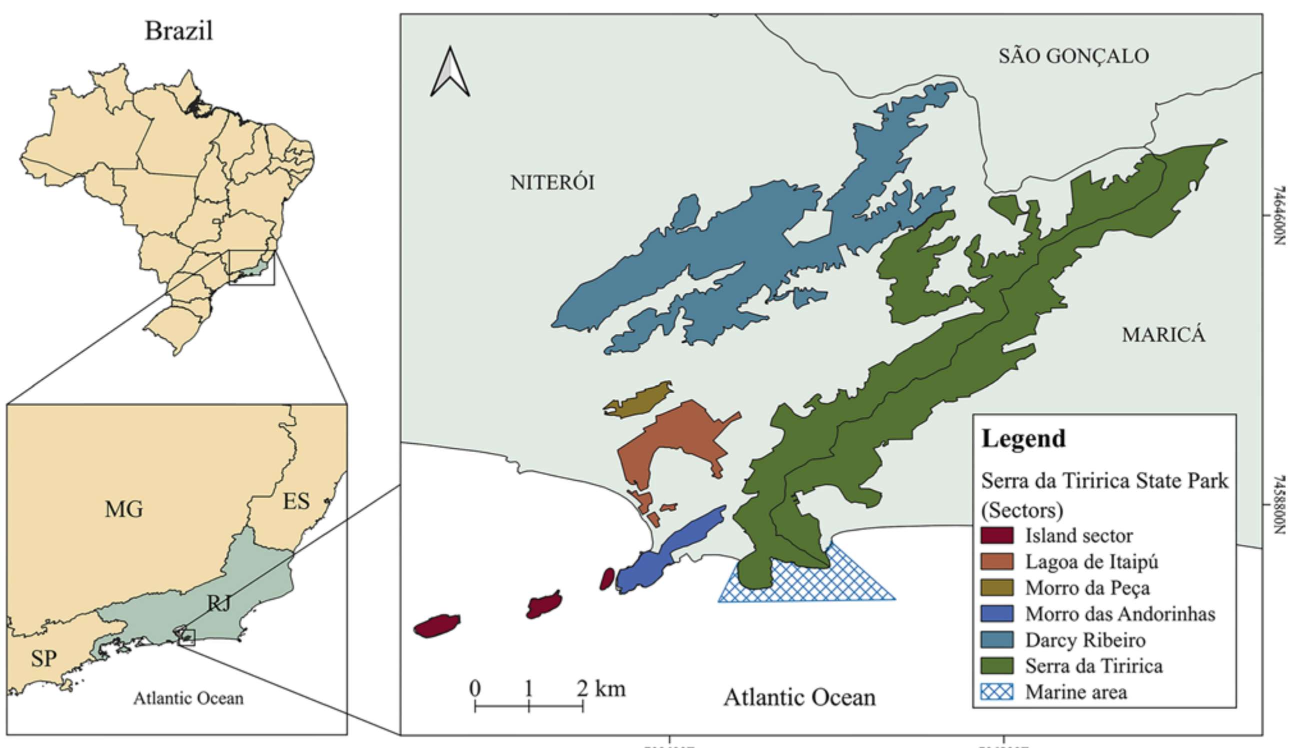

Figure 1. Location of the study area showing the sectors of the Serra da Tiririca State Park in Rio de Janeiro, Brazil.

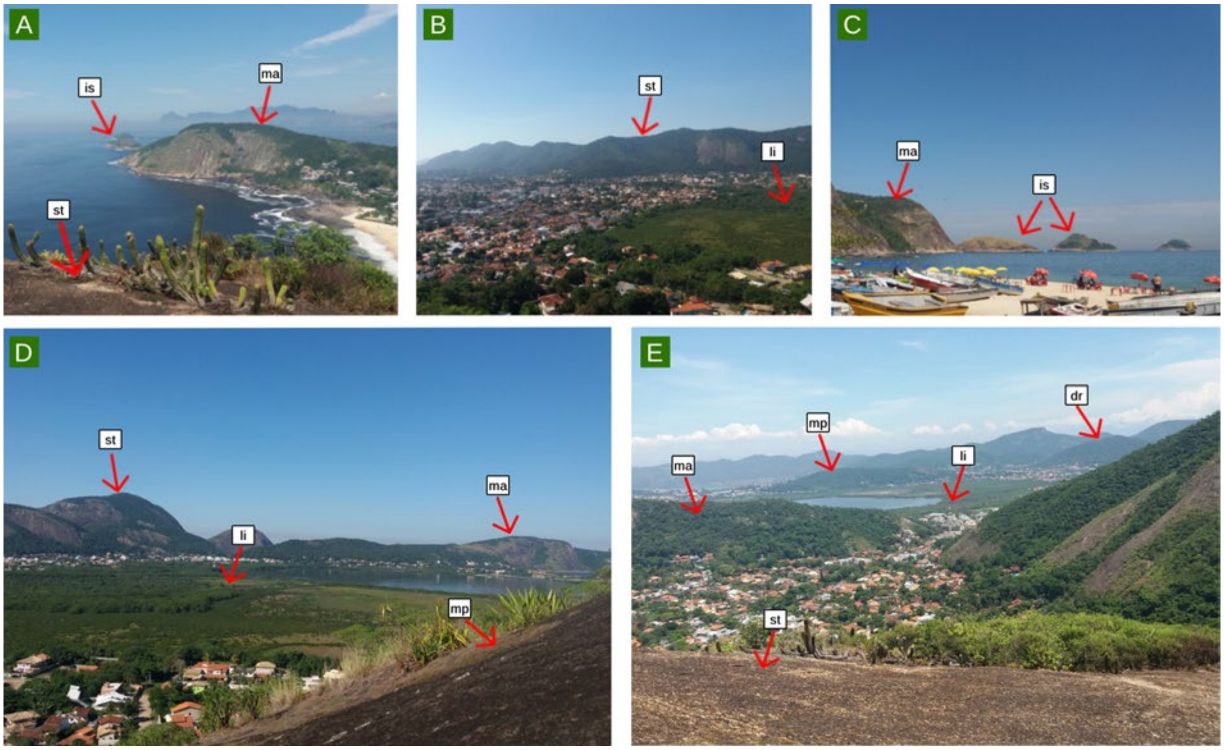

Figure 2. A-E: Images of the study area. Lowercase letters above the red arrows indicate the sectors of PESET: st = Serra da Tiririca; ma = Morro das Andorinhas; li = Lagoa de Itaipú; mp = Morro da Peça; dr = Darcy Ribeiro; is = Insular sector.

learning via the Google Earth Engine platform, reaching an overall accuracy of level 1 and 2 classes for the Atlantic Forest biome of 87 and 83 per cent, respectively (MapBiomas 2024).

The MapBiomas land use and land cover classification system operates with a hierarchical order compatible with the classification systems of the Food and Agriculture Organization (FAO) and the *Instituto Brasileiro de Geografia e Estatística* (IBGE), both of which have different classes and levels (MapBiomas 2024). We only considered as response variables the level 2 of the classes found within the boundaries of PESET Classes with low area representativity and minimal variation were grouped, while the remaining classes retained the designations provided by MapBiomas (Table 1). The images from MapBiomas were clipped from the PESET shapefile, and the values of each class were extracted in hectares using the QGIS *r.report* function in QGIS 3.36 software (QGIS Development Team 2024).

To obtain the explanatory variables values of human population density (hereafter population density), average annual temperature and cumulative annual precipitation, we initially acquired the data of population sizes of Niterói and Maricá from the demographic censuses of 1991, 2000, 2010, and 2022, by accessing the IBGE database (https://www.ibge.gov.br/, accessed on: March 26, 2024). Subsequently, using the arithmetic method, we projected the population growth for the period of 1985-2022, preserving the original values from the censuses. The arithmetic method assumes short-term population growth through a constant growth rate (Tsutiya 2006) and is calculated using equations (1) $K_a = P_2 – P_1 / t_2 – t_1$ and (2) $P_2 = K_a(t_2 – t_1) + P_1$, where: K_a = population growth rate as a function of time, P_2 = population of the last year considered, P_1 = population of the penultimate year considered, t_2 = year of the last year considered, t_1 = year of the penultimate year considered.

The population density was obtained from the projected values for the period, expressed by the ratio between the population size and the surface areas of the territories of Niterói and Maricá (129.4 and 362,480 square kilometers, respectively). Consequently, the population density data of the municipalities were considered separately for comparison purposes, yet related to the analyses.

Although it is recognized that climate conditions are driven by human activities, here we describe them as an environmental factor to contrast them with human population density derived from anthropogenic factors (Lynas et al. 2021). The data for average annual temperature and cumulative annual precipitation (hereafter temperature and precipitation) from the stations of Maricá (code 83089) and Niterói (code A627) were acquired from the website of the *Instituto Nacional de Meteorologia* – INMET (https://portal.inmet.gov.br/, accessed on: March 27, 2024). The conventional meteorological station in Maricá made records from 1991 to 2018 (when it was deactivated), and the automatic station in Niterói made complementary records from 2018 to December 2022. Although data from different municipalities and types of stations were utilized, historical climate patterns in Maricá and Niterói are generally similar due to the atmospheric phenomena affecting the region, which typically influence the climate of the State of Rio de Janeiro (INEA 2015). The monthly temperature and precipitation records from both meteorological stations were converted to an annual frequency using arithmetic mean calculation. Then these numbers underwent a missing data analysis using the functions from the Amelia II package (Honaker et al. 2011) in the R 4.4.0 software

Table 1. Land use and land cover classification system for MapBiomas collection 8 found in Serra da Tiririca State Park, Rio de Janeiro, Brazil. ID = Abbreviation for level 2 classes.

Class		ID	Description
Level 1	**Level 2**		
Forest	*Forest formation*	For	Dense, Open and Mixed Ombrophilous Forest, Semi-deciduous and Deciduous Seasonal Forest, and Pioneer Formation.
Non-forest natural formation	*Wooded sandbank vegetation (Restinga)*	Res	Forest formations on sandy soils in the coastal region, with predominantly shrub-tree vegetation.
	Wetland	Wet	Wetlands with fluvial influence.
	Rocky outcrop	Roc	Naturally exposed rocks without soil cover, often with the partial presence of rupicolous vegetation and high slope.
Farming	*Farming (Pasture and Mosaic of uses)*	Far	Pasture area, predominantly planted, linked to livestock production activities. Areas of natural pasture are predominantly classified as grassland or wetland, that may or may not be grazed. / Farming areas where it was not possible to distinguish between pasture and agriculture.
Non-vegetated area	*Beach, dune and sand spot (Sandy areas)*	San	Sandy areas, with bright white color, where there is no vegetation predominance of any kind.
	Urban area / Other non-vegetated areas	Urb	Urban areas with a predominance of non-vegetated surfaces, including roads, highways and constructions. / Non-permeable surface areas (infrastructure, urban expansion, or mining) not mapped into their classes and regions of exposed soil in natural or crop areas.
Water	*Water bodies (River, Lake and Ocean)*	Wat	Rivers, lakes, dams, reservoirs and other water bodies.
Not observed		Not	Areas blocked by clouds or atmospheric noise, or with the absence of ground observation masked out from analysis.

(R Core Team 2024). Finally, all variables (response and explanatory) were organized and incorporated into a single data matrix.

3. Data analysis

Firstly, the population density, the variation in temperature and precipitation over time, and the change in hectares and percentage for LULC classes within PESET were described. Subsequently, we subjected the explanatory variables to a normality analysis (Shapiro-Wilk test) (Razali & Wah 2011). Since they did not meet the assumptions of the test (normality and heteroscedasticity), even after conversions into logarithmic or square root values, we treated the variables as non-parametric and used the unconverted data for analysis. To examine relationships between the explanatory variables and identify potential multicollinearities in the models testing our hypotheses, we applied the Spearman correlation test (Myers & Sirois 2004). In light of this analysis, before constructing our models, a significant and strong positive correlation between temperature and population density was found (rho = 0.68, $p < 0.01$), along with a non-significant and extremely weak positive correlation with precipitation (rho = 0.01, p = 0.95). Population density and precipitation did not show a significant correlation and exhibited a very weak positive correlation with each other (rho = 0.19, p = 0.25). Complementary to the Spearman correlation test, we calculated the Variance Inflation Factor (VIF) using functions from the "car" 3.1-3 package (Fox & Weisberg 2024). The VIF quantifies how much the variance of a regression coefficient is inflated due to collinearity among predictors. A VIF of 1 indicates no collinearity, values between 1 and 5 suggest moderate correlation, and VIF >5 signals high collinearity that may compromise model reliability (Miles 2014). All explanatory variables had a VIF <1.8 (for details, see Table S1). Based on these analyses, explanatory variables that exhibited significant Spearman correlations were not considered in the final model construction to avoid redundancy and ensure statistical robustness, even though some presented VIF values indicating minimal collinearity.

To test our hypotheses, we determine the effects of population density, temperature, and precipitation on changes in LULC in PESET by applying a Generalized Linear Model (GLM). As GLMs operate with parsimonious explanations, we select the best models using a Gaussian distribution with the '*identity*' link. We then subjected the explanatory variables to an analysis of variance (ANOVA) with an F-test to evaluate the model's goodness of fit, examining the measures of discrepancies through deviance residuals and selecting models with the lowest values according to the Akaike Information Criterion (AIC) (Cavanaugh & Neath 2019). Subsequently, we calculated the D-squared (D^2), an R^2 analogue for GLMs that measures the (adjusted) deviance explained by the models using the formula: 1 - (Residual Deviance / Null Deviance). The D^2 was estimated using functions from the using functions from the Model Evaluation and Analysis "modEvA" (Barbosa et al. 2013).

Finally, we randomly split the data matrix with explanatory variables into 70 per cent for training and 30 per cent for testing. This division was performed using the *createDataPartition* function from the Caret package (Kuhn et al. 2016). With the variables data partitioned, and using the "forecast" package along with its model optimization functions (Hyndman et al. 2023), we obtained the predictions for the univariate temporal series of the explanatory variables for ten years in the future. These forecasted values were then incorporated into the GLMs to predict LULC changes in PESET for the year 2032. The predictions were generated using the following equation: $Y = a + b1X1 + ... + bkXk$; where Y represents the predicted value for each LULC class, a is the intercept, $b1$ to bk are the estimated coefficients for each explanatory variable, and $X1$ to Xk are the forecasted values of the explanatory variables for the ten-year projection period. All analyses and figures were conducted in R, and the maps were created in QGIS.

Results

For the period between 1985 and 2022, Niteroi's population density increased from 3205.06 to 4046.86 people/km^2, while Marica's increased from 0.10 to 2.06 people/km^2 (Figure 3a). The growth rate for the period in Niterói was 22.74 people/km^2/year, while in Maricá it was 0.01 people/km^2/year. The maximum average temperature ranged between 25.23 °C (2019) and 25.53 °C (1997), while the minimum average temperature ranged between 22.13 °C (1985) and 22.24 °C (1988). The average temperature for the period was 21.78 °C (Figure 3b). On the other hand, the average precipitation was 1204.31 mm. The years with the highest rainfall were 2003 (1635.48 mm) and 1996 (1602.34 mm), and the years with the lowest precipitation were 2021 (915.72 mm) and 2017 (919.68 mm) (Figure 3b).

Of the total area covered by PESET in 1985, forest formations accounted for 74.59%, *restingas* 0.56%, wetlands 2.08%, rocky outcrops 1.30%, farming 10.21%, sandy areas 0.21%, urban areas 2.49%, and water bodies 0.78%. Unobserved areas represented 7.77%. In 2022, it was observed that forest formations represented 76.82%, *restingas*

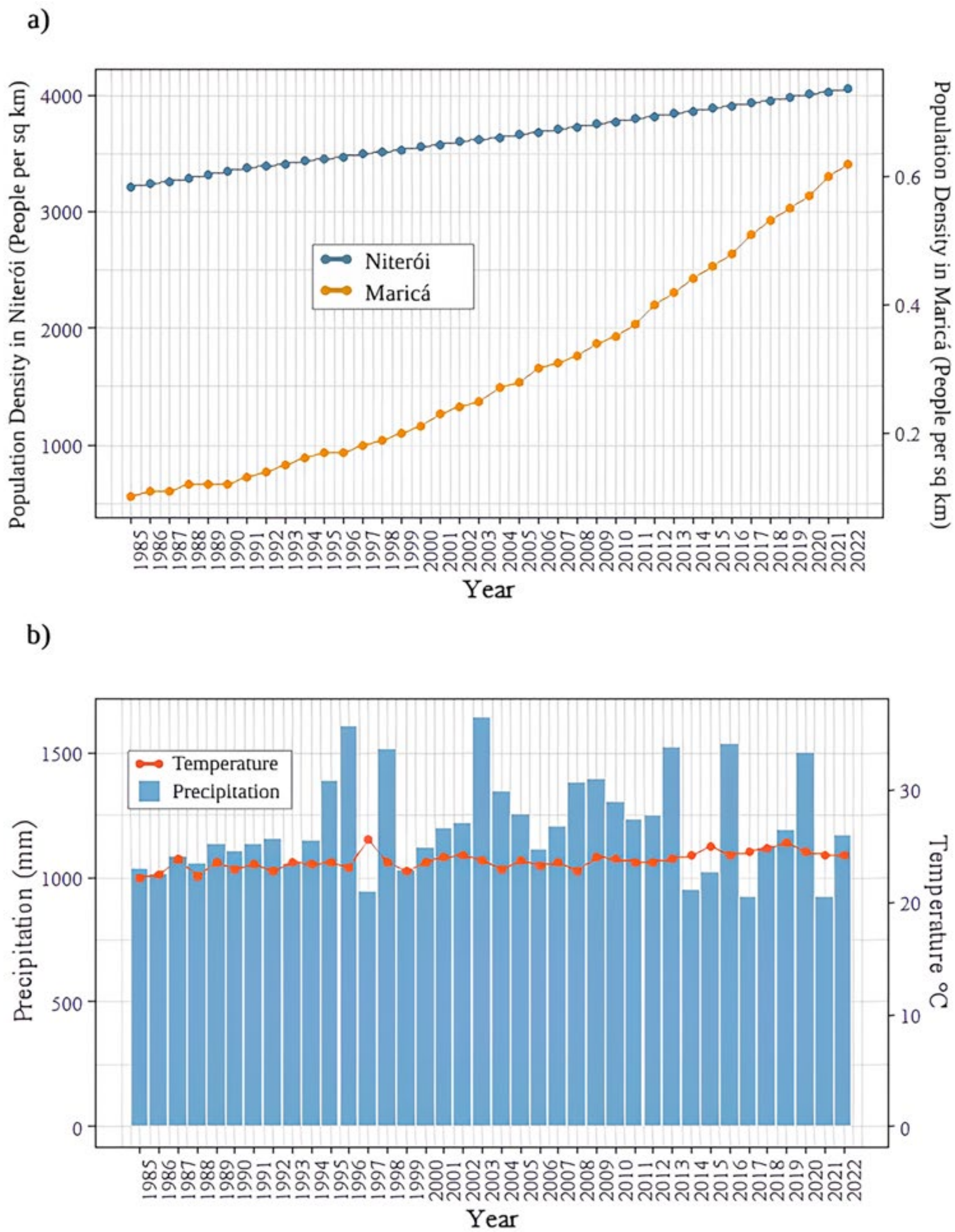

Figure 3. Plots of explanatory variables for 1985–2022. a) Average annual population density of Niterói and Maricá. b) Mean annual temperature and annual cumulative precipitation in Niterói and Maricá meteorological stations.

Table 2. Changes in hectares of the main classes of land use and land cover between 1985–2022 in Serra da Tiririca State Park, Rio de Janeiro, Brazil.

Year	Land use and land cover class								
	Forest formation	Restinga	Wetland	Rocky outcrop	Farming	Sandy areas	Urban area / Other non-vegetated areas	Water bodies	Not observed
	(ha)								
1985	2604.71	19.57	72.74	45.50	356.70	7.35	87.03	27.08	271.25
1986	2600.42	17.51	72.08	45.41	361.40	7.35	89.26	27.08	271.41
1987	2520.66	14.70	64.24	43.93	457.93	7.35	85.54	26.34	271.25
1988	2515.95	14.78	66.14	43.43	463.71	7.51	85.38	23.95	271.08
1989	2486.00	14.45	67.13	42.94	493.76	7.51	83.48	24.94	271.72
1990	2468.97	14.37	65.23	42.69	509.53	7.10	79.68	32.95	271.41
1991	2511.90	16.43	67.29	42.69	467.75	5.28	81.25	28.24	271.08
1992	2512.56	16.43	66.30	42.77	471.63	4.87	76.21	29.39	271.74
1993	2548.81	16.84	67.13	42.28	433.82	6.44	75.22	29.73	271.66
1994	2559.30	17.01	66.63	41.37	425.23	7.60	70.35	32.78	271.66
1995	2562.44	16.93	66.63	41.95	421.51	7.27	74.15	29.15	271.91
1996	2576.31	15.11	72.08	42.61	409.95	5.95	73.65	24.61	271.66
1997	2572.59	15.03	72.17	44.17	410.37	2.81	73.82	28.98	271.99
1998	2593.59	14.68	67.23	44.54	387.53	2.47	80.34	33.49	268.05
1999	2589.44	14.20	66.22	43.76	391.71	2.81	78.85	33.69	271.25
2000	2589.52	13.29	69.61	43.68	395.01	2.73	80.34	26.51	271.25
2001	2592.66	12.06	71.17	43.02	395.17	2.81	79.43	24.61	271.00
2002	2610.49	12.39	70.35	43.02	382.13	2.15	78.85	21.55	271.00
2003	2654.75	12.39	69.69	42.77	346.38	1.65	68.70	24.28	271.33
2004	2656.32	12.39	69.69	41.04	350.42	2.06	65.81	23.28	270.92
2005	2665.48	12.72	67.71	41.53	349.10	2.31	58.38	23.62	271.08
2006	2669.12	13.38	62.01	41.37	353.06	3.55	54.25	23.78	271.41
2007	2664.57	14.37	56.48	42.03	362.23	3.22	56.06	21.55	271.41
2008	2669.69	15.28	50.94	41.37	364.13	3.47	55.16	20.23	271.66
2009	2672.50	16.60	54.25	40.62	363.96	4.13	51.03	16.93	271.91
2010	2680.67	17.17	57.72	40.54	358.35	4.13	47.15	14.78	271.41
2011	2679.11	17.51	59.04	39.39	360.99	3.14	46.16	15.28	271.33
2012	2680.59	17.51	61.93	40.21	357.52	2.06	45.08	15.85	271.16
2013	2679.11	17.42	64.49	40.38	359.01	1.24	45.08	14.62	270.59
2014	2670.85	17.67	66.14	40.21	365.86	0.99	45.99	13.29	270.91
2015	2660.12	17.75	69.19	39.30	373.71	1.07	47.73	12.47	270.59
2016	2660.46	18.50	61.51	39.14	378.33	1.07	50.04	12.96	269.92
2017	2657.64	19.16	61.10	38.89	380.31	1.16	50.20	13.62	269.84
2018	2658.63	19.82	65.23	38.64	377.34	1.16	48.14	12.72	270.26
2019	2670.60	22.62	67.13	38.89	361.32	1.16	48.72	10.98	270.50
2020	2678.20	23.45	70.76	40.54	348.77	1.24	47.72	10.16	271.08
2021	2684.06	23.45	70.27	41.45	342.66	1.24	47.81	9.66	271.32
2022	2682.66	23.62	71.59	41.04	339.77	1.24	49.21	12.39	270.42

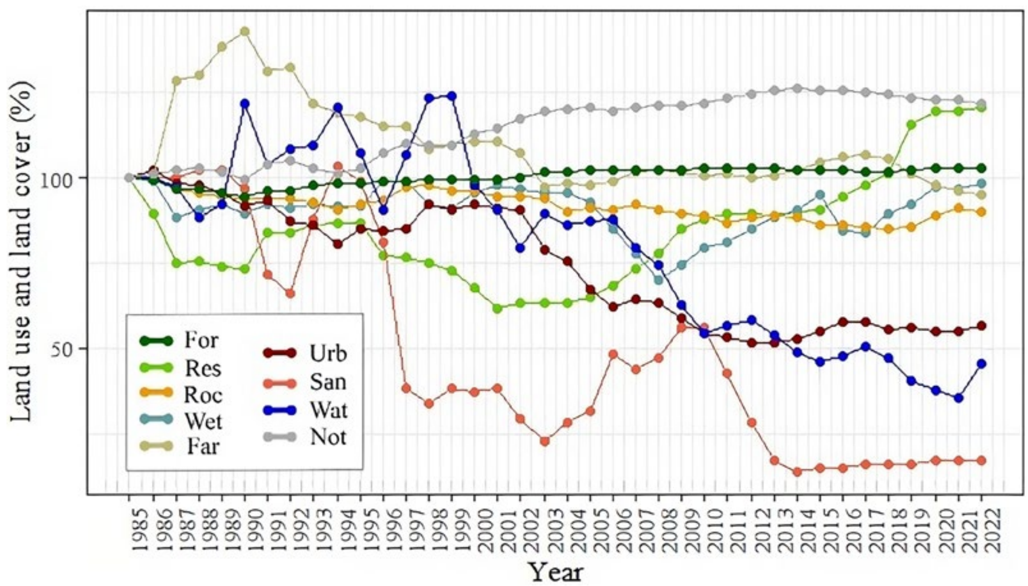

Figure 4. Temporal trends of land use and land cover classes between 1985-2022 in the Serra da Tirirca State Park, Rio de Janeiro, Brazil. For = Forest formation; Res = *Restinga*; Roc = Rocky outcrop; Wet = Wetland; Far = Farming; Urb = Urban area / Other non-vegetated areas; San = Sandy areas; Wat = Water bodies; Not = Not observed.

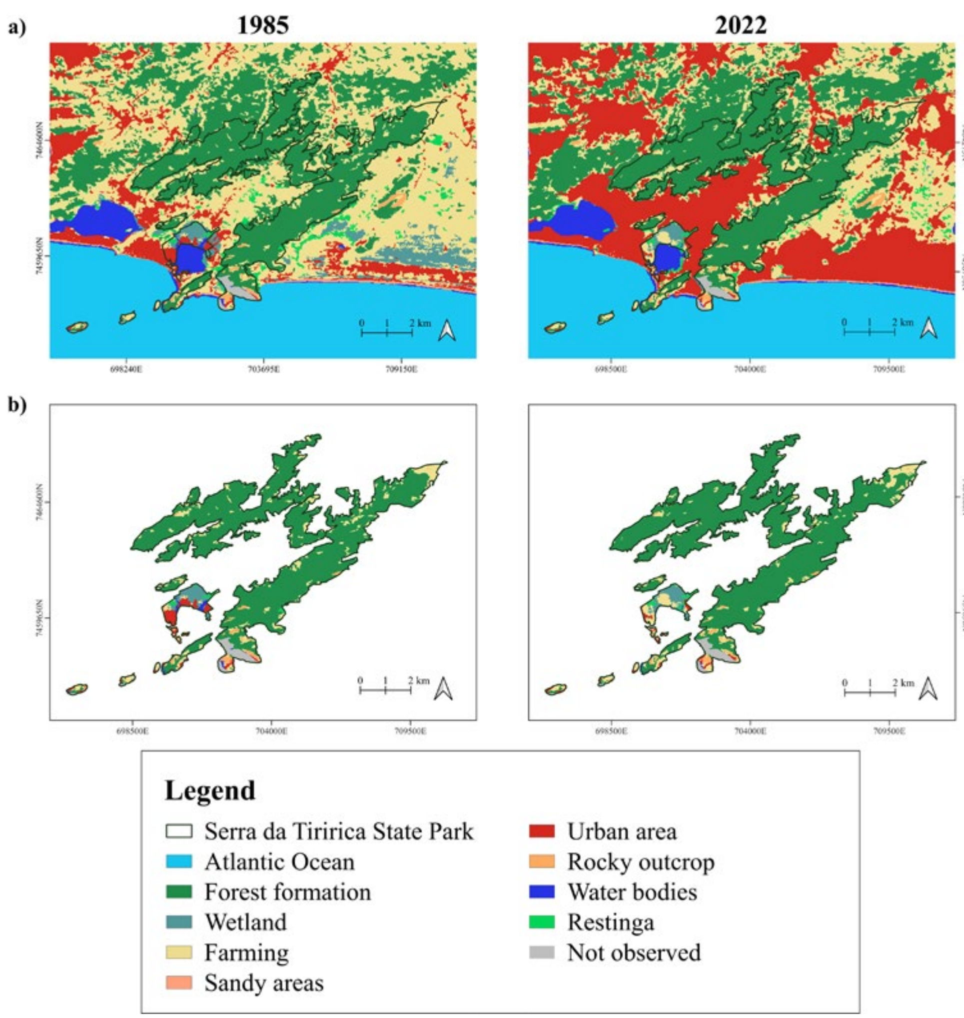

Figure 5. Land use and land cover changes in 1985–2022 in Serra da Tirirca State Park, Rio de Janeiro, Brazil. a) Map showing the PESET and their adjacent areas. b) map showing only the PESET.

Table 3. General linear model (GLM) generated from the relationship between classes and the predictor variables and predicted land use and land cover (LULC) change for 2032 in the Serra da Tiririca State Park, Rio de Janeiro, Brazil. GLMs show the coefficients of the most important variables of the models in each class. Positive parameters in GLMs indicate positive effects and negative parameters indicate negative effects. p <(F) = 0.001 ***; ns = not significant.

*Classes/*variables	Estimate (Std. error)	Res. Deviance (AIC)	LULC prediction for 2032 in hectares (gain/loss in %)
Forest formation	2269.79 (40.75)	104628 (385.71)	2781.37 (6.78)
Population density	217.62 (25.32) ***	50996	
Restinga	7.02 (3.36)	362.58 (175.66)	23.25 (18.81)
Population density	8.47 (1.61) ***	213.67	
Precipitation	−0.003 (0.002) ns	198.50	
Wetland	72.5 (5.58)	992.36 (236.37)	62.85 (−13.26)
Population density	−4.09 (3.46) ns	955.26	
Rocky outcrop	51.42 (1.17)	122.67 (117.84)	37.19 (−18.26)
Population density	−6.03 (0.72) ***	42.22	
Farming	584.46 (37.38)	75834 (380.95)	296.37 (−16.91)
Population density	−122.07 (23.23) ***	42913	
Sandy areas	16.49 (1.46)	209.34 (134.44)	−2.56 (−134.77)
Population density	−8.07 (0.91) ***	65.35	
Urban area	155.82 (7.13)	8795.6 (255.06)	20.80 (−76.09)
Population density	−57.21 (4.43) ***	1562.41	
Water bodies	65.12 (3.49)	2015.13 (200.86)	48.03 (77.36)
Population density	−7.24 (2.17) ***	375.27	

0.68%, wetlands 2.05%, rocky outcrops 1.18%, farming 9.73%, sandy areas 0.04%, urban areas 1.41%, and water bodies 0.35%. Unobserved areas represented 7.74% (Table 2).

Observing the annual time series for the period (1985–2022), it was possible to note an increase in area of 77.94 ha (2.99%) for forest formation and 4.05 ha (20.68%) for *restingas* (Figure 4 and 5). On the other hand, all other classes experienced losses in coverage proportion, with the most significant being sandy areas with a loss of 83.14% (6.11 ha), followed by water bodies with 54.27% (14.70 ha) and urban areas with 43.45% (37.82 ha). Rocky outcrops lost 9.80% (4.46 ha) of coverage, farming 4.75% (19.93 ha), and wetlands 1.59% (1.15 ha). Unobserved areas were represented with losses of 0.83 ha (0.31%) (Figure 4 and 5).

For the construction of the GLM models, population density was the variable that best explained the LULC of PESET across all classes (Table 3). A strong and significant relationship was observed for urban areas ($D^2 = 0.82$, $p < 0.001$), water bodies ($D^2 = 0.81$, $p < 0.001$), forest formations ($D^2 = 0.67$, $p < 0.001$), sandy areas ($D^2 = 0.68$, $p < 0.001$), and rocky outcrops ($D^2 = 0.66$, $p < 0.001$). Farming also showed a marginally significant relationship ($D^2 = 0.43$, $p < 0.001$). Wetlands exhibited a weak and non-significant relationship with population growth ($D^2 = 0.37$, $p > 0.5$). *Restinga* was the only class associated with both an anthropogenic and an environmental variable, showing a weak but significant relationship ($D^2 = 0.45$, $p < 0.01$).

The predictions generated from the GLMs showed that for the year 2032, the forest formation and *restinga* classes would continue to increase their coverage by 6.78% and 18.81%, respectively. On the other hand, the other classes will lose coverage or even vanish, as observed for the sandy areas class, with an estimated decrease in coverage of 134.77% (Table 3). All tested models, ranked by AIC, including those with correlations between explanatory variables, can be found in the supplementary material.

Discussion

By 2030, it is estimated that 1,2 billion people will inhabit urban areas (WUP 2018), leading to the conversion of approximately 290,000 square kilometers of natural habitats into anthropized landscapes (McDonald et al. 2020). This scenario raises concerns about how protected areas, such as those in the Atlantic Forest, will respond to increasing anthropogenic pressures. Although legal measures, such as the Atlantic Forest Law, have contributed to mitigating habitat loss, the challenge remains in balancing sustainable human development with environmental conservation. Our study contributes to this debate by assessing long-term changes in land use and land cover in a protected area and analyzing how anthropogenic and environmental factors influence these dynamics.

Although anthropogenic activities in the past had a significant impact on the landscape configuration of PESET in recent centuries, it was conservationist movements that led to the creation of PESET (Pimentel & Lindenkamp 2023), alongside the implementation of laws (e.g., Rio de Janeiro State Law No. 1.901/91 and Federal Law No. 11.428/06) and the establishment of regulatory agencies (e.g., the *Instituto Nacional do Ambiente* - INEA), which have directed PESET's

LULC over the last four decades. The local increase in forest formation and *restinga* cover, along with the decrease in urban areas and farming, contrasts with the broader negative trend of decreasing forest cover and increasing urbanization and farming in the AF (e.g. Rezende et al. 2018, Lira et al. 2021, Rosa et al. 2021). Notably, forest cover in the AF has been increasing in recent years in some states, such as Rio de Janeiro, due to natural regeneration (Crouzeilles et al. 2020).

The farming in PESET is associated with the edges and mostly in the extreme west of the Serra da Tiririca sector. Farming in the Serra da Tiririca, given the predominantly herbaceous composition of these areas, is more vulnerable to anthropogenic fires (Zuñe-da-Silva et al. 2022). However, the gradual decrease in farming coverage in recent years indicates significant progress in the actions to prevent and combat fires and recover degraded areas stipulated in the management plan of PESET (INEA 2015). Also, we observed in figure 5 that farming in the Lagoa de Itaipú sector has expanded into areas that previously represented urban and wetlands. The significant decrease in urban areas is explained by the expansion of farming in the Lagoa de Itaipú. Nevertheless, in some places, such as the Serra da Tiririca sector, this coverage remains constant. This could be due to the presence of traditional communities and residences that settled within the boundaries of PESET before its creation (Pimentel & Lindenkamp 2023).While we can observe a trend toward the increase of losses in natural areas due to the weakening of regulatory agencies (Faria et al. 2021), such as the *Sistema Nacional de Meio Ambiente* (SISNAMA) and the *Conselho Nacional do Meio Ambiente* (CONAMA), and continuous changes in laws and regulations, it is essential to recognize that this may not accurately reflect the situation in PESET. In fact, the establishment of this PA has contributed to a positive trend in forest and *restinga* coverage, suggesting that well-implemented conservation measures can yield beneficial outcomes even amid external pressures. Moreover, recent estimates of aboveground biomass stocks in PESET indicate that this protected area plays a crucial role in carbon storage and ecosystem stability (Zuñe et al. 2024a). This reinforces the importance of conservation strategies that not only promote LULC resilience while enhancing ecosystem services provided by the Atlantic Forest remnants. However, the weakening of regulatory frameworks has historically led to a reduction in the legal protection of native areas, facilitating real estate speculation in vulnerable regions, such as *restingas* (Santos et al. 2023). Despite being recognized as ecosystems rich in biodiversity (Zamith & Scarano 2006), *restingas* face threats. Nevertheless, in this study, the *restingas* fluctuated, reaching a minimum area of 12.06 ha in 2001, the same year that Rocha et al. (2007) recorded 20.71 ha for the Itaipú *restinga*. Today, only the area within the boundaries of PESET (23.62 ha) exceeds the values estimated by Rocha et al. (2007) and by INEA (2015) in 2011 (1.43 ha), which highlights a notable restoration, possibly due to natural regeneration or the implementation of monitoring and reforestation programs observed in the PESET management plan (INEA 2015).

The decrease in the coverage of sandy areas, wetlands, and water bodies can be explained by the expansion of the *restingas* in the Lagoa de Itaipú sector. The degradation of surrounding ecosystems and increased anthropogenic and climate pressures can lead to the gradual loss of sandy areas, as evidenced by Orlando et al. (2018), who demonstrate that these habitats are particularly sensitive to changes in land use and climate. This potential for sandy areas to diminish or even disappear over time raises concerns about their long-term viability. The decrease in rocky outcrops follows the trend of projected loss of areas for the AF (Rezende et al. 2018). This loss is due to changes in climatic and the edaphic conditions of the habitats (Esser et al. 2019). In PESET, in addition to environmental factors, the increase in the number of invasive species (Machado et al. 2020) could explain the decrease in coverage of rocky outcrops.

The positive and significant correlation between population density and temperature could serve as evidence linking recent climate changes directly to contemporary anthropogenic activities. However, when refining our models, we observed that precipitation emerged as a key predictor of LULC changes, particularly in restinga ecosystems, where lower precipitation levels were associated with increased restinga cover. This result may be linked to the ecological characteristics of restinga environments, which develop on sandy coastal deposits influenced by marine processes and exhibit a vegetation mosaic adapted to water scarcity and high soil drainage capacity (Brasil 2012). These findings highlight the combined influence of temperature and precipitation in shaping environmental conditions essential for biome distribution (Colombo & Joly 2010). Also, we found that the environmental gradients were within the average estimates for the region (INEA 2015). We strongly recommend conducting further GLMs incorporating a variety of anthropogenic variables to enhance both the descriptive and predictive capacity of the models aimed at ecological studies in the Atlantic Forest.

Our findings highlight the importance of anthropogenic and environmental factors in forest conservation. While conservation initiatives effectively protect biodiversity, as demonstrated in the Serra da Tiririca State Park, where species diversity is significant (Zuñe et al. 2024b), they may present challenges for PESET management. This underscores the necessity for balanced management that considers both ecological integrity and the effectiveness of conservation strategies. The conservation of forests remains feasible in AF, even amid increasing population pressure, if appropriate protective measures are implemented (Resende et al. 2024). Thus, enhancing management practices at PESET requires not only collaboration with stakeholders but also the integration of adaptive management strategies that prioritize both ecological resilience and community engagement, ultimately ensuring the long-term sustainability of this crucial ecosystem.

Conclusion

This study suggests that the patterns of change in LULC over approximately four decades in PESET are dynamic and predominantly influenced by anthropogenic factors, with environmental variables playing a secondary role. There is a trend of increasing forest formations and *restinga* cover and a decrease in urban and farming areas. Areas predominantly characterized by sparse or absent vegetation, even when under protection, are more susceptible to adverse effects from anthropogenic and environmental factors. The growth in human population density outside the PA plays a fundamental role in the variation of the PESET landscape and is not always related to a negative effect on biodiversity. These findings provide an initial insight into the state of LULC changes in PESET and offer predictions that will assist the management of the PA in implementing conservation policies and strategies aimed at preserving the main classes of public interest.

Supplementary Material

The following online material is available for this article:

Table S1 – General Linear Models (GLMs) with Gaussian distribution ranked by Akaike Information Criterion (AIC), detailing the coefficients for each model

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Conflicts of Interest

The authors declare that they have no conflict of interest related to the publication of this manuscript

Ethics

This study did not involve human beings and/or clinical trials that should be approved by one Institutional Committee.

Data availability

The datasets generated during and/or analyzed during the current study are available at: https://doi.org/10.48331/scielodata.JNXC1Y

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