Marine Pollution Bulletin 216 (2025) 118006

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

# Extinction risk of the endemic soft coral *Phyllogorgia dilatata* (Esper, 1806) in a remote island of the Brazilian coast

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ARTICLE INFO

*Keywords:*
Local extinction
Soft corals
Oceanic Islands
Conservation
Brazilian coast
Southwestern Atlantic
Functional extinction

ABSTRACT

The Brazilian endemic octocoral *Phyllogorgia dilatata* (elephant ear sea fan) plays a crucial ecological role in the marine ecosystems of the Brazilian coast. Our work investigates the local extinction of *P. dilatata* on Trindade Island, a remote oceanic island in the Southwestern Atlantic, and assesses the potential impacts of climate change on its distribution. Field surveys conducted over two years (2016–2019) revealed no live individuals of *P. dilatata*, with only dead peduncles remaining, marking the first observed local extinction of this species. Species distribution models (SDMs) incorporating current and historical climate data were used to estimate the species' habitat suitability and project future distribution under different climate scenarios. Results indicate that *P. dilatata* currently inhabits approximately 93,090 km$^2$ of suitable area, primarily within tropical ecoregions, but faces significant habitat loss under future climate projections. By 2090–2100, models predict a 63.38 % loss of habitat under the high-emission RCP 8.5 scenario, with severe impacts on tropical regions, including Trindade Island. Environmental variables such as temperature, oxygen concentration, and salinity were identified as key drivers of the species' distribution, while non-climatic factors like seawater velocity, were also significant. The extinction on Trindade Island is attributed to a combination of historical isolation, climate change, and local anthropogenic stressors, including pollution and overfishing. The current investigation highlights the urgent need for conservation efforts, including the establishment of marine protected areas and restoration programs, to protect this vulnerable species and similar marine organisms again climate change.

## 1. Introduction

Soft corals (Octocorallia) are considered marine animal forests (MAFs) (Macrina et al., 2024) that play a crucial role in providing biocomplexity and/or variability to biodiversity related to reef ecosystems (Sánchez, 2015; Slattery and Lesser, 2021). These corals have remarkable ecological functions that contribute to the health and resilience of marine ecosystems (Sánchez, 2015; Steinberg, 2022). However, there are pronounced scientific gaps on the knowledge about the response of soft corals to a combination of local and global stressors since most research to date has focused on scleractinian corals (Sánchez, 2015; Vollstedt et al., 2020).

The subclass Octocorallia comprises soft corals, sea fans, blue corals, and sea feathers, representing the largest known group of corals, with about 3000 existing species, composed of 47 families and 340 valid genera (Araújo, 2016; Pérez et al., 2016). Octocorals exhibit a wide distribution, ranging from shallow to deep waters (~6000 m) (Bayer, 1961; Cairns, 2007; McFadden et al., 2006; Pérez et al., 2016; Macrina

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https://doi.org/10.1016/j.marpolbul.2025.118006
Received 12 December 2024; Received in revised form 15 April 2025; Accepted 15 April 2025

et al., 2024), occurring from the Arctic to the Antarctic. The presence of octocorals in nearly all benthic marine habitats suggests they are extraordinary adaptive if compared to other groups of Cnidaria (Araújo, 2016; Macrina et al., 2024).

In the southwestern Atlantic, the Brazilian coast harbors a high percentage of endemic soft corals (nine species, 50 % endemic) and should be considered a priority for Atlantic biodiversity conservation (Cassola et al., 2016). The octocoral *Phyllogorgia dilatata* (Esper, 1806) is one example of a Brazilian endemic species which occurs from the northern tropical portion of the Brazilian coast (e.g., Parcel do Manuel Luiz, Maranhão State) to the subtropical reefs of the southeastern coast (e.g. Arraial do Cabo, Rio de Janeiro State), including nearshore and some oceanic islands (Cassola et al., 2016; Castro et al., 2010). During the past two decades, there was a decline in the population of *P. dilatata* along the Brazilian coast (Cassola et al., 2016; Francini-Filho et al., 2008). There are records of large-scale collection for souvenirs (Pinheiro et al., 2018), but the general cause is still unknown. Like in other biogeographic realms, the South Atlantic reefs had suffered from overfishing (Norderhaug et al., 2021), pollution and intense aquatic tourism (Magris and Giarrizzo, 2020; Monteiro et al., 2018) plus ocean water warming (Soares et al., 2021; Chidichimo et al., 2023). In addition to anthropogenic pressures and ocean warming, recent studies have identified biogenic stressors-such as diseases, parasites, and predation-as important factors influencing soft coral health and persistence. For instance, *P. dilatata* is known to suffer from specific diseases (Francini-Filho et al., 2008), and faces predation pressure from the gastropod *Cyphoma macumba* (Dias et al., 2016), while reports of parasitic copepods in other gorgonians (e.g., *Gorgonia ventalina*) raise the possibility of similar interactions in *P. dilatata* (Pardo et al., 2024). These biogenic agents may act synergistically with environmental stressors, compounding the vulnerability of endemic soft corals. All these factors alone or their interactions can influence the adaptive capacity of marine forests, limiting their resistance and resilience (Orejas et al., 2022).

Herein, we report the first monitored local extinction of a soft coral (*P. dilatata*) on a near pristine remote Island of the Brazilian coast. Such species, reported for the Trindade and Martin Vaz archipelago since 1919 (Castro et al., 2010), have not been recorded after two expeditions 2016 and 2019 when only dead peduncles were detected. Distributional patterns of *P. dilatata* along its native range and projections of past and future scenarios (Species Distribution Models — SDMs) were also used to explore the influence of climate changes on the distribution of *P. dilatata*. Conservation strategies for the biodiversity of these oceanic locations and the selection of priority areas for the conservation of the species are also discussed.

## 2. Material and methods

### 2.1. *P. dilatata* monitoring on Trindade Island

Trindade Island (TRI) is the largest emerged landmass situated within the Vitória Trindade Chain (VTC) seamounts complex, located at the Central portion of the Brazilian Coast [Fig. 1(a, b)]. The VTC geologic formation is constituted by assorted volcanic seamounts disposed in an E–W alignment between 19 and 21°S latitude, extending from 200 to 1200 km far from the Brazilian Central Coast. TRI, the largest island of the VTC complex, harbors a diverse assemblage of marine species, making it a focal point for ecological research (Pinheiro et al., 2015; Anderson et al., 2023). The population of *P. dilatata* was

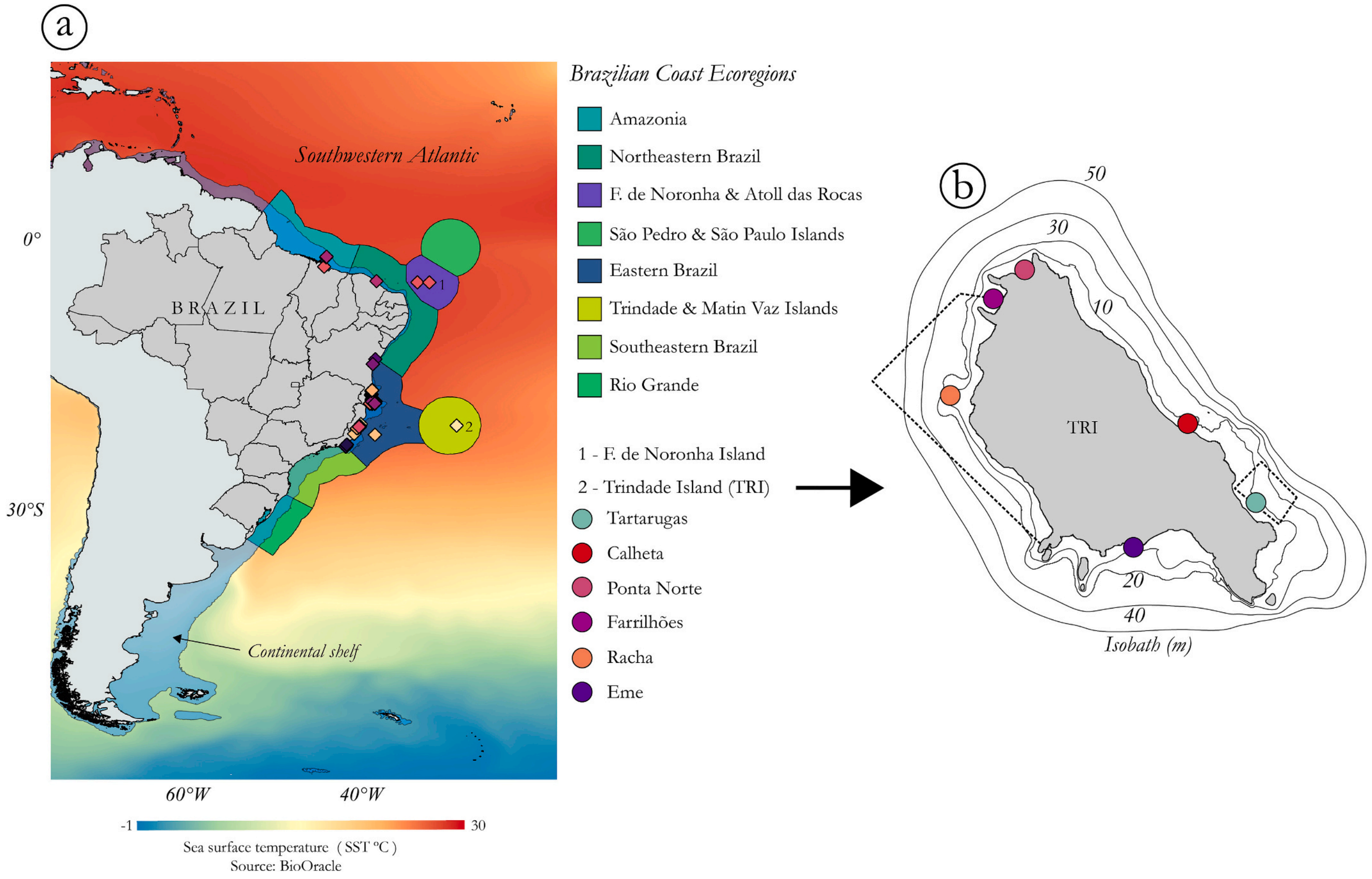

**Fig. 1.** a) Map of the Southwestern Atlantic showing the occurrence records of *P. dilatata* across the Brazilian Coast's Ecoregions. The colored diamonds represent the "true presence" extracted from data repositories and literature. b) Zoomed map of the Trindade Island and the sampled sites (colored circles). The dashed lines represent the Marine Protected Areas.

sampled during two expeditions: in June/July 2016 and September/October 2019. Six sites were selected in TRI: two sites located at the east portion of the island (Tartarugas and Calheta); two sites positioned at the north portion of the island (Ponta Norte and Farrilhões); Racha and Eme positioned at the west portion of the island [Fig. 1(b)]. Standard ($20 \times 2 = 40$ m$^2$ sample) strip belt transects [Underwater Visual Censuses/UVCs (20 m in length by 2 m in width (1 m left and 1 m right)] were applied (Jonker et al., 2008; Anderson et al., 2019; Anderson et al., 2020). A total of 120 standard strip transects were performed covering an area of 4800 m$^2$. In each of the six sites 20 transects were performed, totaling 800 m$^2$ sampled. Water transparency during sampling ranged from 10 to 50 m; minimum reef depth during the study was 5 m at Calheta, and the deepest was 25 m at Racha, water temperature ranged from 25 to 28 °C.

### 2.2. *Modeling procedures*

Georeferenced presence data for the whole distribution of *Phylogorgia dilatata* octocoral were compiled from the Global Biodiversity Information Facility (GBIF, 2024), iNaturalist (iNaturalist, 2024), Ocean Biodiversity Information System (OBIS, 2024) and literature (Fig. 1; Appendix 1). The distribution of *P. dilatata* encompasses five Ecoregions of the Brazilian coast (including oceanic islands), ranging from the Parcel Manoel Luiz (Maranhão state, Northern Brazilian coast) to Arraial do Cabo (Rio de Janeiro state, Southeastern Brazilian coast) (Cassola et al., 2016) [Fig. 1(a)].

The distribution patterns of *P. dilatata* under present-day conditions, past and future climate changes were explored using the SDM approach (Araújo and Peterson, 2012), following well-established criteria for biodiversity assessments (Araújo et al., 2019). These models were constructed with three high-performance machine learning algorithms, namely Boosted Regression Trees (BRT; Elith et al., 2008; Krause-Jensen et al., 2020), Adaptive Boosting (AdaBoost; Krause-Jensen et al., 2020), and Extreme Gradient Boosting (XGBoost; Chen and Guestrin, 2016). Considering our approach of presence-only models, pseudo-absences were randomly generated in regions where no occurrences have been recorded. The entire process of generating pseudo-absences is detailed in Gouvêa et al. (2024).

Climate data for modeling was obtained from Bio-ORACLE v2.0 (Assis et al., 2024), including last glacial maximum (LGM: ~21 kya BP), present-day conditions (decade 2010–2020), and two contrasting future scenarios of climate change in 2090–2100 (RCP 2.6 and 8.5). Seven biologically meaningful predictor variables were considered for each period and scenario: benthic temperature (long-term average of monthly maximum and minimum), nutrient conditions (nitrate), seawater velocity, salinity, oxygen, and primary productivity. Additionally, to account for the typical depth range of *P. dilatata* octocoral (0 to 30 m depth), the layers were constrained to a maximum depth of 30 m using a bathymetric dataset. Before modeling, Pearson's correlation coefficient and variance inflation factor (VIF) were evaluated between predictors (Fig. S1).

To reduce overfitting, hyperparameter tuning was performed through cross-validation using all hyperparameter combinations for each algorithm tested (Elith et al., 2008; Gouvêa et al., 2024). To further reduce overfitting in the models, monotonicity constraints were applied in the predictors based on the expected biological outcome of the models' response (Hofner et al., 2011). In particular, positive for minimum temperature, sea water velocity, salinity, oxygen, productivity, nutrient conditions and negative for maximum temperature.

We assessed the performance of SDMs by using the Boyce index, as it is a recognized metric for presence-only models (Boyce et al., 2002), as well as area under the receiver operating characteristic curve (AUC), sensitivity and specificity parameters (Allouche et al., 2006). Full models, considering all predictor variables and the combination of hyperparameters retrieving lower prediction error in cross-validation, were built to explore the relative contribution of predictors and to develop partial dependence plots reflecting the effect of each predictor on the response of models (Anderson et al., 2021; Assis et al., 2017; Elith et al., 2008). Distribution maps were developed for present-day conditions, past and for the different RCP future climate change scenarios by averaging the predictive responses of the three algorithms and the multiple cross-validation rounds (i.e., ensemble modeling; (Araújo et al., 2006). These maps were reclassified to represent presence and absence (i.e., binomial maps) with the minimum training area threshold, which is based on setting a minimum predicted area while maintaining a sensitivity higher or equal to 0.95 (Vignali et al., 2020). All analyses were performed in the R programming language (R Core Team, 2023). Data and code are openly available for reproducibility in Figshare (https://figshare.com/s/f0877502487f67c57ed6) and Github (https://github.com/jorgeassis/speciesDistributionModelling), respectively.

## 3. Results

### 3.1. *The absence of P. dilatata on TRI*

After two expeditions to TRI (2016 and 2019), 120 standard strip transects performed covering an area of 4800 m$^2$ not a single individual of *P. dilatata* was recorded alive. Only skeletons and dead peduncles of the soft coral were recorded at the western portion of TRI between Ponta Norte and Calheta [Fig. 1(b)].

### 3.2. *Distribuition modeling of P. dilatata along the Brazilian coast*

Occurrence data compilation after removing duplicates and implementing spatial autocorrelation steps over the initial 223 records resulted in 80 records to model the distribution of *Phylogorgia dilatata*. The performance of models was high across the three algorithms, both in cross-validation and the final predictions, with further improvement when combined into a unique ensemble (final prediction Boyce index: 0.74; AUC: 0.98). The ensemble models had low uncertainty of up to 0.14 (based on the standard deviation of the algorithms).

Minimum and maximum temperature largely explained the distribution of the octocoral (combined relative contribution of 59.47 %), followed by oxygen availability, productivity and salinity with 15.22 %, 12.47 % and 9.98 %, respectively. Nitrate and Sea Water Velocity had residual contribution in the model (relative contribution <5 %, Fig. S2). These results are supported by the generally low correlation found between predictor layers. Only temperature predictors showed a stronger correlation (Pearson's correlation 0.83; VIF > 10; Fig. S1; Table S1), yet their opposite fit, as forced by monotonicity constraints, removed potential confounding inferences regarding their contributions to the response of models.

Considering the most contributive predictors (>5 % of relative contribution), occurrence of *P. dilatata* indicated conditions with temperatures ranging from 17.96 °C to 28.58 °C, oxygen and productivity above 201.48 mol·m$^{-3}$ and 2.87 g·m$^{-3}$·day$^{-1}$, respectively, and salinity of 28 (Fig. S3).

The present-day potential distribution of *P. dilatata* estimated a potential area of 93,090 km$^2$, with high suitability (i.e., 88 % of the area) within the Tropical Atlantic realm, particularly in Eastern, Northeastern and Amazonia regions of the Brazilian coastline. When compared to models reflecting past climate conditions, the projected area was 27,089 km$^2$, indicating a significant increase of 70.9 % in the current distribution (Table 1). This expansion translates to an increase in area of 61.57 % for the Tropical Atlantic and of 71.10 % for Temperate South America at the Realm level (Table S2). Despite the overall patterns of expansions of *P. dilatata* under present conditions, the models showed a contraction of the potential coral distribution by over 100 % (Table 1) for Fernando de Noronha and Atol das Rocas, as well as Trindade and Martin Vaz Islands.

Considering the two RCP scenarios of future change, projections showed distribution areas of 78,466 km$^2$ and 34,089 km$^2$ (RCP 2.6 and

**Table 1**
Potential distribution areas (km$^2$) and changes in area (%) of *P. dilatata* predicted per marine Ecoregion according to Spalding et al. (2007) for the past, present and future conditions (RCP scenarios). The minus (and plus signs represent areas with losses and gains of *P. dilatata*, respectively. Blue and green color indicate the Brazilian oceanic islands.

| Ecoregion | LGM | Present | Changes (%) | RCP 2.6 | Changes (%) | RCP 8.5 | Changes (%) |
|---|---|---|---|---|---|---|---|
| Amazonia | 11,496.89 | 25514.10 | +54.94 | 17,580.73 | −31.09 | 8103.52 | −68.24 |
| Eastern Brazil | 6296.22 | 46073.41 | +86.33 | 41,924.24 | −9.01 | 10,628.40 | −76.93 |
| Fernando de Noronha and Rocas Atoll | 150.24 | 65.54 | −129.23 | 64.41 | −1.72 | 21.45 | −67.27 |
| Guianan | 0.00 | 21.43 | +100.00 | 25.96 | +21.16 | 8.06 | −62.40 |
| Northeastern Brazil | 4994.69 | 10,761.10 | +53.59 | 7482.80 | −30.46 | 2677.92 | −75.11 |
| Trindade and Martin Vaz Islands | 59.52 | 11.90 | −400.34 | 9.78 | −17.81 | 9.43 | −20.69 |
| Rio Grande | 693.20 | 2653.85 | +73.88 | 2725.81 | +2.71 | 3502.18 | +31.97 |
| Southeastern Brazil | 3396.66 | 7988.82 | +57.48 | 8651.60 | +8.30 | 9137.22 | +14.38 |

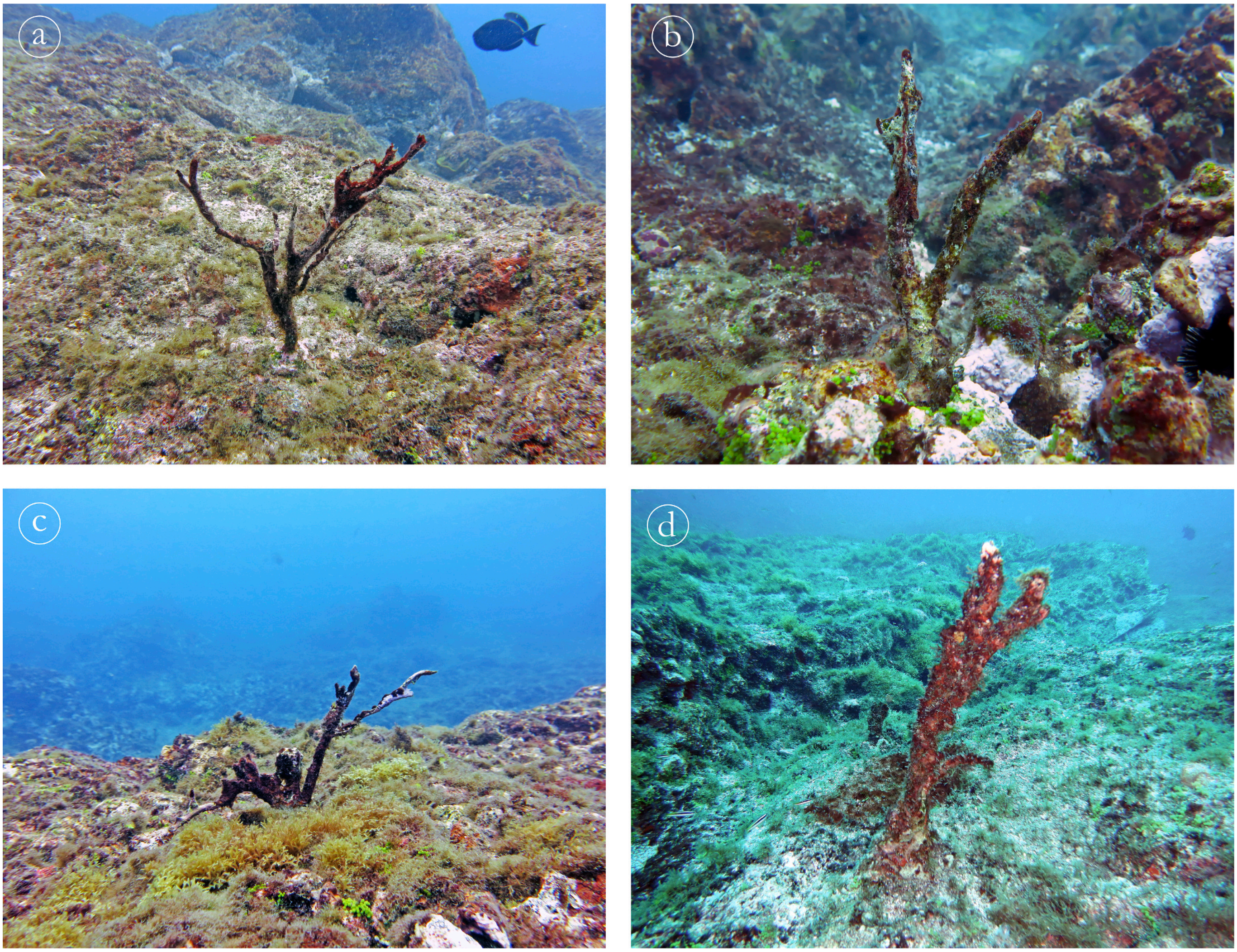

**Fig. 2.** Skeletons/peduncles of *P. dilatata* photographed at the eastern portion of TRI island (a, b, c and d). b) 2019 Images from PELD-ILOC (Projeto Ecológico de longa duração — Ilhas Oceânicas Brasileiras).

RCP 8.5, respectively), reflecting losses of 15.70 % and 63.38 % of area when compared to the current extent. These reductions were pronounced along the Eastern, Northeastern, Amazonia, Fernando de Noronha and Atol das Rocas and Guianan coastlines with losses exceeding 60 % in suitable areas (Table 1, Fig. S4). Additionally, the TRI islands, where our field surveys were conducted, is estimated to lose up to 21 % under future climate change scenarios (Table 1, Fig. 2). The changes in potential distribution of the endemic coral were also marked by expansions along the temperate coastlines, notably in regions like Southeastern Brazil and Rio Grande with an estimated increase in area of up to 15 % and 32 % under future scenarios, respectively (See Fig. 3).

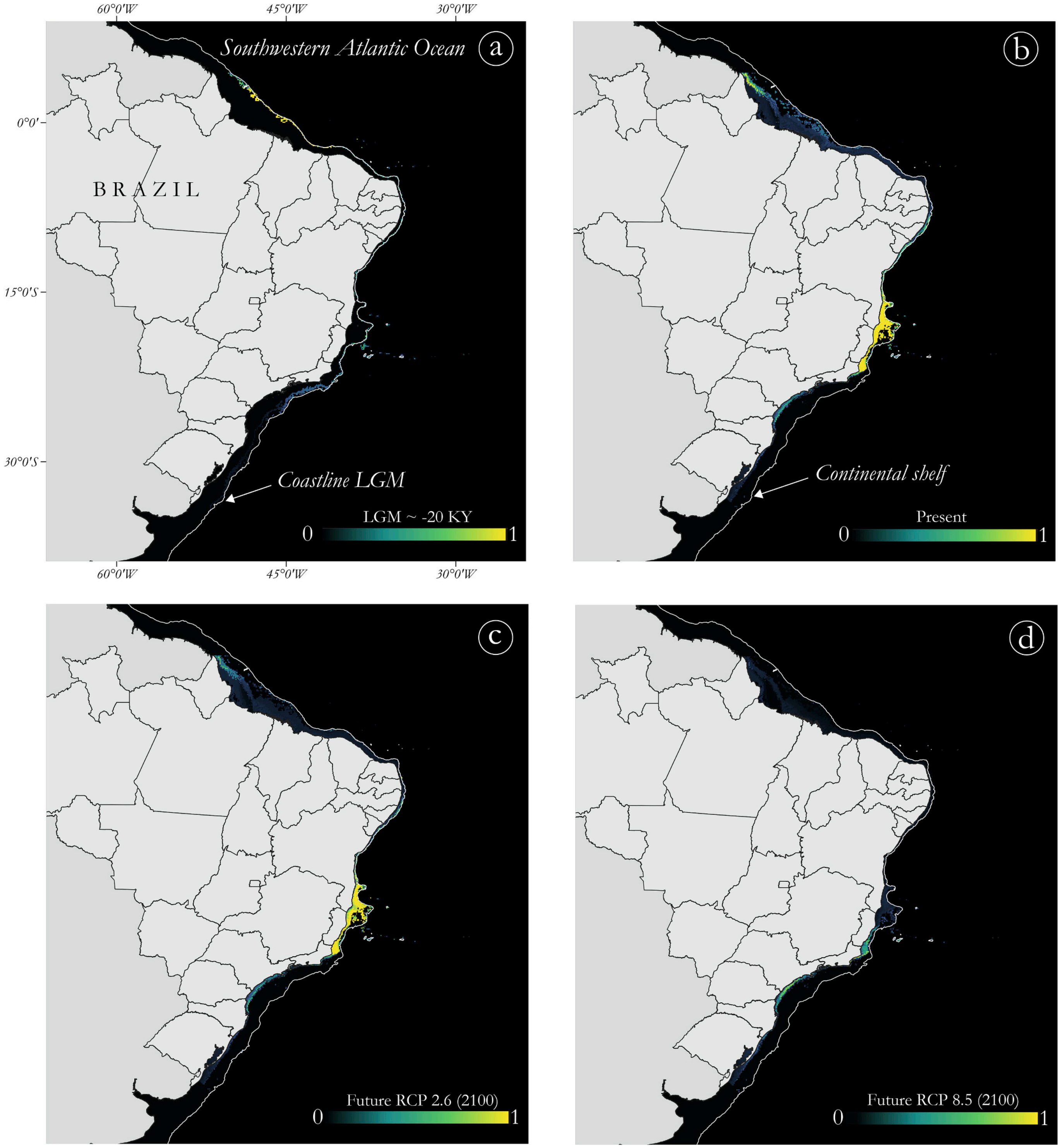

**Fig. 3.** Potential distribution of *P. dilatata* under (a) Last Glacial Maximum (LGM), (b) Present day conditions, and two scenarios of climate changes (c) RCP 2.6 and (d) RCP 8.5. The habitat suitability maps are shown on a blue (low suitability) to red (high suitability) scale. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

## 4. Discussion

### 4.1. The extinction on Trindade Island

The local extinction of *Phyllogorgia dilatata* on Trindade Island, as evidenced by its absence in recent surveys and the presence of only dead peduncles, likely results from a combination of biogeographic, ecological, and climatic factors. One plausible hypothesis is that the population was isolated since the Last Glacial Maximum (LGM), as suggested by species distribution models (SDMs) indicating limited suitable habitat connectivity between Trindade and other parts of the Brazilian coast during this period. This isolation may have restricted gene flow and the recruitment of new individuals, rendering the population vulnerable to demographic stochasticity and environmental changes over time. Alternatively, the population may have arisen from recent colonization events by vagrant individuals transported via ocean currents or rafting. However, the absence of living specimens during multiple expeditions implies that if colonization occurred, it did not establish a sustainable population, possibly due to unsuitable environmental conditions or lack of sufficient propagule supply. A third possibility is natural extinction driven by a bottleneck effect in an isolated population (Fauvelot et al., 2003; Ludt and Rocha, 2014; Nimbs et al., 2023; Sherpa et al., 2021). This scenario could involve a delicate balance between colonization and extinction events, where the geographic isolation of Trindade Island failed to provide a consistent source of recruits to maintain population viability, eventually leading to collapse.

Climate change emerges as a significant factor in the extinction of *P. dilatata* at Trindade Island. Rising sea surface temperatures, compounded by localized stressors such as potential shifts in water quality and habitat conditions, may have exceeded the physiological thresholds of the species (Hofmann and Todgham, 2010; Lesser, 2013). SDMs projecting future climate scenarios under high-emission pathways (RCP 8.5) reinforce this hypothesis, as they predict habitat contractions of over 60 % in tropical regions, including oceanic islands such as Trindade. Our projections for the period spanning 2090 to 2100 estimate changes in the distribution of *P. dilatata*, particularly intensified under the higher emission scenario RCP 8.5 (projected area losses of 63.38 %). These shifts were particularly strong along the Tropical Atlantic regions in the Brazilian coastline. Aligning with global efforts to minimize environmental alterations alongside local-scale habitat availability may reduce the losses up to four times (i.e., ~16 % under RCP 2.6 scenario) (Dixon et al., 2022; Gurney et al., 2013; Staude et al., 2019; van Woesik et al., 2022; Wiens and Bachelet, 2010). Biogenic factors such as diseases, parasitism, and predation may have also contributed to the local extinction of *Phyllogorgia dilatata* at Trindade Island. Although not addressed in the original modeling, these biological interactions are increasingly recognized as drivers of soft coral decline (Francini-Filho et al., 2008; Steinberg et al., 2020). Disease outbreaks, such as the one described by Cassola et al. (2016) and later documented in detail for *P. dilatata* by Francini-Filho et al. (2016), could cause rapid population declines, especially in isolated environments. While specific studies on parasites of *P. dilatata* are lacking, analogues from the Caribbean show that gall-forming copepods significantly affect gorgonians such as *Gorgonia ventalina* (Korzhavina et al., 2024). Predation is also a plausible mechanism, with the ovulid gastropod *Cyphoma macumba* reported as a specialized predator of *P. dilatata* (Pinto et al., 2017), and the crab *Banareia palmeri*, known to predate on Caribbean gorgonians, occurring in Brazilian waters (Ozten Low et al., 2025). These biotic pressures, especially when synergizing with abiotic stressors like warming and isolation, could have accelerated the collapse of this endemic coral population. Future studies should prioritize the integration of biotic stressors in models assessing extinction risk for marine foundation species such as *P. dilatata*.

The combined impacts of these factors highlight the intricate interplay between historical biogeographic processes and contemporary climatic shifts, underscoring the vulnerability of isolated endemic populations in the face of rapid environmental changes. This points out the potential impact of future climate change on the coral *P. dilatata* and emphasizes how compliance with global efforts (e.g., Kyoto, Montreal and Paris agreements) could mitigate these expected changes in its distribution.

### 4.2. Present-day habitat suitability and environmental drivers: insights into physiological thresholds and coral productivity

The models estimated a potential distribution area of 93,090 km$^2$ for present-day conditions, consistent with the known range of *P. dilatata* along the Brazilian coastline. The regions of highest suitability were concentrated within the Tropical Atlantic realm, extending into parts of Temperate South America, highlighting the species' preference for warm-water ecosystems. The modeled distribution patterns were primarily explained by temperature-related variables, with minimum and maximum temperature contributing a combined relative importance of 59.47 %. The predicted suitable temperature range for *P. dilatata* was between 17.96 °C and 28.58 °C, a finding that aligns with observed physiological thresholds reported for closely related genera, emphasizing the critical role of thermal conditions in defining coral habitats (McClanahan et al., 2020; Yuan et al., 2023). These thresholds suggest that *P. dilatata* is highly sensitive to deviations beyond this temperature range, with potential impacts on metabolic processes such as respiration, calcification, and reproduction.

In addition to temperature, other environmental variables influenced the distribution of *P. dilatata*. Oxygen concentration and primary productivity were secondary but significant contributors, reflecting the species' reliance on nutrient-rich and well-oxygenated waters to sustain growth and survival. High primary productivity supports the energetic demands of coral metabolism, particularly under fluctuating environmental conditions. Salinity was also identified as a relevant predictor, suggesting the importance of stable salinity regimes in maintaining physiological homeostasis (Fox et al., 2018; Hofmann and Todgham, 2010; Lesser, 2013; Spence and Tingley, 2020). These findings highlight how *P. dilatata* may thrive in environments with moderate nutrient availability and stable oceanographic conditions, aligning with broader patterns of octocoral ecology.

Non-climatic drivers (e.g., seawater velocity) play a role in shaping the distribution of *P. dilatate*. Low wave energy conditions, as suggested by Sheppard et al. (2005), are particularly favorable for the establishment of sessile organisms like soft corals, as excessive hydrodynamic forces can hinder larval settlement and substrate attachment. But this ecological balance will collapse under the current scenario of future greenhouse gas emissions, causing severe changes on seawater temperature, velocity and circulation with direct impacts on nutrients availability (Ditlevsen and Ditlevsen, 2023), which will directly impact the health of the Brazilian endemic soft coral *P. dilatata*. This factor underscores the importance of sheltered reef environments and highlights how local habitat features interact with larger-scale climatic variables to influence distribution patterns.

The integration of these environmental drivers into species distribution models provides critical insights into the ecological requirements of *P. dilatata* and the potential tipping points that could disrupt its persistence. For instance, rising sea temperatures and altered oxygen levels under climate change scenarios may push environmental conditions beyond the physiological tolerance of the species, potentially leading to population declines or local extinctions (see Assis et al., 2017; Hofmann and Todgham, 2010; Spence and Tingley, 2020). Understanding these relationships is essential for predicting future distribution shifts and designing conservation strategies, particularly in regions where coral populations are already stressed by anthropogenic impacts. By linking environmental variables to the physiological thresholds of *P. dilatata*, this study contributes to a deeper understanding of the complex interplay between abiotic factors and coral health, ultimately informing efforts to preserve these vital components of marine biodiversity.

### 4.3. *Shifts in distribution under past and future climate scenarios: regional patterns of habitat loss and field observations from Trindade Island*

The models allowed us to project the future extent of the endemic coral at Brazilian coastline for the first time. Poleward range shifts were projected within the Temperate South America ecoregion (i.e., Southeastern Brazil and Rio Grande) regardless of the scenario considered, in line with additional studies already reporting the expansion of coral in temperate regions (Yamano et al., 2011). Such shifts have been associated with gradual temperature increases over decadal time scales (Tuckett et al., 2017). These areas that remain suitable under past and future conditions (Table 2), during periods of climate changes (e.g., past and future) are crucial for the species persistence over time (Kavousi and Keppel, 2018). The general trend under the higher emission scenario is of severe losses, strongly impacting corals in sites located in Tropical Brazilian coastline. In the same way, ongoing reports align with our future projections, showing climate-induced losses caused by increasing sea temperature worldwide (Babcock et al., 2020; Brown, 1997). Additionally, our field survey in TRI islands revealed the absence of *P. dilatata* across two expeditions, which add up to the projected losses of up to 20 % in its potential distribution (Table 2).

### 4.4. *Limitations of models*

Despite the high performance of our models, the SDM has some limitations that should be acknowledged. Projecting the effects of climate change on *P. dilatata* distributions in areas facing future conditions unlike currently experienced by species may lead uncertainties in the models (Gouvêa et al., 2022). Additionally, the models do not include other important predictors like the consequences of human activities, sea level rise or the ecological relationships among species (such as competition and symbiosis) that have a significant impact on the spatial and temporal distribution of species. Additionally, the lack of information on the available substrata (e.g., rock bottoms for marine benthic biota), as well as future light conditions, could have resulted in over-prediction of suitable habitats (Krause-Jensen et al., 2020). To deal with this limitation, the predicted distribution of species was restricted to their maximum known depth.

**Table 2.**
Relative contribution (%) of environmental predictors used in ensemble species distribution models (SDMs) for *Phyllogorgia dilatata*. The values (Var. importance) reflect the average importance of each variable across the modeling algorithms.

| Environmental variables | Units | Var. importance | Model |
|---|---|---|---|
| Bathymetry | m | 53.573 | 21ky |
| Mean annual sea surface salinity | psu | 9.849 | 21ky |
| Annual variance in sea surface temperature | °C | 9.464 | 21ky |
| Sea surface temperature of the month | °C | 9.397 | 21ky |
| Minimum monthly sea surface salinity | psu | 9.291 | 21ky |
| Annual range in sea surface salinity | psu | 8.427 | 21ky |
| Bathymetry | m | 54.522 | 6ky |
| Mean annual sea surface salinity | psu | 12.366 | 6ky |
| Annual variance in sea surface salinity | psu | 8.676 | 6ky |
| Annual range in sea surface temperature | °C | 6.228 | 6ky |
| Sea surface temperature of the month | °C | 6.205 | 6ky |
| Sea surface temperature of the coldest month | °C | 6.068 | 6ky |
| Annual variance in sea surface temperature | °C | 5.936 | 6ky |
| Depth phytoplankton min | μmol·m$^{-3}$ | 21.276 | Present |
| Bathymetry | m | 12.850 | Present |
| Depth primary productivity max | g·m$^{-3}$·day$^{-1}$ | 9.029 | Present |
| Depth dissolved oxygen mean | mol·m$^{-3}$ | 7.747 | Present |
| Depth chlorophyll min | mg·m$^{-3}$ | 7.013 | Present |
| Depth dissolved oxygen max | mol·m$^{-3}$ | 6.640 | Present |
| Depth iron min | μmol·m$^{-3}$ | 5.590 | Present |
| Depth phytoplankton max | μmol·m$^{-3}$ | 5.234 | Present |
| Depth iron max | μmol·m$^{-3}$ | 5.197 | Present |
| Salinity | PSS | 5.107 | Present |
| Depth chlorophyll max | mg·m$^{-3}$ | 4.999 | Present |
| Depth iron mean | μmol·m$^{-3}$ | 4.860 | Present |
| Depth chlorophyll mean | mg·m$^{-3}$ | 4.459 | Present |
| Bottom temp future | °C | 36.052 | 2100 |
| Bathymetry | m | 24.503 | 2100 |
| Salinity future | PSS | 20.779 | 2100 |
| Primary productivity future | g·m$^{-3}$·day$^{-1}$ | 18.667 | 2100 |

### 4.5. *Conservation strategies*

The conservation status of *P. dilatata* is alarming due to the dramatic population decline in the past two decades (Cassola et al., 2016). Conservation strategies aimed at protecting this species are urgently needed to prevent its extinction and preserve the biodiversity of Brazilian soft corals. One key aspect of conservation efforts is the transplantation of nursery-grown corals (Ferse et al., 2021; Hutagalung et al., 2024). Still, we lack basic information about demographic and physiological aspects of this species, which may limit any successful repopulation initiative (Steinberg et al., 2020), especially because *P. dilatata* was mostly sensitive to water temperature in models (see Fig. 4 for examples of healthy populations in Brazil). Additionally, the establishment of marine protected areas (MPAs) can help mitigate threats to *P. dilatata* by restricting human activities such as fishing, anchoring, and coastal development within designated zones. Collaborative efforts involving government agencies, non-governmental organizations, researchers, and local communities are crucial for the implementation of comprehensive conservation strategies (Cordeiro et al., 2022) to safeguard the future of *P. dilatata* and other endangered coral species in Brazil's coastal waters. Also, private corporations could support to foster *P. dilatata* conservation and restoration strategies through the implementation of biodiversity credits projects (highlighted by the Global Biodiversity Framework) which is an emerging strategy to to drive financial supports to enhance ecosystems and therein biodiversity up to a nature positive perspective (Antonelli et al., 2024). By addressing the underlying causes of decline and implementing proactive conservation measures, we can work towards the recovery and long-term survival of *P. dilatata* and contribute to the resilience of coral reef ecosystems in Brazil.

## 5. Conclusions

The findings of this study underscore the pressing conservation challenges facing the endemic octocoral *P. dilatata* along the Brazilian coastline. The documented local extinction of the species on Trindade Island highlights the vulnerability of isolated marine populations to a combination of historical biogeographic factors, ecological dynamics, and contemporary climate change impacts. Species distribution models revealed that *P. dilatata* currently occupies approximately 93,090 km$^2$ of suitable habitat, with areas of high suitability concentrated in tropical ecoregions. However, projections under future climate scenarios, particularly under high-emission pathways (RCP 8.5), predict significant contractions in habitat availability, with potential losses exceeding 63 %.

The reliance of *P. dilatata* on narrow environmental thresholds, particularly temperature and oxygen availability, emphasizes its sensitivity to ongoing ocean warming and deoxygenation. Non-climatic drivers, including habitat degradation and altered hydrodynamic conditions, further compound the threats to this species, particularly in isolated or marginal populations. Field observations from Trindade Island revealed no live individuals, providing alarming evidence of the direct impacts of these stressors. These results highlight the urgent need for targeted conservation measures.

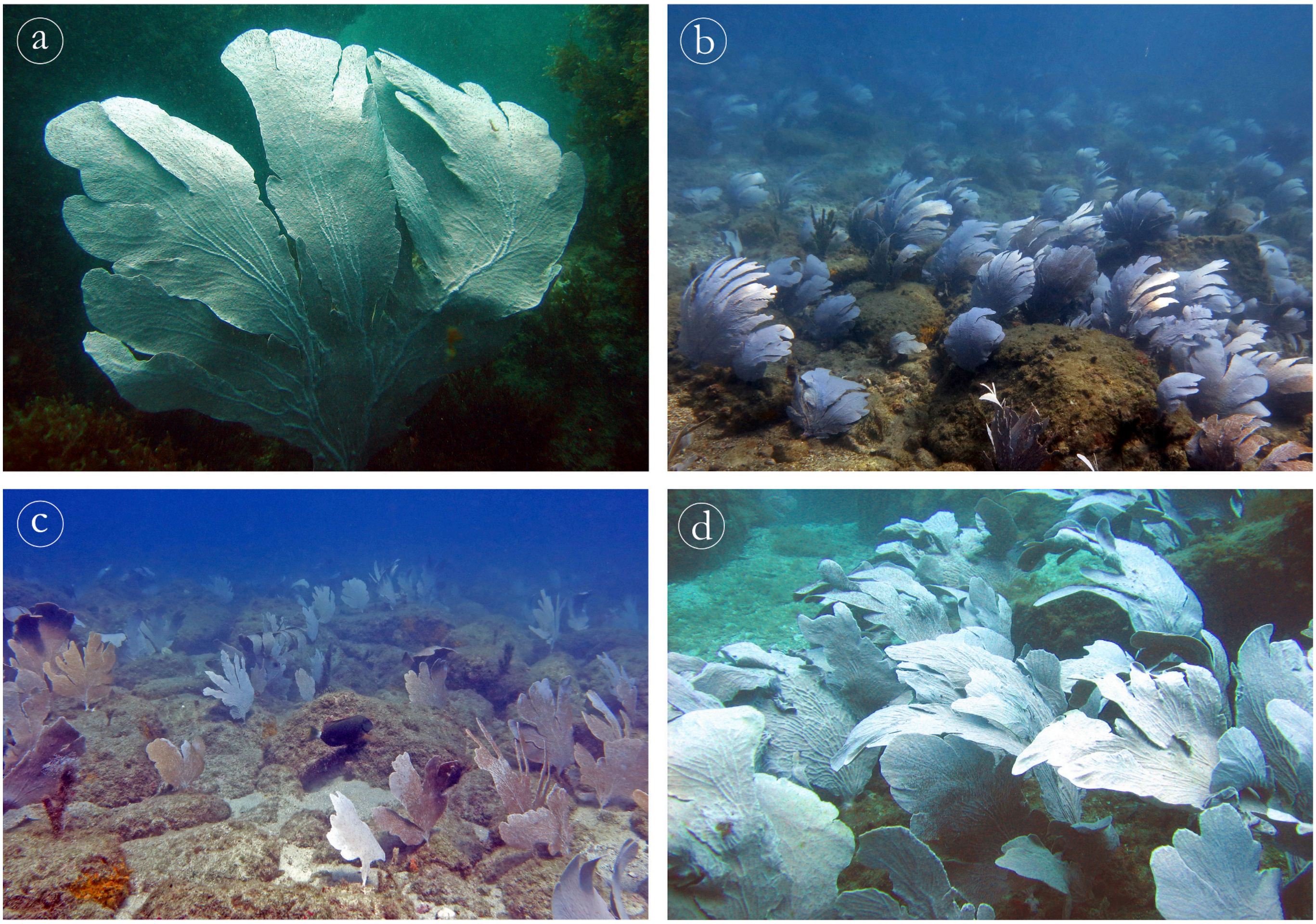

**Fig. 4.** Photographs showing healthy individuals/colonies of *P. dilatata* at Arraial do Cabo, Rio de Janeiro State (a, b, c and d). Images from PELD-ILOC.

Expanding marine protected areas (MPAs) to encompass critical habitats, implementing active restoration strategies such as coral transplantation, and fostering international commitments to mitigate climate change are essential for safeguarding the persistence of *P. dilatata*. This study also underscores the importance of incorporating species distribution models into conservation planning, enabling the identification of potential refugia and priority areas for intervention. Furthermore, by linking biogeographic history, ecological requirements, and climate change impacts, this research provides invaluable insights into the challenges facing endemic marine species in the Southwestern Atlantic. The lessons learned from *P. dilatata* can inform broader efforts to preserve marine biodiversity in the face of rapid environmental changes.

## CRediT authorship contribution statement

**A.B. Anderson:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **L. Gouvêa:** Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Data curation. **J. Assis:** Writing – review & editing, Methodology, Formal analysis. **E. Serrão:** Writing – review & editing. **H.T. Pinheiro:** Writing – review & editing. **C. Vilar:** Writing – review & editing. **R.B. Francini-Filho:** Writing – review & editing. **P.A. Horta:** Writing – review & editing. **A.F. Bernardino:** Writing – review & editing. **C.A.M.M. Cordeiro:** Writing – review & editing. **L.E.O. Gomes:** Writing – review & editing. **J.-C. Joyeux:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization. **C.E.L. Ferreira:** Writing – review & editing, Writing – original draft, Validation, Supervision, Conceptualization.

## Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the first author (Dr. Anderson, A. B.) used Chat GPT 4.0 on the Abstract and Discussion sections in order to improve text clarity and fluidity among paragraphs. After using this tool/service, the author reviewed and edited the content as needed and take full responsibility for the content of the publication.

## Declaration of competing interest

The authors declare no competing interests related to this work. All funding sources and institutional affiliations are transparently disclosed within the manuscript, ensuring no conflicts of interest influence the presented findings.

## Acknowledgements

We thank the RESTORESEAS project funded by Water JPI, Biodiversa+ and the Europe Union for A. B. A. Postdoctoral fellowship and research funding [funds supervised by FAPES (Fundação de Amparo à Pesquisa e Inovação do Espírito Santo, Brazil]. Thanks to PELD-ILOC and the Brazilian Navy for logistics support. L. P. G. thanks support from the CNPq-National Council for Scientific and Technological Development, Brazil (442685/2023-8).

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2025.118006.

## Data availability

Data will be made available on request.

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