MODELLING THE DISTRIBUTION OF THE ANEMONE *METRIDIUM SENILE* (LINNAEUS, 1761) IN THE CHILEAN PATAGONIA: PROJECTION OF INVASION UNDER CLIMATE CHANGE SCENARIOS

Tesis

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Dedicatoria:

A mis amados padres.

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ABSTRACT

Invasive species are among the primary threats to marine biodiversity. *Metridium senile*, a sea anemone introduced to the Southern Hemisphere, has been recorded in Patagonia, Southeast Pacific, where its spread has negatively impacted native benthic species, fisheries, and aquaculture. This study aimed to project the habitat suitability of *Metridium senile* in Patagonia under current climatic conditions and to analyse potential changes in its distribution under various climate change scenarios. Species distribution models were developed using MaxEnt, based on occurrence data from its native range and environmental sea surface predictors provided by BioOracle. The contribution and correlation of each variable were assessed using Pearson analysis. Potential shifts in distribution and the magnitude of change over the long term were determined under two Shared Socioeconomic Pathways (SSP2 and SSP5).

The projected potential distribution of *Metridium senile* spans the coasts of the Pacific and Atlantic Oceans from -37°S southward, consistent with its observed distribution in both regions. The environmental predictors with the highest contribution, lowest correlation, and greatest ecological relevance were temperature, salinity, pH, and dissolved oxygen. Climate change scenarios SSP2 and SSP5 suggest a progressive decline in habitat suitability in northern Patagonia, followed by a gradual increase in central and southern Patagonia (between -46°S and -51°S) during the 2040–2090 period. This indicates a poleward shift in the species distribution.

These findings highlight the potential impact of climate change on the spread of *Metridium senile* in Patagonia, emphasizing the need for monitoring and management strategies to mitigate its ecological and economic consequences.

Keywords

Metridium senile; invasive Anthozoa, alien species; climatic suitability; Species Distribution Model; Chilean Patagonia

INTRODUCTION

Invasive alien species are one of the main threats to biodiversity, with significant biological, economic, and human health impacts (Therriault et al. 2021; United Nations Environment Programme (UNEP). 2002). Invader establishment is favoured in marine ecosystems already stressed or degraded because of human impacts (Crooks et al. 2011), and this process is amplified by environmental alterations, human dispersal, and climate change (Glon et al. 2019; Therriault et al. 2021).

Anthropogenic climate change has affected the physical and chemical state of the ocean (García-Soto et al. 2021). Since the beginning of the twentieth century, sea surface temperature has increased at an average rate of 0.62 ± 0.12 °C per century. In the last decade (2009-2018) an average warming rate of 2.56 ± 0.68 °C per century has been observed, much higher than the long-term trend (García-Soto et al. 2021). Most ocean areas around the world are warming with a few exceptions at the regional level, such as the southeastern Pacific Ocean where a significant cooling trend has been recorded from at least 1979 to the mid-2000s along most coastal areas of the Humboldt Current Large Marine Ecosystem (4° to 40° S) (García-Soto et al. 2021; Gutiérrez et al. 2016).

Global salinity changes in the ocean near the surface and subsurface have been registered since 1950, low salinity regions have become fresher, and regions of higher salinity have become more saline (García-Soto et al. 2021). Along with the above, changes in pH and dissolved oxygen have also been recorded. Projections estimate an additional 0.2 to 0.3 ocean pH decline over the next century, unless global carbon emissions are reduced (García-Soto et al. 2021). Schmidtko et al. (2017) point out that the overall oxygen budget in the ocean has decreased by 2%, representing a loss of 4.8 ± 2.1 petamols since 1960.

Altered abiotic conditions directly affect marine invertebrates (Prather et al. 2013). Changes in the latitudinal distribution and depth of various taxa have been predicted in response to changes in ocean temperature (García Molinos et al. 2016; Pinsky et al. 2013). García Molinos et al. (2016) projected changes in the community composition in various regions around the globe, particularly in the Southern Ocean, mainly driven by the combination of extinctions and invasions derived from changes in sea surface temperature.

Invasive alien species can affect marine invertebrate communities and occasionally become a dominant pressure, particularly on native benthos (Jørgensen et al. 2021; Martin et al. 2015; Molinet et al. 2024). The biological and ecological features of certain species favour their introduction into new habitats, for example, sea anemones (Glon et al. 2020). This group of invertebrates has an extreme tolerance to environmental stress (Glon et al. 2019; Podbielski et al. 2016) which, combined with its rapid clonal reproduction, may determine its invasion success (Podbielski et al. 2016).

Metridium senile (Linnaeus, 1761), is a Cnidarian Anthozoa introduced in several regions of the southern hemisphere, with consolidated and robust populations in South America, South Africa and the Falkland Islands (Glon et al. 2020; Martin et al. 2015). In Chile, this species has been recorded in the northern and southern Patagonia area, with a geographically intermittent distribution ranging from the Chacao Channel in the north of Chiloé Island (-41.8 °S; -73.5°W) to the Beagle Channel in the Strait of Magellan (-53.3°S; -70.55°W) (Häussermann et al. 2022). The propagation of *M. senile* can occur in three ways: (a) larvae produced by sexual reproduction, (b) through the displacement of adult individuals and (c) through the formation of clonal groups resulting from asexual reproduction due to pedal laceration. The latter denotes the highest risk of invasive expansion (Häussermann et al. 2022).

Intertidal species of anemones, as predators, can produce changes in the community structure by decreasing the population density of other organisms (Dethier 1980). *M. senile* is a dominant competitor over other species in encrusting communities, especially in areas where they are invasive (Martin et al. 2015; Molinet et al. 2024). In northern Patagonia, the expansion of this anemone has decreased the potential occupation of the native benthos (Molinet et al. 2022). It has been described that this invasive anemone affects the movement and feeding of the sea urchin *Loxechinus albus*, affecting the growth and fishery production (Molinet et al. 2024). On the other hand, on the Atlantic Ocean coast, a competitive interaction between *M. senile* and bivalve species such as *Aulacomya atra* and *Mytilus edulis platensis* has been described (Martin et al. 2015).

Tested models, such as species distribution models (SDMs), are used to predict suitable habitats (Franklin 2010), for native and invasive species (Alaniz et al. 2021; Bidinger et al. 2012; Gimenez et al. 2023). Species Distribution Modelling is a technique that requires observations of occurrence and environmental variables, that influence the presence of species, to estimate potential geographic distributions (Bentlage et al. 2013; Franklin 2010). SDMs have been used to describe the suitability of habitat to support a target species, community, or biodiversity (Hirzel et al. 2006), and they are also known as Habitat Suitability Models (Franklin 2010).

Because biological invasions are expected to be enhanced by climate change (García Molinos et al. 2016; Therriault et al. 2021) and the effect that *M. senile* has had on encrusting communities in its invasive distribution (Martin et al. 2015; Molinet et al. 2024), this paper aims to project the habitat suitability of *Metridium senile* in Patagonia under the current climate scenario, using species distribution models (SDM). Subsequently, based on this projection, we seek to determine the possible changes in the distribution of this species under different climate change scenarios.

We address the hypothesis that, if changing abiotic conditions have induced shifts in the distribution of marine species, it is expected that the distribution of *Metridium senile* will also be altered in response to climate change. In addition, the direction of the geographical dispersion is expected to follow the trends observed in other taxa.

Estimating possible changes in the distribution of invasive species is crucial to anticipate the effects that these species may have on biodiversity and is relevance for proper conservation management.

MATERIAL ADN METHODS

1. Records of occurrence of *Metridium senile* in Chile.

Records of the occurrence of *M. senile* in its native range were obtained from the open-access Global Biodiversity Information Facility (GBIF, 2024) database. The occurrences in the invasive range of the species in Patagonia were obtained from Häussermann et al. (2022) who surveyed from Metri in northern Patagonia (-41.6ºS; -72.7ºW) to the Beagle Channel (-55.0ºS; -68.4ºW) in southern Patagonia during a period between 1998 and 2021. In addition, the occurrence records available in Molinet et al. (2024), correspond to fourteen sites located in Northern Patagonia, eight of which are Benthic Resources Management and Exploitation Areas (AMERBs) and seven are free access fishery areas. These sites are distributed from Punta Quillagua, on the coast of the Pacific Ocean (-41.6ºS; -73.8ºW), through the Chacao Channel (-41.7ºS; -73.3ºW), to Cheniao Island (-42.2ºS; -73.3ºW) in the inland sea of the Chiloé Archipelago. A database of occurrences was built by eliminating duplicate records and registers with zero records.

2. Bioclimatic Variables

The environmental predictors considered in the models were temperature, salinity, pH, and dissolved oxygen. These variables were selected because they: 1) are affect directly the survival, reproduction, metabolism, physiology, and distribution of marine invertebrates (Compton et al. 2007; Glon et al. 2019; Newell & Branch 1980; Verween et al. 2007; Zacherl et al. 2003); 2) have a significant effect on *M. senile* mortality (temperature and salinity) (Glon et al. 2019); and 3) have registered changes due to the effect of climate change (Jørgensen et al. 2021).

The environmental predictor layers were obtained from the Bio-Oracle database (Assis et al. 2024), as layers in 5-arcmin raster format. The datasets of surface layers (sea surface condition) in the period 2010-2020 were considered representative of the current climate for this analysis (Assis et al., 2024).

3. Species Distribution Model (SDM).

The potential distribution for *M. senile* was evaluated from the "machine-learning" technique Maximum Entropy Model using MaxEnt software version 3.4 (Bentlage et al. 2013; Elith et al. 2011). In order to obtain a model that would represent the habitat suitability of the species under the current climate scenario, four exploratory models were generated: SDM-Max, SDM-Min, SDM-Mean and SDM-all, using bioclimatic variables in either their maximum, minimum and medium ranges, or taking all into account, respectively. The variables considered were sea surface temperature, salinity, pH and dissolved molecular oxygen. Because MaxEnt incorporates a reliable method of regulation (L1 regularization), which implicitly handles trait selection by relegating some coefficients to zero, it is more stable against correlated variables, reducing the need to remove them unless they are deemed to be ecologically unsuitable (Elith et al. 2011).

Consequently, the use of a correlation method was not considered in this step. The selected exploratory model was validated by comparing the known distribution of the species in Patagonia with the estimated suitability.

All models were run with random test percentage = 0%, regularization multiplier = 1, maximum iterations = 500, convergence threshold = 0.00001, maximum number of background points = 10,000 (Bentlage et al. 2013). 10 replications of the model were made using MaxEnt's Cloglog format output, generating suitability values between 0 (not adequate) and 1 (optimal). For the validation of the model, the cross-validation technique with 10 subsets (folds) was applied, so in each iteration of the process, one subset was used as test data and the other nine as training data. The results were generated with a 95% confidence level.

To determine the appropriate range of abiotic conditions in which the species is most likely to survive, an existence threshold of 10% was defined (Lai et al. 2023). Response curves were elaborated using the output data delivered by MaxEnt and the Matplotlib package version: 3.8.4 in Python version 3.12.4. To project the potential distribution of *M. senile* under climate change scenarios, the variables with the highest percentage contribution in the exploratory model were used, removing the variables with the lowest contribution. Pearson's correlation analysis was performed in RStudio software version 2024.09.0+375 between bioclimatic variables to select the most representative for the environment.

Two Shared Socioeconomic Pathways (SSPs) were used as future scenarios (SSP2 and SSP5). These scenarios are specific combinations of socio-economic challenges for mitigation and adaptation and describe futures characterised by medium (SSP2) and high (SSP5) CO2 emissions (O’Neill et al. 2017). The environmental layers that describe the scenarios were obtained from the

Bio-Oracle database (Assis et al. 2024; Newell & Branch 1980) considering the period 2010-2020 as the current climate scenario and projecting the future scenarios for the 2040s, 2070s and 2090s. To assess changes in potential distribution over time under climate change scenarios, the long-term magnitudes of change for each scenario were calculated by decadal intervals in Python version 3.12.4 using the grid probabilities delivered by MaxEnt. Maps representing habitat suitability for *M. senile* and magnitudes of long-term change in the invasion zone were generated using the Matplotlib package version: 3.8.4 in Python version 3.12.4 and QGIS version 3.36.3.

RESULTS

All four models achieved good fits with areas under the curve (AUC) > 0.952, meaning that the SDM predictions were reliable. The total number of occurrence records (ROs) used to train each model was 665 and 74 sample was used for validation in the four models. Table 1 shows the results for the exploratory SDM models.

The values of the regularized gains (RT-gain) in each model were lower than the values of the unregulated gain (UT-gain), indicating that regularization had an effect on model fitness. In addition, the regularized gain was lower than the test-gain, suggesting that none of the models are overfitted and that they all generalize well to new data. The highest value of regularized gain was obtained in the SDM_all model (2,258), which suggests that this model, which includes all the ranges of each variable, achieves a better fit to the training data, better separating the areas of presence of the species from those of absence.

The suitability of habitat to support *M. senile* in the invasion area in Southamerica is shown in Fig. 1. Areas of high suitability are observed on the coasts of the Atlantic and Pacific Oceans around -37.0º S (Figure 1a). In Chile, areas with high suitability are observed in Tubul Bay (Araucanian)

(Figure 1b), Reloncaví Sound, Ancud Gulf and Comau Fjord (North Patagonia) (Fig. 1c), Jacaf Channel, Gala Sound, northern area of the Moraleda Channel, Vicuña Channel, Chacabuco Channel, Barros Arana Estuary, Messier Channel, Fallo Channel and Albatros Channel (North and Central Patagonia) (Fig. 1c-d). When contrasting the known distribution of the species with the modelled distribution, it is observed that those areas with the highest density of occurrences (x on the map) coincide with areas of suitability greater than 0.8. In general, the modelled distribution covers the observed distributions quite well but extends further north to -35º South latitude where there are no records of occurrences (Fig. 1b and 2b). In addition, the records of occurrences in the Magallanes region between -50 and -56º S are not consistent with the low suitability observed (Fig. 2).

The analysis of the contribution of the variables shows that the SDM-all model is explained in 39.4% by the sea maximum surface temperature (T MAX), this being the variable with the highest percentage contribution. Maximum dissolved molecular oxygen (O2 MAX) and minimum salinity (SAL MIN) contributed to the model by 38.2% and 13.4% respectively. These three bioclimatic variables represent more than 90% of the total contribution to the model. On the other hand, the pH variable is the one with the lowest contribution to the model, being <2% in the three values (Fig. 3a).

Fig. 3 shows the variation in habitat suitability according to the three bioclimatic variables with the highest percentage contribution. The curve represents a single bioclimatic variable, where the abscissa denotes the numerical range of the variable and the ordinate the logical output value (Cloglog) expressed as the numerical probability of the climatic variable in which the species may exist, i.e., the degree of suitability. The results obtained from the modelling in MaxEnt show that the threshold of existence of 10% was on average 0.46. Accordingly, the appropriate range of the main bioclimatic variables affecting the distribution of *M. senile* are: 294 - 365 mmol/m^3 maximum dissolved molecular oxygen (O2 MAX), 2 – 30 PSU minimum Salinity (Sal min), 15 – 20 ºC maximum sea surface temperature (T MAX) (Fig. 3b, c, d).

The potential distribution of *M. senile* under climate change scenarios is shown in Fig. 5. Contributions for the tested variables, maximum sea surface temperature (T Max), maximum dissolved oxygen (O2 Max) and minimum salinity (Sal min), were shown in Figure 3 with their percentage contributions (39.4%, 38.2% and 13.4%, respectively) and correlation coefficients Sal Min - T Max (ρ = 0.43), Sal Min - O2 Max (ρ = - 0.54) and T Max - O2 Max (ρ = -0.95) (Fig. 4).

The modelling process provides predictions regarding the redistribution of suitable climatic space over time under climate change scenarios. The SSP2 scenario shows a change in the potential distribution compared to the current climate scenario (Fig. 5a), with an expansion of the geographical areas of maximum suitability (Fig. 5 b, c, d). A progressive decrease in suitability is observed in northern Patagonia (-45º south latitude) towards the decade of 2090 (Fig. 5d).

The future scenario SSP5 shows, like SSP2, more extensive geographical areas of maximum suitability with respect to the current climate scenario. A progressive decrease in suitability is observed in southern Patagonia towards the 2090s (Fig. 5 e, f, g).

Fig. 6 shows the change in the distribution of *M. senile* between the present conditions and the predicted SSP2 and SSP5 scenarios, expressed as their absolute difference (Fig. 6). A progressive decrease in predicted suitability is observed in Northern Patagonia (areas in blue), followed by a gradual increase in suitability (areas in red) in Southern Patagonia between -46º and -51º S from the 2040s to 2090. These changes suggest a progressive and constant alteration of the distribution of *M. senile* in different climate change scenarios (Fig. 6).

DISCUSSION

Potential distribution of *Metridium senile* in Chilean Patagonia

In this study, we modelled the habitat suitability for *Metridium senile* in a known invasion region in Chilean Patagonia, using species distribution models (SDMs). SDMs have been increasingly used to determine the locations where an invasive species can settle, making it possible to predict the geographical potential of an invasive species in a new region, based on information about its habitat preferences in its native area, often using climatic variables (Franklin, 2010).

Our results show that the potential distribution of *M. senile* spans the coasts of the Pacific and Atlantic oceans from -37ºS southwards. The predicted habitat suitability to support *M. senile* in the invasion area in Southamerica is consistent with prior reports by Gimenez et al. (2023) in the Atlantic Ocean. These authors point out that *M. senile* has a widespread potential distribution in Argentina and in the Falkland Islands/Malvinas.

In Chilean Patagonia, the estimated areas of high suitability coincide with the observed distribution from the Chacao Channel (-41.8 °S; -73.5°W) in Northern Patagonia to the Beagle Channel (-53.3°S; -70.55°W) in Tierra del Fuego, in Southern Patagonia (Häussermann et al. 2022; Molinet et al. 2024). This overlapping between the modelled and observed distributions occurs in the areas of Chacao Channel (-41.8 °S; -73.5°W), Reloncaví Sound (-41.6°S; -72.9°W), Gulf of Ancud (-42.0ºS; -73.0ºW), Comau Fjord (-42.1 – -42.4ºS; -72.5 – -72.4ºW), Comau Pass (-42.1ºS; -72.6ºW), Puyuhuapi Channel (-44.4 – -44.9ºS; -72.6 – -73.2ºW), near Isla Humos (-45.6ºS; -74.1ºW), Errázuriz Channel (-45.5ºS; -73.8ºW) and south of Moraleda Channel (-45.4ºS; -73.7ºW) in Northern Patagonia, as well as in Central Patagonia, in the Messier Channel (-48.1ºS; -74.6ºW). However, our results show that the modelled distribution extends beyond Northern Patagonia, with areas of high suitability in Tubul Bay (-37.1ºS; 73.4ºW) in La Araucanía, an area influenced by the Humboldt Current. To our knowledge, there are no records of occurrence in this area. In addition, the model predicts a low suitability in the Magallan area between -50.0ºS and -56.0ºS, which is not consistent with existing occurrence records (Häussermann et al. 2022).

The modelled distribution was performed using sea surface parameters, previously described as useful when modelling associations between occurrence records and observed environmental parameters (Bentlage et al. 2013). Our results indicate that the variables with the highest contribution were temperature (39.4%), dissolved oxygen (38.2%) and salinity (13.4%). The appropriate temperature range identified in our study was 15 -20ºC, which coincides with the wide tolerance range of *M. senile* of 0 to 20ºC (Glon et al. 2019). In addition, we found that the species exhibits considerable salinity tolerance, with a range of 2-30 PSU, which differs from the range experimentally determined by Glon et al. (2019) of 20-37 ppt (≈PSU). However, the salinity range with the highest suitability that we identified was 12 to 20 PSU, which approximates the tolerable levels of salinity for the species, with more than 50% survival (Glon et al. 2019). Lastly, the optimal range of dissolved molecular oxygen determined in this study was 294 – 365 mmol/m^3. We have not found literature on the optimal range of the species; however, we know that *M. senile* is strongly affected by oxygen stress, although it can rapidly recolonise areas shortly after reoxygenation (Wahl, 1985).

Projections under climate change scenarios

A model calibrated for current climate conditions can be used to project potential distributions of species in order to predict the impact of environmental changes on those distributions (Franklin, 2010). The result of our models allowed us to obtain predictions about the redistribution of the ideal climate space under different climate change scenarios.

Under the SSP2 scenario, our results show a change in the potential distribution with an expansion of the geographical areas of maximum suitability in La Araucanía, Northern Patagonia and Central Patagonia, followed by a progressive decrease in suitability in northern Patagonia (-45.0ºS) towards the 2090s. On the other hand, the SSP5 scenario showed wide geographical areas of maximum suitability towards the 2040s, with a gradual reduction culminating in a concentration of suitability in Central Patagonia towards the 2090s. Changes in species distribution with both climate change models have been described before (García Molinos et al. 2016; Lai et al. 2023).

A common pattern observed in both models was a climate-driven distribution shift towards the polar regions, a phenomenon that has been previously described for other species (Chen et al. 2011). Meta-analyses have revealed that species move away from the equator at an average rate of 16.9 km per decade, although there is a great diversity of range shifts in recent decades that depend on multiple factors (Chen et al. 2011; Pinsky et al. 2013). However, not all models show a poleward shift of marine species in response to climate, as different taxa move at different rates and in different directions by being able to closely track local climate speeds (Pinsky et al. 2013).

Latitudinal changes in marine species richness have also been described under these scenarios. For example, in a high emissions scenario (RCP8.5, equivalent to the current SSP5), species richness tends to increase towards the poles (40.0°N and -30.0°S), with large areas of richness loss near the equator, where species migrate north or south due to global warming. Under a moderate emissions scenario (RCP4.5, equivalent to the current SSP2), the highest concentration of species richness is observed around 20°N and 20°S, that is, closer to the tropical zones (García Molinos et al. 2016).

The harmful interactions described between *M. senile* and the native benthos cause a particular challenge, especially considering that in Chile, sea urchin is an important artisanal fishery product with 24,527 t annual landings (Sernapesca 2023), and mollusc exports account for 29.3% of the country's aquaculture production. These exports are explained by the harvest of farmed *Mytilus chilensis*, with a total of 380,000 t exported in 2019, representing 76.7% of the national mollusc production and positioning Chile as the second-largest mussel producer in the world (Barría et al. 2022).

CONCLUSIONS

The present work provides information on the potential distribution of the introduced anemone *Metridium senile* in Chilean Patagonia. The modelling process using MaxEnt allowed projecting the areas of northern and central Patagonia as geographical areas with high suitability for the species under current climatic conditions, finding that the modelled distribution coincides with the observed distribution of the species in the known invasion area. Likewise, the modelled distribution is primarily determined by sea surface temperature, dissolved oxygen and salinity, with ranges that approximate previously reported data.

The potential distribution of *M. senile* changed under the modelled climate change scenarios. The SSP2 model showed high suitability in the regions of La Araucanía (north of Patagonia), Northern Patagonia and Central Patagonia, followed by a slight and progressive decline towards the 2090s in La Araucanía and Northern Patagonia. On the other hand, the SSP5 model evidenced the greatest change in the potential distribution of the species, with a redistribution of the areas of greatest suitability in Central and Southern Patagonia towards the 2090s, and a considerable decrease in suitability in La Araucanía Northem Patagonia. An overall shift in the potential distribution of *M. senile* was found towards the south pole.

Metridium senile represents a pressure on native benthos in the Pacific and Atlantic oceans. In Chile, the shellfish and aquaculture industries, notably the mussel culture, may also be impacted by the harmful effects that this invasive species could have. Our predictions on the distribution of this species can serve as a valuable tool to guide monitoring efforts and management of priority areas in Patagonia.

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

PH conceived, designed the research and wrote the manuscript. FT helped with data analysis and manuscript edition. DO edited and corrected the different versions of the manuscript. All authors read and approved the final manuscript.

DATA AVAILABILITY

The datasets from this study are available from the corresponding author on request and agreement with authors.

Conflict of interest

The authors declare that they have no conflict of interest.

TABLES

Table 1. Results of the Species Distribution Models (SDM): SDM_MIN (model with the minimum ranges of environmental variables), SDM_MEAN (model with the mean ranges of environmental variables), SDM_MAX (model with the maximum ranges of environmental variables), SDM_ALL (model with all ranges for each environmental variable) obtained. The occurrence records (RO) used for training, area under the curve for the test data (AUC ±SD), regularised gain (RT-gain), unregularized gain (UT-gain), Test-sample (number of samples used to validate the model), and Test-gain (model gain on the test data) are shown.

MODELS	RO	AUC	SD (±)	RT-gain	UT- gain	Test-sample	Test gain
SDM_ALL	665	0.962	0.005	2.258	2.381	74	2.348
SDM_MIN	665	0.956	0.006	2.056	2.130	74	2.104
SDM_MEAN	665	0.952	0.006	1.926	2.037	74	2.015
SDM_MAX	665	0.957	0.005	2.127	2.208	74	2.190

FIGURES

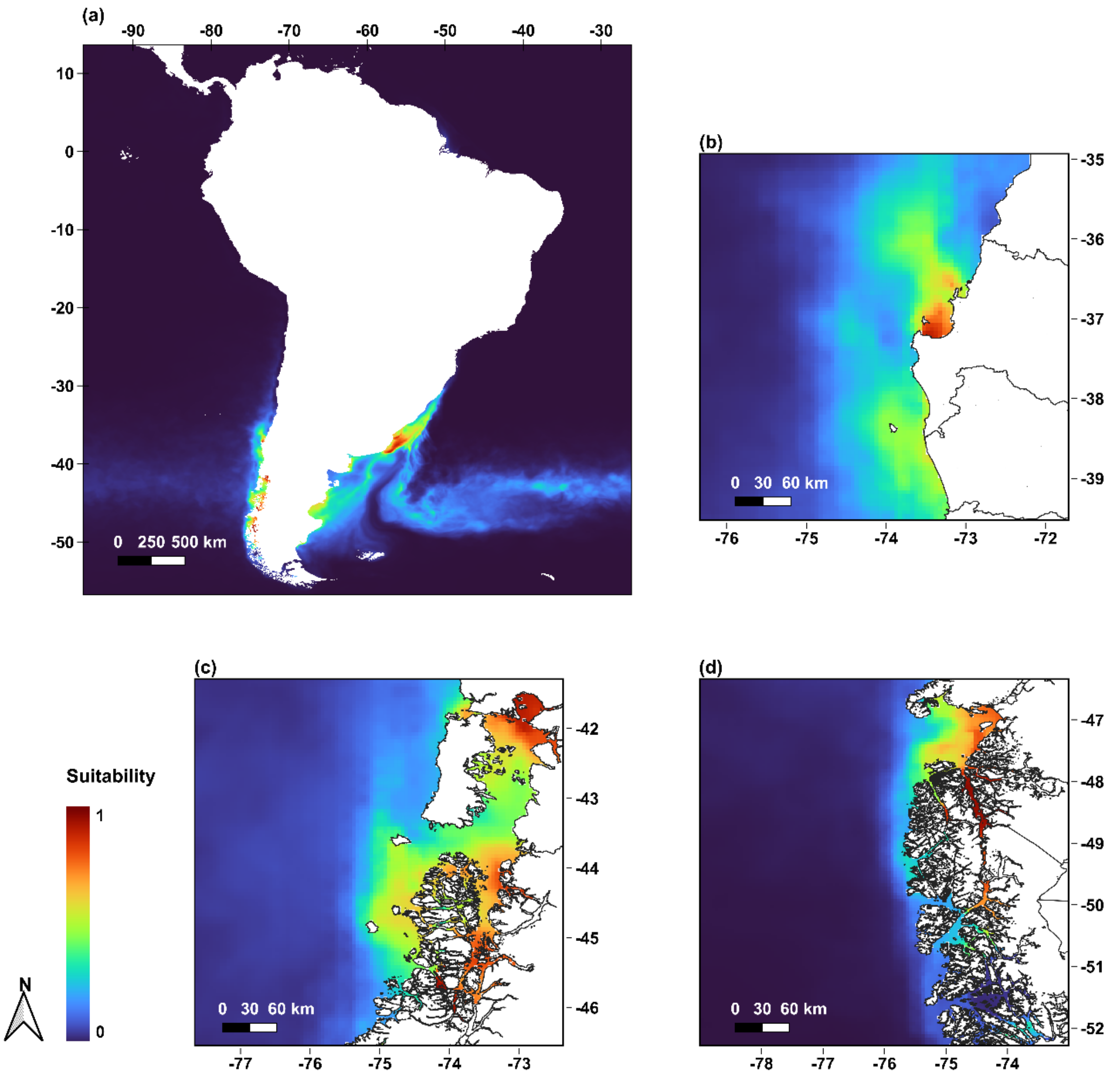

Fig. 1 Modelled habitat suitability (SDM-all model) for the invasive species *Metridium senile* in a) Southeast Pacific and Southwest Atlantic Ocean, b) La Araucanía, c) Northern Patagonia and d) Central and Southern Patagonia. The warmer colours represent the areas with the highest predicted suitability for the species.

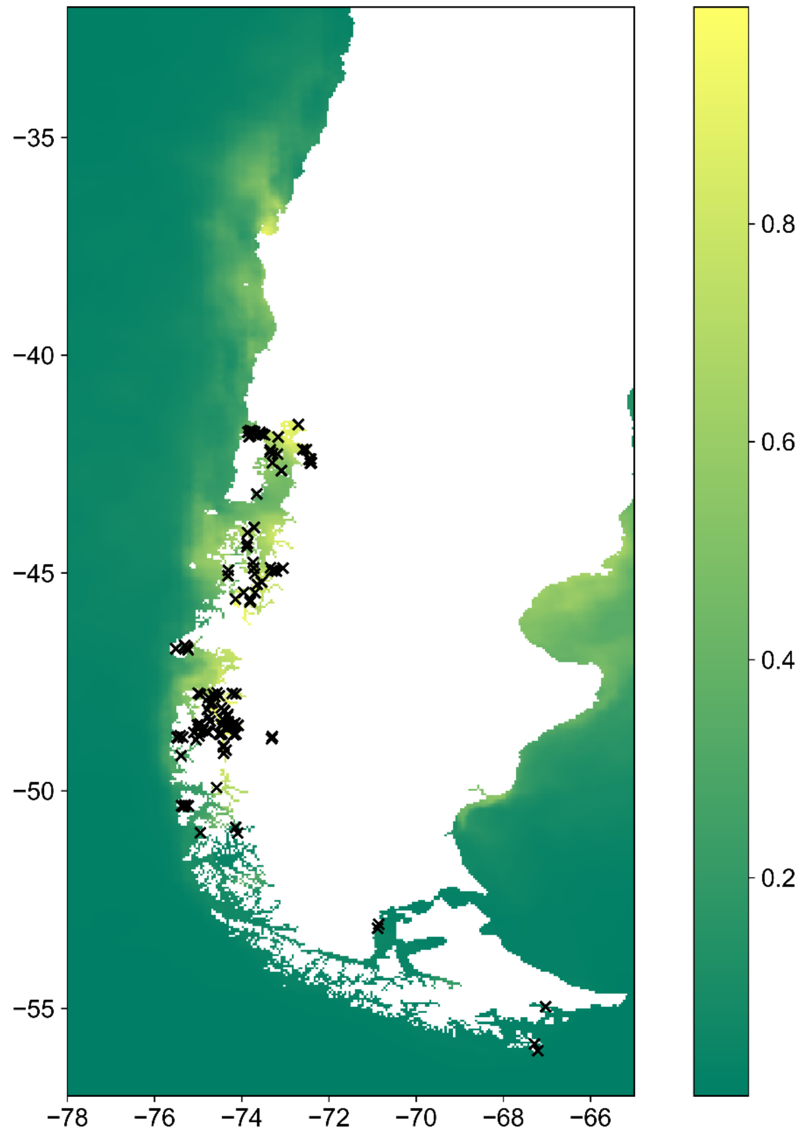

Fig. 2 Comparison between the observed distribution (occurrences marked as x) and the modelled habitat suitability (SDM-all model) for *Metridium senile* in Chile. The colour scale represents habitat suitability, with areas of higher predicted suitability shown in yellow and areas of lower suitability in green.

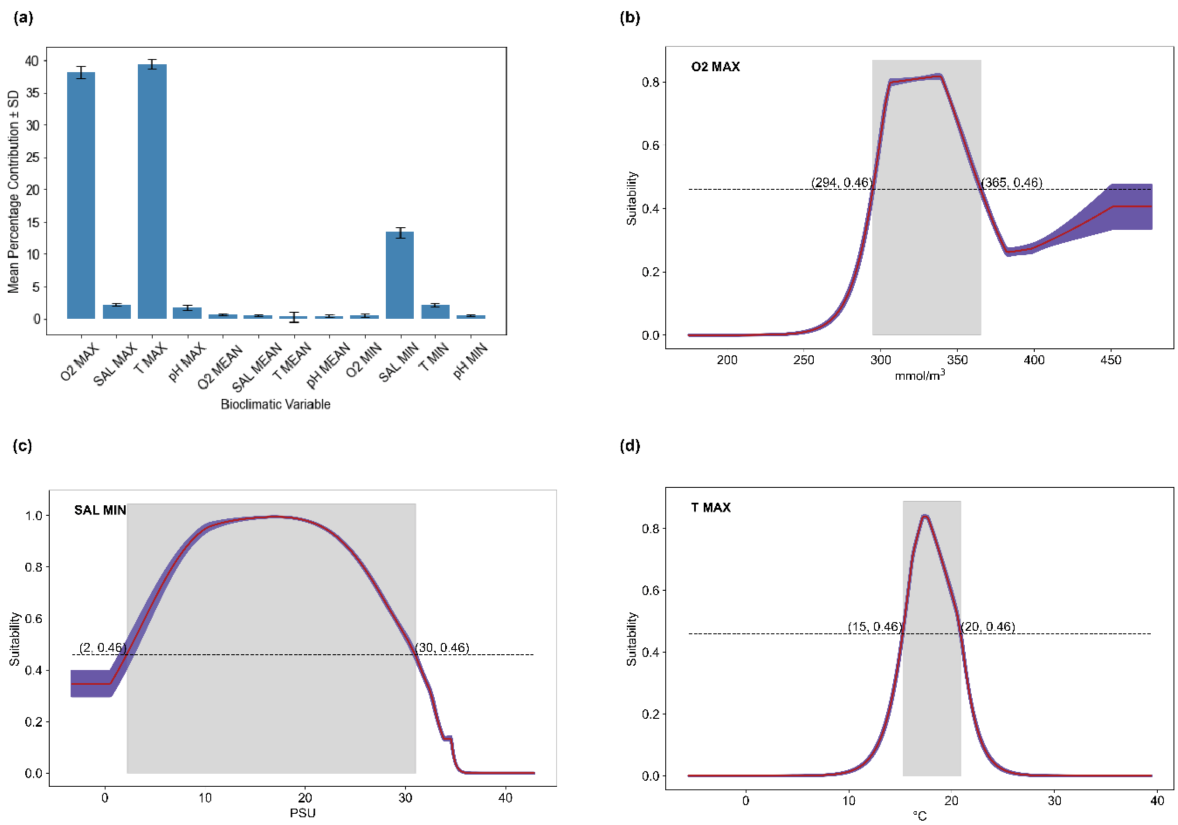

Fig. 3 Mean percentage contribution (±SD) of bioclimatic variables and response curves in the SDM-all model. (a) Relative contribution of each bioclimatic variable to the model and response curves for the three variables with the highest contribution: (b) maximum dissolved molecular oxygen (O2 MAX), (c) minimum salinity (Sal MIN) and (d) maximum sea surface temperature (T MAX). The red curve represents the median of the model replicas and the blue band the standard deviation. The area shaded in grey shows the abiotic range in which the species may exist (above 10% suitability).

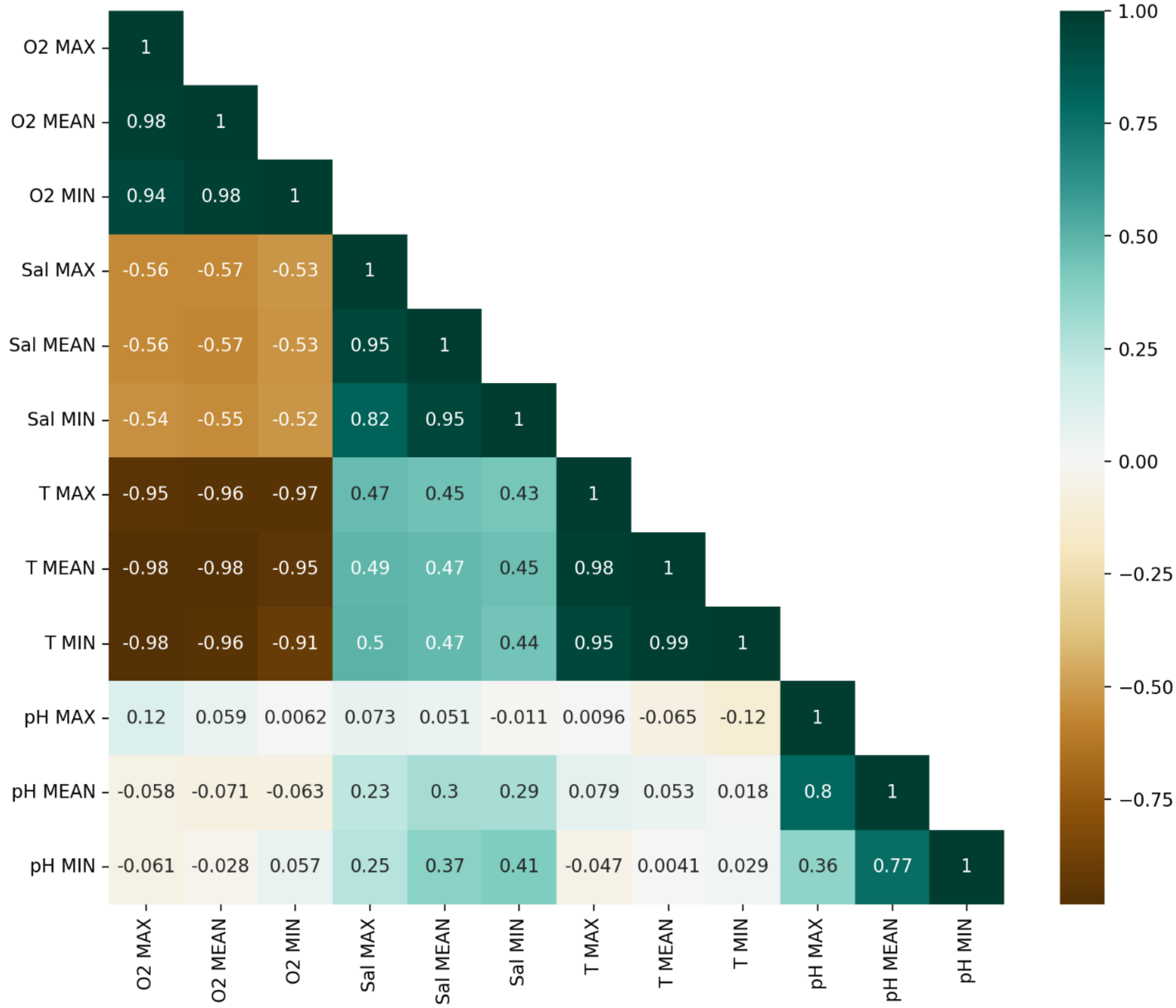

Fig. 4 Pearson's correlation matrix for the twelve bioclimatic variables used in the modelling.

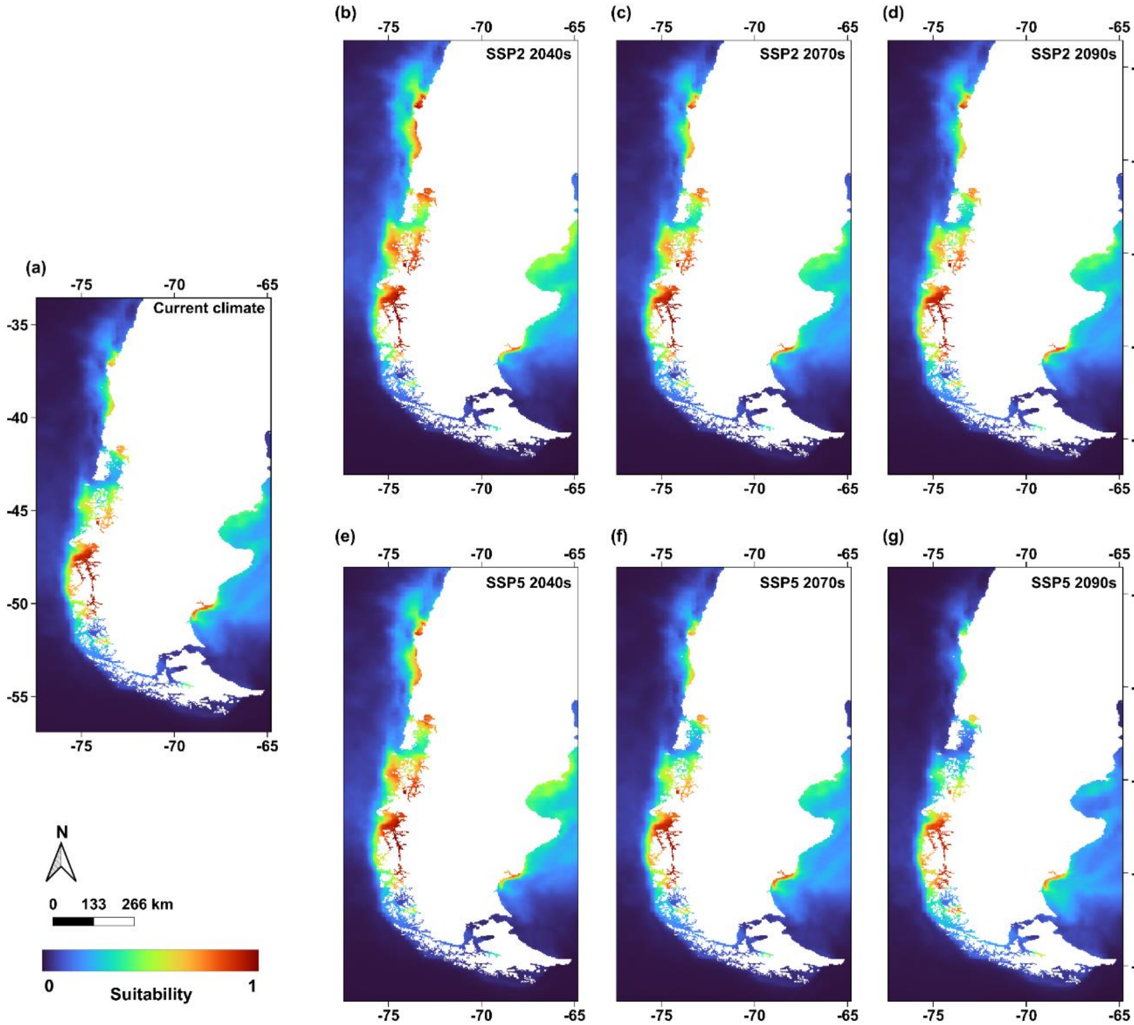

Fig. 5 Projection of the potential distribution of *Metridium senile* under climate change scenarios, modelled based on the Shared Socioeconomic Pathways (SSP). (a) Current climate scenario. (b), (c), and (d) projections under the SSP2 scenario. (e), (f), and (g) projections under the SSP5 scenario. The projections correspond to the decades of the 2040s, 2070s, and 2090s.

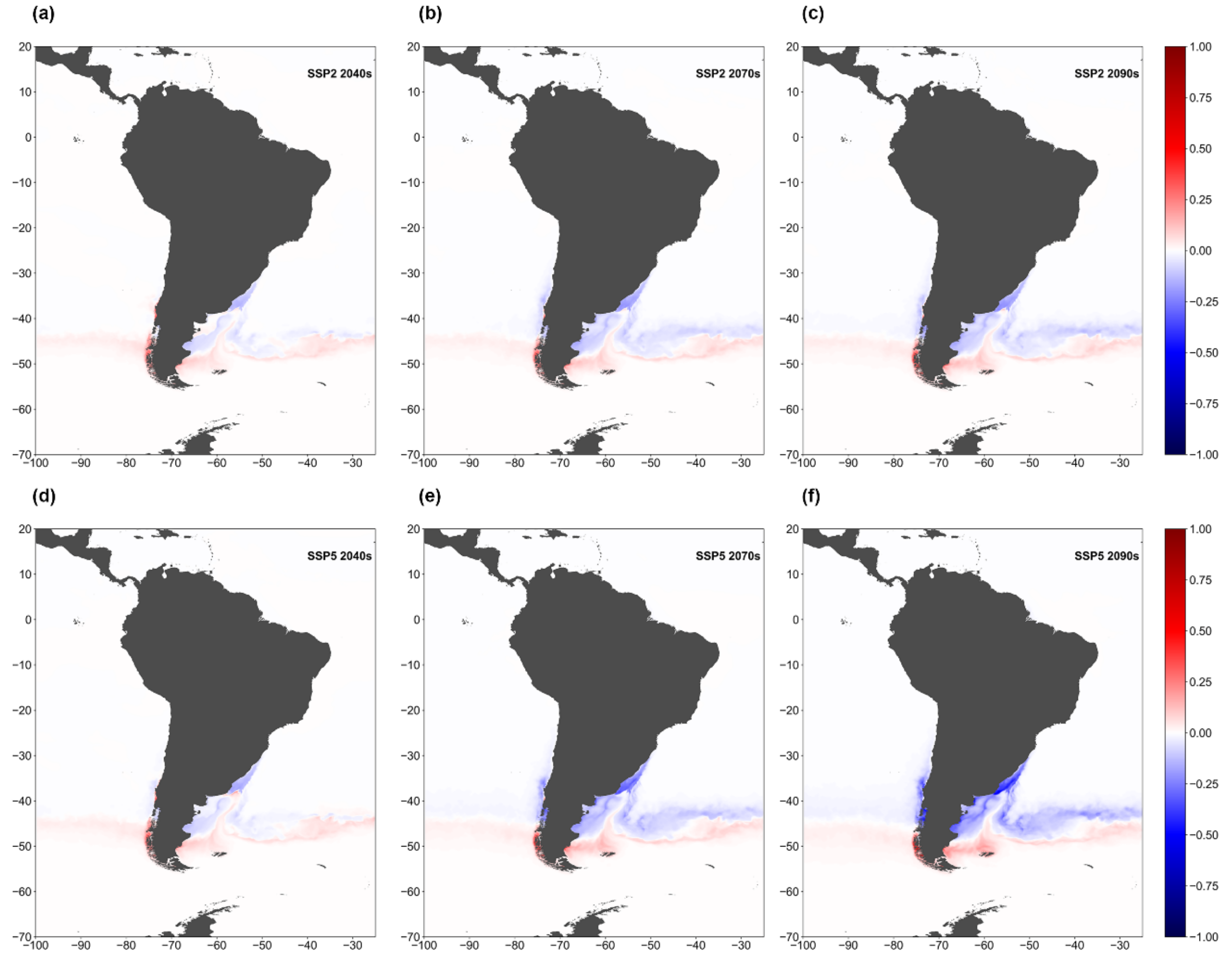

Fig. 6 Magnitude of change in the potential distribution of *Metridium senile* under climate change scenarios, modelled from the Shared Socioeconomic Pathways (SSP), expressed as the absolute difference between the current model and projected distribution. (a), (b) and (c) projection according to SSP2 scenario. (d), (e) and (f) projection according to SSP5 scenario. Projections are for the 2040s, 2070s, 2090s. An increase in suitability is shown in red, a decrease in blue and no change is shown in white.