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Vulnerability of the Small-Scale Fishery to Climate Changes in the Northern-Central Adriatic Sea (Mediterranean Sea)

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Abstract: Climate change is altering the functioning of ecosystems and species distribution worldwide, with negative impacts on human activities, including fisheries. The Adriatic Sea is an extremely productive area for fisheries, due to the strong outflow of nutrients from rivers and the periodic mixing of nutrients from the Mediterranean. However, the Adriatic Sea is also a semi-closed basin, where species do not have the ability to move to higher latitudes to avoid warming of the waters. Climate change acts on biodiversity in a variety of ways, such as causing changes in the trophic network—favoring the intake of thermophilic alien species, often in competition with local species—and altering the biological cycles of acclimatized marine species to temperate–cold climates. These problems become critical factors for the survival of species and for fisheries relying on these resources. Within this context, to have estimates of possible modifications of the nektonic community in the near future could be quite useful for preparing adaptation plans. In this paper, using Maximum Entropy models under RCP 4.5 and 8.5 scenarios, we estimated the future habitat suitability for a set of marine nektonic species of different thermal affinity (e.g., cold, temperate and warm species) within GSA17 (Northern and Central Adriatic Sea), among the most productive—and most exploited—areas of the Mediterranean Sea. This study shows how, at the current pace, climate change could modify marine ecosystems to the extent that future habitat suitability will decrease for nearly half of the species considered, with a decrease in landings from 13.5 to 86.9%, depending on the scenario. Only for the blue crab *Callinectes sapidus* has an increase in habitat suitability been observed. For most of the species considered, temperature was the most important variable to explain the probability of relative presence within the GSA17. On the other hand, GSA17 climatic conditions in the near future under the tested scenarios could become a suitable environment for tropical species, which could find here a suitable habitat, at least in terms of thermal features. Results of the present study can help the management of fishery resources and local markets in the near future, providing information to predict changes in the composition of the aquatic community and draw up management plans that take into account the effects of climate change.

Keywords: small-scale fishery; climate change; meridionalization; tropicalization; Mediterranean Sea

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1. Introduction

Aquatic marine systems worldwide are undergoing significant changes because of global warming, and projections indicate that these changes will be accentuated in the near future [1–3]. Among the different effects of global warming, the shifts in the spatial distribution of species and the alteration in larval transport or tolerance to stress (not only the thermal one) determined changes in productivity and growth rates of many aquatic species, with consequences also on fishing and aquaculture activities. For these reasons, as never before, climate change is putting at risk the food and economic security of more than 3 billion people globally who depend on marine ecosystems [4–8].

Climate change effects also have been detected in the Mediterranean Sea, an important biodiversity hotspot worldwide [9], causing a decrease in atmospheric precipitation, a warming of the water, an increase in salinity and in the intensity and frequency of extreme events such as heatwaves [10]. In particular, the warming water of the Mediterranean Sea is expected to cause changes in the abundance, survival, growth and reproduction rates of many species, also modifying their phenology and migratory patterns [11]. At the same time, warmer water will favor the probability of the presence and the geographical expansion of thermophilic species, including the lessepsian migrators from the Red Sea and the Indo-Pacific region [12–14]. In a semi-closed basin of the Mediterranean, such as the Adriatic Sea, these modifications could become particularly critical for the survival of species since they do not have the chance to move to higher latitudes to avoid warming waters, being in a real "cul-de-sac" [15].

Indeed, chemical-physical and oceanographic features of the north Adriatic are changing under the combined effects of the anthropogenic impact and regional climate changes, leading to prominent modifications in its biological communities. Historical ecological studies suggest that the Northern Adriatic fish community structure has been changing for centuries [16,17]: a decline of elasmobranchs, tuna, swordfish, marine mammals and large demersal/large-sized/late maturing species proportion in fish composition as well as diadromous fish (eels, sturgeons) and small pelagic has been described by many authors [16–21]. However, recent analyses of the sea surface temperature have evidenced marked increases (up to 5 °C) in all seasons in the period 1988–1999, with respect to the period 1911–1987 [22]. Since 2000, a significant increase in the salinity was also observed, mainly due to a reduction in freshwater discharge and a stronger ingression of eastern Mediterranean water [23].

According to IPCC scenarios, sea surface temperature and salinity of the Adriatic Sea are projected to increase in the future, together with changes in the precipitation regime. Indeed, rainfalls are expected to increase in winter and decrease in summer by 20% [24]. On the other hand, despite regional and global factors that will modify future climate conditions in the Adriatic Sea, there is no evidence for more (or less) frequent extreme events such as marine storms [25].

In relation to these changes, a meridionalization (i.e., the expansion of thermophilic species from the Southern Mediterranean towards northern regions) of the Adriatic Sea is therefore being observed. In particular, in recent decades an increasing number of thermophilic taxa have been reported to be expanding northward in the Adriatic Sea [26–28], with well-established populations as for the bluefish (*Pomatomus saltatrix*) and the barracuda (*Sphyraena viridensis*). At the same time, the Mediterranean Sea seems to also be affected by the so-called tropicalization, with the appearance and progressive expansion of tropical species, mainly through the Suez Canal [12,29,30].

The expansion of thermophilic species could produce both positive and negative effects on fishing activities [31]. Fisheries in the Mediterranean Sea are multi-target and multi-fleet activities, with mainly small-scale fisheries (SSF), including up to 80% of the Mediterranean fleet and the largest number of operators by boat [32]. The two main SSF fleets in the Adriatic, the Italian and Croatian, comprise approximately 4000 vessels, with total annual landings of nearly 10,000 tons worth EUR 65 million (source: STECF 19-06). According to Regulation CE 1139/2021, "Small-scale coastal fishing is carried out by marine and inland fishing vessels of an overall length of less than 12 metres and not using towed fishing gear, and by fishers on foot, including shellfish gatherers. That sector represents nearly 75% of all fishing vessels registered in the Union and nearly half of all employment in the fisheries sector". Therefore, the impact of climate change on fisheries depends on the adaptability of these extremely diverse fleets. The multi-targeting nature of the Mediterranean SSF, targeting many different species with a composite set of gears [33], makes it potentially more adaptable and consequently more resilient to changes that could occur. However, at the same time, the characteristics of this fleet segment (e.g., fishing in the range of 0.5–1.5 nautical miles from the coast and low mobility due to low-power engine, determining a strong reliance on target species distribution) could increase its vulnerability to climate change, mainly because fishers specialize in one or a few *métiers*, often using gears specific to a single species. The multi-target and multi-gear features of the Mediterranean SSF [33] represent, at the same time, a condition increasing its resilience (since it would be able to shifts among different species) and vulnerability (given the strong specialization in terms of 'one gear for one species').

Management efforts should therefore be aimed at anticipating the probability of arrival, creating risk areas with the adaptive ability to withstand anticipated pressures [34,35]. A key aspect would be to assess the vulnerability of natural ecosystems before the actual arrival; but in the Mediterranean marine environment, relatively little effort has been made to improve predictions about the spatial distributions of these species under different climate scenarios [36–38]. Nowadays, this knowledge is of primary importance for the Mediterranean Sea, among the most invaded marine regions in the world [13,39] and which is warming faster than the global average [40].

Here, using predictive models of spatial distribution, we tried to depict future projections of the habitat suitability for a set of nektonic species in relation to the climate change effects, in order to assess how climate change could affect part of the Adriatic renewable resources in the near future. Therefore, the aim of the present work is to evaluate the vulnerability of the SSF to warming water through the estimation of the habitat suitability for the main target species under different scenarios. With this paper, we tried to answer two questions:

(1) In the near future, would the Northern-Central Adriatic Sea be subjected to a meridionalization trend (*sensu* [41])?

(2) Based on habitat suitability analysis, will SSF catch composition be affected by climate change and, if so, could warm-affinity species be considered a valid alternative option for the SSF in the area?

2. Materials and Method

The central and northern parts of the Adriatic Sea (identified by FAO GSA17 fishing area) constitute a semi-enclosed shallow water basin in the northern part of the Mediterranean Sea (Figure 1). This basin shows biogeographic peculiarities, which make it strongly atypical within the Mediterranean context. As far back as 1913, [42] mentioned the "Adriatic lacuna", which [43] later described more precisely as the "Venetian biogeographic lacuna" (lacuna = lack, gap; figurative, from latin). This term was introduced to explain the climate of the Northern Adriatic shores, which presents sub-Atlantic features while lacking Mediterranean ones. This is because the main surface circulation in the Adriatic basin brings southern warm waters along Croatian coasts, and then up to the Northern Adriatic, where they are affected by cold north-easterly winds, reducing water temperature, especially in autumn and winter. Furthermore, the area is located close to one of the most windy and rainy sectors of the Alps, the sea basin is quite shallow on average, and it is excluded from the main Mediterranean water circulation [44].

All these morphological and climatic features have been supposed to produce a lack of Mediterranean species, favoring, on the other hand, the presence of boreal taxa (species and subspecies typical of the middle-European Atlantic coasts), which in many cases can be considered as glacial relicts within the Mediterranean context [45]. For the climatic and geomorphological characteristics of this area, under the effect of climate change, cold-affinity species are prevented from migrating northward or from seeking refuge in deeper and cooler waters, as the basin is very shallow (the average depth of the Northern Adriatic is approximately 35 m).

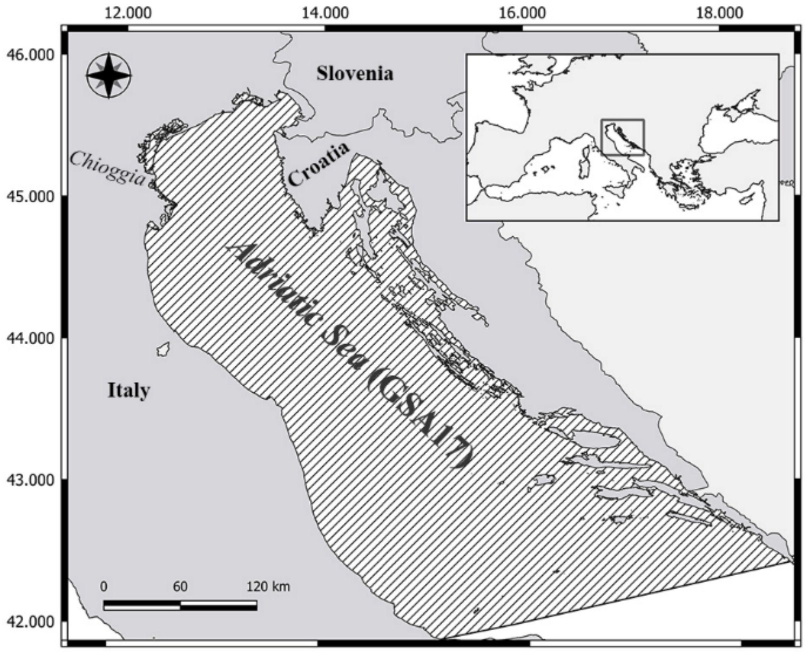

Figure 1. The study area corresponding to the Northern and Central Adriatic Sea (GSA17, Central Mediterranean Sea).

Based on unpublished catch data and the available literature [33,46–48], a list of 17 species has been defined, as representative of the main SSF catches in the GSA17 (Table 1). Global distributional data of each species were obtained by consulting the Ocean Biogeographic Information System (OBIS; accessible on the URL https://www.obis.org/ website, accessed on 18 February 2021, is an open-access international network and data collection infrastructure aimed at providing everyone, everywhere, data on all forms of life on Earth) and the Global Biodiversity Information Facility (GBIF; accessible on the URL https://www.gbif.org/ website, accessed on 18 February 2021, GBIF is an open-access international network and data collection infrastructure aimed at providing everyone, everywhere, data on all forms of life on Earth). Duplicate records were deleted and, in order to obtain a picture as close as possible to the current spatial distribution of the species considered and to match the time window of the predictors, records were filtered retaining only records between 1950 and 2010.

For each one of these species, their thermal affinity has been assigned (Table 1) according to the latitude-based method proposed by [49], considering only Northern hemisphere records. Arbitrary latitudinal thresholds were set at 30° N (Southern limit of the Mediterranean Sea basin) and 45° N (Northern limit of the basin, excluding the Northernmost parts of the Adriatic and Black Seas), defining a Northern cold zone (>45° N), a Central temperate zone (between 45° and 30° N; typical of the Mediterranean Sea) and a Southern warm zone (<30° N). The main latitudinal ranges for the species were estimated by means of the median and interquartile range of the latitudinal component of their distributional data. Finally, the climatic affinity for each taxon was attributed based on whether its median fell in the cold, temperate or warm zone. In cases where the interquartile range was not fully included in the same zone as the median, an intermediate thermal affinity was attributed, leading to six groups of climatic affinity: cold, cold/temperate, temperate, temperate/warm, warm and ubiquitous species.

Table 1. The 17 species targeted by SSF considered in the present study, with their climatic affinity (see text for further information).

Species	Common Name	Acronym	Climatic Affinity
Callinectes sapidus	Blue crab	CSA	Warm
Chelidonichthys lucerna	Tub gurnard	CLU	Ubiquitous
Chelon ramada	Thinlip grey mullet	CRA	Cold/Temperate
Coryphaena hippurus	Common dolphinfish	CHI	Warm
Dicentrarchus labrax	European seabass	DLA	Cold
Lichia amia	Leerfish	LAM	Warm
Merlangius merlangus	Whiting	MMG	Cold
Merluccius merluccius	European hake	MMC	Cold
Mullus surmuletus	Surmullet	MSU	Cold/Temperate
Mustelus mustelus	Smooth-hound	MMU	Temperate
Pomatomus saltatrix	Bluefish	PSA	Temperate/Warm
Scorpaena scrofa	Red scorpionfish	SSC	Temperate
Sepia officinalis	Common cuttlefish	SOF	Cold
Seriola dumerili	Greater amberjack	SDU	Warm
Solea solea	Common sole	SSO	Cold
Sparus aurata	Gilthead seabream	SAU	Temperate
Squilla mantis	Mantis shrimp	SMA	Temperate

It is well known how, in the northern hemisphere, climate change is shifting the ranges of many species northwards [50]. Therefore, we have tried to estimate the habitat suitability (present and future) of the GSA17 also for three tropical species of commercial interest (in their native countries), which presence has been already reported in the Mediterranean Sea but not yet exploited by Mediterranean fishing activities [51–53]: *Epinephelus coioides* (Hamilton, 1822), *Scarus ghobban* Forsskål, 1775 and *Terapon th*eraps Cuvier, 1829. We created spatial distribution models for 20 species using Maximum Entropy software (MaxEnt, version 3.4.4) [54,55], a machine learning method widely used for ecological applications that performs well in its predictive accuracy [56,57], also with the default features configuration [58], the same used in the present work. Using presence-only data, along with baseline data, MaxEnt models predicts the relative probability of species presence, conditioned by environmental constraints [54,59]. The MaxEnt software was specifically designed for the use of presence-only data and showed a good performance even when a small dataset was used [56,60–62]. As suggested by [63], it is possible to simply interpret the relative probability of occurrence estimated as an index of habitat suitability.

In this work, the habitat suitability for each of the 20 species was estimated, in the present and future, by constructing models based on six variables (minimum, mean and maximum temperature and salinity), on a 10 × 10 km grid. As reported by several authors [64–66], among the factors influencing the distribution of aquatic species, temperature is the most important, not only in the context of climate change studies. In addition to the temperature, we have taken into account salinity as a second predictor [66–68]. Indeed, in the Central-Northern Adriatic, due to the presence of important freshwater inputs (mainly by the Po river) combined with its shallow depth, salinity plays an important ecological role [52,69] and is expected to be deeply affected by variations in the rainfall regime in the next decades, due to climate changes. In order to also take into account the seasonal variations, in addition to the average values of temperature and salinity, the minimum and maximum values of the monthly averages were also considered for both variables [70]. In fact, in some cases, it is the extremes of the variability range that most influence the distribution of organisms. For example, [71] indicate the minimum winter temperature as the limiting factor in the colonization of the Mediterranean Sea by Lessepsian tropical species, while the intensification of maximum summer temperatures could accelerate the decline of native species [32].

The MaxEnt habitat suitability maps were created using the environmental data obtained by the www.bio-oracle.org (accessed on 9 November 2022) database. Bio-ORACLE is a set of GIS rasters that provide geophysical, biotic and environmental data for marine ecosystems on a global scale. Marine data layers for present conditions (i.e., minimum, maximum and mean values of surface temperature and salinity) were produced with climate data describing averages for the period 2000–2014, obtained from pre-processed global ocean re-analyses combining satellite and in situ observations at regular two- and three-dimensional spatial grids. Future layers were produced for 2040–2050 and 2090–2100 by averaging data from distinct atmosphere-ocean general circulation models provided by the Coupled Model Intercomparison Project (CMIP5). The most recent Representative Concentration Pathways (RCP) are provided in order to model the ecological implications of future climate change. In the present study, two scenarios adopted by the IPCC (The Intergovernmental Panel on Climate Change) were considered: the RCP 4.5 (a good scenario, considering the stabilization/reduction in the present greenhouse gas emissions level) and the RCP 8.5 (the worst scenario, considering the Business as Usual, that is the maintenance of the present increasing greenhouse gas emissions trend), both applied to two time snapshots: a short-term (2040–2050) and a medium-term (2090–2100) prediction.

On the basis of the output generated maps, the mean habitat suitability (as the average probability across the background grid) in GSA17 was calculated for each species, for the present and the four future situations. A paired-samples Wilcoxon test (significance difference at $p < 0.001$) was applied to test the significance of differences between present and future habitat suitability. Furthermore, habitat suitability (present and future) has been used to formulate an index R according to the equation $R = HS_f/(HS_f + HS_p)$, where HS_f is the habitat suitability of the species in the future and HS_p is the probability of the presence of the species in the present conditions. Index R can vary between 0 and 1 and was chosen in order to standardize the results and make them comparable. $R < 0.5$ means that the habitat suitability for the species in the future will be lower than in the present, while $R > 0.5$ means that the habitat suitability in the future will be greater than in the present. For values around 0.5, the habitat suitability for the species in the future could be considered equal to that in the present.

In order to quantify the effect of the four tested situations on the SSF landings, the fish market of Chioggia has been chosen as an example. Landing data were analyzed considering two case studies: fishery at sea and fishery within one of the largest transitional areas in the Mediterranean (Venice lagoon). To this end, the predictions of the probability of occurrence in GSA17, obtained with the method described above, were applied to the landing quantities of the two case studies in the period 2017–2019 for the 17 species considered. Since the expected changes in landed quantities could lead to changes in SSF earnings, a rough estimate of the effect of climate change on SSF earnings was also made using wholesale 2019 prices at Chioggia fish market. ANOVA followed by Tukey post hoc test was used to test for differences in landing losses between scenarios.

3. Results

According to the different projections, water temperature in GSA17 is forecast to increase by 2 to 4 °C (Figure 2a), and salinity is also expected to increase by one to two points (Figure 2b).

The habitat suitability for each species in the GSA17, under the four tested situations is reported on Figure 3: the habitat suitability to date is compared with the habitat suitability in the future, according to the four predictions. This information is summarized with the R-index values in Table 2. Only *C. sapidus* showed R values well above 0.5, indicating a significant future increase in the presence under both scenarios in the short and medium term. For nearly half of the species, future mean habitat suitability will clearly decrease with respect to present-day values under both scenarios over both the short and medium term, while R values are mostly around or slightly above 0.5 for the remaining species, indicating a stable–decreasing habitat suitability. Despite having values close to the 0.5 threshold, the Wilcoxon test still showed significant differences between present and future habitat suitability, particularly in the medium term (Table 2).

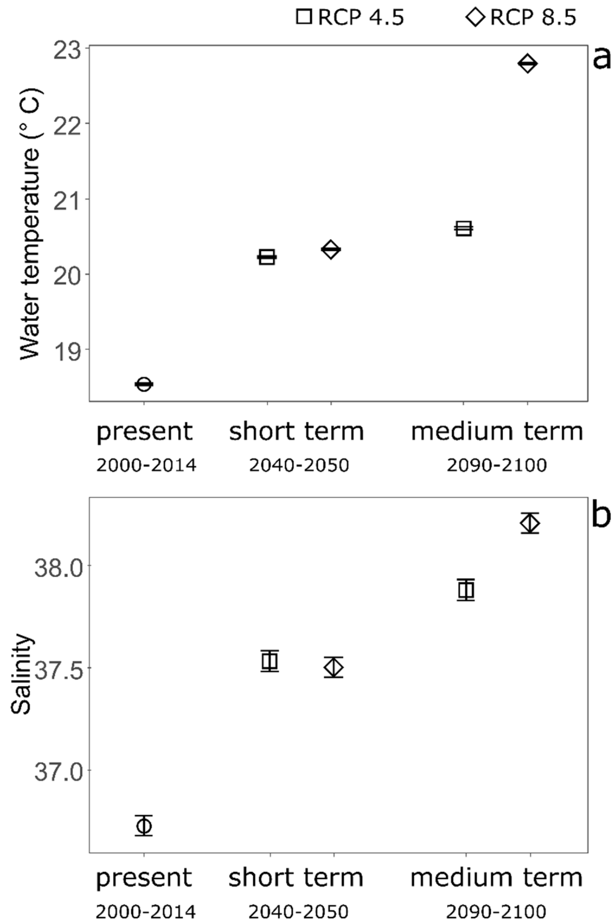

Figure 2. Mean (±st. err.) water temperature (**a**) and salinity (**b**) in the GSA17 at present (2000–2014, circle) and their expected values in the short (2040–2050) and medium (2090–2100) term according to the two IPCC scenarios RCP 4.5 (squares) and 8.5 (diamonds).

Table 2. Mean R-index values calculated in the GSA17 for the 17 species considered by the present study. AUC (Area Under the Curve) metric was used to test for model performance according to the scale proposed by Hosmer and Lemeshow (1989): <0.5 = none; 0.5–0.7 = poor; 0.7–0.8 = acceptable; 0.8–0.9 = excellent; >0.9 = outstanding. Values in bold highlight when the difference between present and future habitat suitability was significant (Wilcoxon test, $p < 0.001$).

Species			**AUC**	**2050**		**2100**	
Latin Name	**Common Name**	**Acronym**		**RCP4.5**	**RCP8.5**	**RCP4.5**	**RCP8.5**
Callinectes sapidus	Blue crab	CSA	0.958	**0.710**	**0.708**	**0.737**	**0.710**
Chelidonichthys lucerna	Tub gurnard	CLU	0.963	**0.445**	**0.453**	**0.415**	**0.061**
Chelon ramada	Thinlip grey mullet	CRA	0.982	**0.364**	**0.374**	**0.347**	**0.142**
Coryphaena hippurus	Common dolphinfish	CHI	0.669	0.500	0.500	**0.476**	**0.476**
Dicentrarchus labrax	European seabass	DLA	0.977	**0.204**	**0.216**	**0.189**	**0.025**
Lichia amia	Leerfish	LAM	0.973	0.514	0.513	0.501	**0.461**
Merlangius merlangus	Whiting	MMG	0.973	**0.395**	**0.420**	**0.393**	**0.159**
Merluccius merluccius	European hake	MMC	0.979	0.494	0.496	**0.463**	**0.208**
Mullus surmuletus	Surmullet	MSU	0.980	**0.312**	**0.305**	**0.344**	**0.046**
Mustelus mustelus	Smooth-hound	MMU	0.931	**0.400**	**0.401**	**0.377**	**0.305**
Pomatomus saltatrix	Bluefish	PSA	0.908	0.482	0.490	**0.467**	**0.431**
Scorpaena scrofa	Red scorpionfish	SSC	0.928	0.500	0.500	**0.476**	**0.350**
Sepia officinalis	Common cuttlefish	SOF	0.973	**0.419**	**0.428**	**0.392**	**0.170**
Seriola dumerili	Greater amberjack	SDU	0.938	0.500	0.497	**0.454**	**0.324**
Solea solea	Common sole	SSO	0.977	**0.452**	**0.461**	**0.427**	**0.301**
Sparus aurata	Gilthead seabream	SAU	0.989	**0.433**	**0.430**	**0.408**	**0.292**
Squilla mantis	Mantis shrimp	SMA	0.980	**0.508**	**0.508**	**0.490**	**0.141**

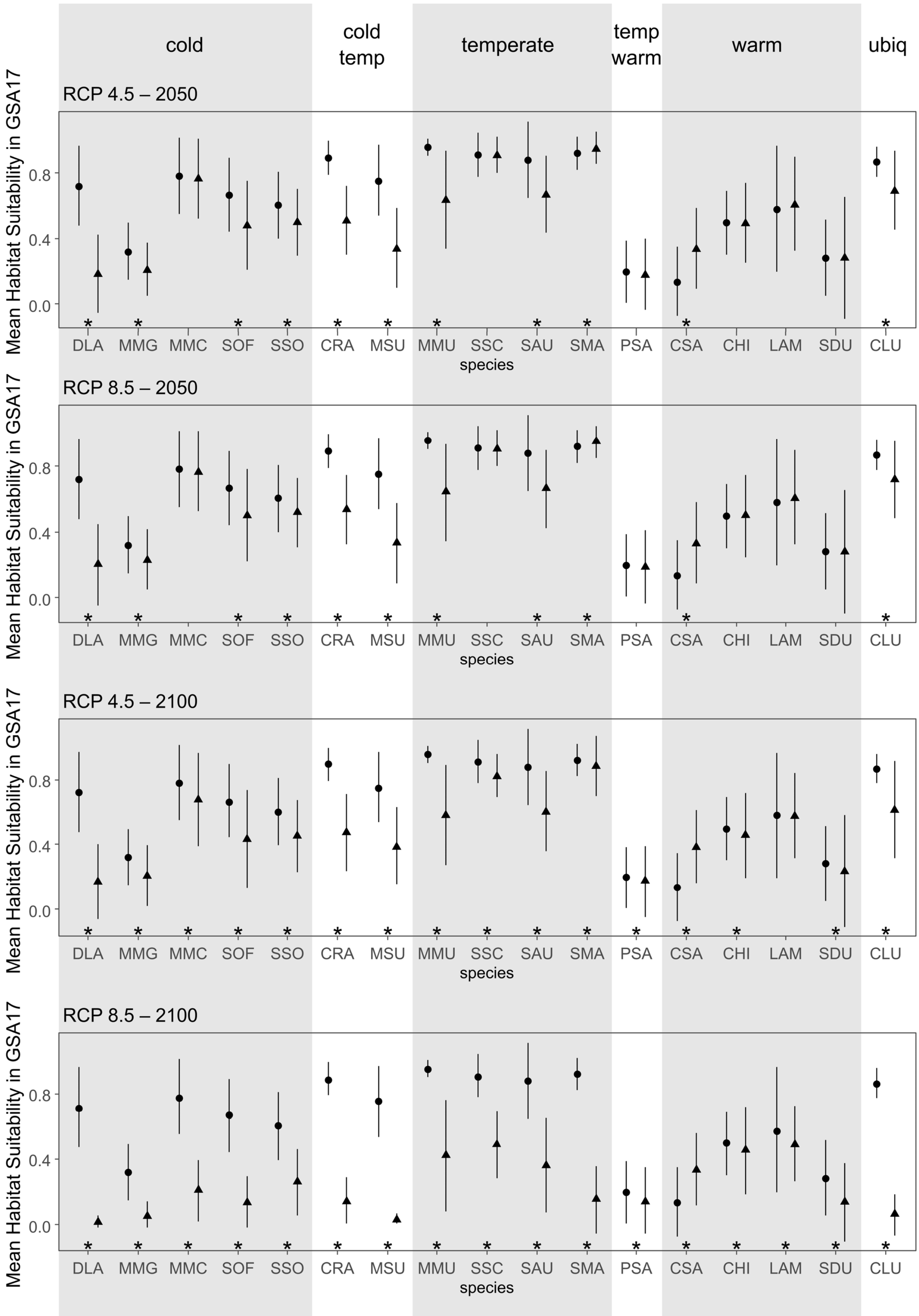

Figure 3. Mean habitat suitability (±st. dev.) of the 17 species targeted by SSF (see Table 1 for species acronyms), at present (circles) and in the future (triangles) according to the four projections considered. * marks significance differences for $p < 0.001$.

The generated models performed well, with all the models but one (i.e., *Coryphaena hippurus*) resulting in an excellent/outstanding performance (i.e., AUC > 0.8, Table 2). For most of the species the jack-knife test of variable importance showed how temperature was the predictor with the highest gain when used in isolation (see Supplementary Materials for jack-knife test results). Indeed, for most of the species considered, the picture that emerges from the models applied shows that temperature is the variable that contributes most significantly to explaining the probability of relative presence within the GSA17.

Maximum and/or minimum temperature, in particular, have a significant relative percentage contribution (from 25.4% to 66.6% for minimum temperature and from 30.8% to 48% for maximum temperature, Table 3) for temperate/warm and warm climate affinity species (*C. sapidus*, *C. hippurus, L. amia*, *P. saltatrix* and *S. dumerili*). In the case of *C. hippurus*, maximum and mean temperature are the two most important variables (with a relative percentage contribution of 48% for the maximum temperature and 37.7% for the mean temperature), while for *L. amia* minimum temperature is the most important variable (66.6%), followed by minimum salinity (13.9%). Minimum salinity also appears to be of some importance for *C. sapidus*, with a relative % contribution of 19.8%.

Table 3. Estimates of relative percentage contributions of the environmental variables to the MaxEnt model.

Thermal Affinity	Species	Percent Contribution					
ubiquitous	*Chelidonichthys lucerna*	Tmean 39.7	Tmin 27	Smax 14.8	Smin 13.9	Smean 3	Tmax 1.6
cold	*Dicentrarchus labrax*	Tmin 48.7	Tmean 28.1	Tmax 12.9	Smax 9.9	Smin 0.3	Smean 0.1
	Merlangius merlangus	Tmin 50.7	Tmean 41.5	Tmax 4.2	Smax 3.1	Smin 0.5	Smean 0
	Merluccius merluccius	Smax 52.7	Tmean 34.7	Tmin 9.8	Smean 1.9	Smin 0.4	Tmax 0.4
	Sepia officinalis	Tmin 49	Tmean 39.4	Smax 7.1	Tmax 2.6	Smean 1.1	Smin 0.8
	Solea solea	Tmin 51.6	Tmean 35.5	Tmax 6.2	Smax 5.6	Smin 1.2	Smean 0.1
temperate/cold	*Chelon ramada*	Tmin 38.9	Tmean 26.4	Smax 25.5	Smin 5.4	Tmax 2.2	Smean 1.6
	Mullus surmuletus	Tmean 41.5	Smax 31.3	Tmin 23.1	Tmax 3.1	Smean 0.8	Smin 0.2
temperate	*Mustelus mustelus*	Tmean 37.2	Tmin 30.1	Smax 21.5	Smin 10.5	Tmax 0.5	Smean 0.2
	Scorpaena scrofa	Smin 27.1	Tmean 26.4	Tmin 17.7	Smax 16.2	Smean 10.7	Tmax 1.9
	Sparus aurata	Smax 54.2	Tmin 27.9	Tmean 17.6	Tmax 0.3	Smin 0.1	Smean 0
	Squilla mantis	Smax 28.8	Tmin 19.8	Tmax 18.3	Tmean 17.8	Smin 13.7	Smean 1.6
warm/temperate	*Pomatomus saltatrix*	Tmin 35.9	Tmax 30.8	Tmean 17.7	Smin 10.4	Smax 2.7	Smean 2.5
warm	*Callinectes sapidus*	Tmax 45.6	Tmin 25.4	Smin 19.8	Smax 7.5	Tmean 1.3	Smean 0.3
	Coryphaena hippurus	Tmax 48	Tmean 37.7	Smax 9	Tmin 3.6	Smean 1.7	Smin 0
	Lichia amia	Tmin 66.6	Smin 13.9	Smax 12.3	Tmean 6	Smean 1.2	Tmax 0
	Seriola dumerili	Tmax 43.4	Tmin 28.7	Tmean 19	Smax 6.3	Smin 2.5	Smean 0.1

Table 3. *Cont.*

Thermal Affinity	Species	Percent Contribution					
tropical	*Epinephelus coioides*	Tmin 42.1	Tmax 34.7	Smin 11.4	Tmean 6.5	Smax 5.1	Smean 0.1
	Scarus ghobban	Tmin 58.6	Tmean 14.9	Tmax 13.6	Smax 12.6	Smin 0.2	Smean 0.1
	Terapon theraps	Tmin 38	Tmean 21.9	Smin 20.9	Tmax 16	Smax 2.6	Smean 0.5

In the case of ubiquitous species and temperate/cold-affinity species, temperature is generally always the variable with the highest relative percentage contribution (in this case mean and minimum temperature), with a relative percentage contribution ranging from 17.6% to 41.5% for mean temperature and from 17.7% to 51.6% for minimum temperature (Table 3). It should be noted that for seven species with temperate to cold climate affinity, salinity also shows a significant percentage contribution. In particular, maximum salinity is important for *C. ramada* (25.5%), *M. mustelus* (21.5%), *M. merluccius* (52.7%), *M. surmuletus* (31.3%), *S. aurata* (54.2%) and *S. mantis* (28.8%), while for *S. scrofa* a significant percentage contribution comes from minimum salinity (27.1%).

Finally, analyzing the habitat suitability for three tropical species (namely, *E. coioides*, *S. ghobban*, *T. theraps*), obtained results showed that, under the tested projections, the GSA17 is expected to transform in a suitable environment for these species: all the three species have R > 0.700 (Table 4). Again, also for these species, the temperature is the most important variable, in particular the minimum temperature, with a relative percentage contribution ranging from 42.1% to 58.6%, followed by the maximum temperature for *E. coioides* (34.7%) or by the mean temperature for *S. ghobban* (14.9%) and *T. teraps* (21.9%).

Table 4. Mean R values in the GSA17 for the three tropical species already recorded in the Mediterranean Sea. AUC (Area Under the Curve) metric was used to test for model performance according to the scale proposed by Hosmer and Lemeshow (1989): <0.5 = none; 0.5–0.7 = poor; 0.7–0.8 = acceptable; 0.8–0.9 = excellent; >0.9 = outstanding. Values in bold highlight when the difference between present and future habitat suitability was significant (Wilcoxon test, $p < 0.001$).

Tropical Species	Common Name	AUC	2050		2100	
			RCP4.5	RCP8.5	RCP4.5	RCP8.5
Epinephelus coioides	Orange-spotted grouper	0.951	**0.748**	**0.743**	**0.779**	**0.980**
Scarus ghobban	Blue-barred parrotfish	0.900	**0.975**	**0.975**	**0.978**	**0.992**
Terapon theraps	Large-scaled terapon	0.936	**0.881**	**0.875**	**0.898**	**0.984**

Landing data from the Chioggia fish market were used to quantify the impact of the decrease in target species availability on SSF landings, both in transitional and coastal waters. Obtained results are reported in Table 5: landings loss was in the range 13–58% and 23–87% in the coastal and transitional areas, respectively. Moreover, the comparison among the scenarios resulted statistically significant (Table 6). Given the difficulty of predicting sales prices in the coming decades, we attempted a gross estimate of future earnings based on wholesale prices in 2019. The forecasted decrease in landings would result in the medium term, under the RCP 8.5 scenario, in an annual economic loss of slightly less EUR 50,000 for transitional waters and EUR 300,000 for coastal waters (Table 5).

Table 5. Estimated annual loss of landings—expressed as % of the average annual landings in the three-year period 2017–2019—and estimated economic loss (EUR y^{-1}) resulting from the expected decrease in landings (only the 17 species analyzed in this study were considered). In brackets the standard error of the estimates.

Time Frame	RCP Scenario	Coastal Waters		Transitional Waters	
		Landing Loss (%)	Economic Loss (EUR y^{-1})	Landing Loss (%)	Economic Loss (EUR y^{-1})
Short term	4.5	−13.5 (1.4)	65,869 (14,347)	−23.2 (2.2)	11,824 (2750)
(2040–2050)	8.5	−15.4 (1.7)	76,050 (16,797)	−26.8 (2.4)	13,756 (3114)
Medium term	4.5	−23.1 (1.7)	112,264 (18,313)	−35.8 (2.5)	18,567 (3904)
(2090–2100)	8.5	−58.4 (2.9)	284,607 (39,329)	−86.9 (1.5)	46,044 (10,086)

Table 6. Differences among scenarios (RCP 4.5 and 8.5) and timeframes (short: 2040–2050; medium: 2090–2100) in the estimated loss of landings tested by ANOVA followed by Tukey post hoc test. The landing data comprises only the 17 species considered in this study. n.s. = not significant.

Scenarios	p adj Coastal Waters	p adj Transitional Waters
RCP4.5_2050–RCP8.5_2050	n.s.	n.s.
RCP4.5_2100–RCP8.5_2100	<0.001	<0.001
RCP4.5_2050–RCP4.5_2100	<0.05	<0.05
RCP8.5_2050–RCP8.5_2100	<0.001	<0.001

4. Discussion and Conclusions

Climate changes are transforming the world oceans and the Mediterranean Sea is not an exception, being subjected to deep modifications of biological communities mainly as a consequence of species redistribution [37,72–74]. These changes, having clear impacts on the geographical distribution of species [3,75], also involve species targeted by commercial fisheries, both in positive and negative ways. Some target species, indeed, could benefit from the new environmental conditions that are created in a given area as a result of climate change [76,77] and expand into areas never previously colonized; others, instead, could be outcompeted by the new thermophilic species, in both cases with significant ecological and socio-economic consequences [39]. Moreover, by modifying species interactions and trophic network dynamics, marine invaders can cause declines in invaded populations, local extinctions and alter the structure and functioning of ecosystems and related ecosystem services [74,78].

In particular, the Adriatic Sea is a good case study for analyzing early warning effects of climate change on the fishery sector since, for the characteristics of the area, modifications due to climate change could be amplified [1]. In this study, the habitat suitability in the near future was calculated for a pool of SSF target species in the GSA17 (Northern and Central Adriatic Sea). Considering the temperature and salinity predictions provided by the IPCC scenarios RCP 4.5 and 8.5, two timeframes were considered: a short (2040–2050) and medium (2090–2100) term. Obviously, the presence and spatio-temporal distribution of marine organisms depend on multiple factors (both abiotic and biotic) and their interactions. Indeed, the high diversity of the forcing affecting marine species, especially demersal species, combined with the geographical variability of these phenomena, makes the application of climate models difficult and decreases their predictive capabilities [32]. For these reasons, the assessments made on the results obtained should therefore be understood as the evaluation of a temporal trend: that is, they provide us with an indication of the possible trend of some nektonic populations of the GSA17.

An increase in thermophilic species from the Southernmost part of the Mediterranean basin has been reported for some years now in GSA17 [53,79–85]. The northward expansion and increase in abundance of Mediterranean native thermophilic species (meridionalization, *sensu* [41]) is probably the first and most clear early warning sign of warming waters in the area, with the first evidence of this phenomenon dating back to the 1980s [86]. However, in addition to the meridionalization phenomenon, according to [41], we have to consider also the tropicalization, i.e., the arrival, settlement and northward expansion of the range of non-native thermophilic species, coming from the tropical areas of both the Atlantic and Indian Ocean. The Northward expansion of thermophilic species may have both positive and negative effects on the colonised areas. On the one hand, the new species could be of commercial interest and, consequently, represent a resource for the fishery. Another positive impact would be, more generally, the increase in biodiversity in the central-northern Adriatic. On the other hand, there could be negative impacts, e.g., the disappearance of endemic and cold/temperate species, with the consequent loss of regional fauna and reduction in fishery-targetable species [32,41].

The results of this study showed that climate changes would lead, in GSA17, to a decrease in the habitat suitability in both the short and medium term, for almost all the species considered, regardless of their climate affinity. Only the blue crab *Callinectes sapidus* showed an increase in the probability of occurrence in the short and medium term in both scenarios considered. *C. sapidus* is a western Atlantic coastal species that lives both in marine and brackish waters [87], with the first Mediterranean record dating back to the 1948 [88]. According to [89], this species is among the worst invasive alien species in the Mediterranean Sea, with negative effects on ecosystems and human activities along the coast. In their natural range, blue crabs are targeted by commercial and recreational fishers [90]; therefore, they could become an exploitable resource also for Mediterranean fishery.

All this suggests that the thermophilic species that recently colonized the area (as dolphinfish, barracudas and blue fish) could not find suitable conditions in the next years. Given the rapid rate at which climate change is occurring, these species could not adapt quickly enough to local changes in environmental conditions [8,77,91,92]. These results seem to suggest that GSA17 will offer less suitable conditions in the short to medium future than at present, even for the warm-affinity species that have recently expanded towards the Northern Mediterranean Sea. Indeed, as found by [77], 20% of Lessepsian migrants cannot spread fast enough to keep up with the speed of change in environmental conditions produced by climate change. This would mean that climatic conditions vary at a faster rate than the rate of spread of these warm-affinity species.

While a lower habitat suitability of GSA17 was predictable for the species with a cold and temperate affinity, the low R-index values for most of the warm-affinity species already present in the area were unexpected. The results of the present study seem to paint a worse picture than that proposed by [93], who suggested the possibility, by 2050, that Lessepsian fish species may have the opportunity to find suitable areas along the south-western coast of Italy and in the Southern Adriatic. However, it is worthy to note that the present study focused on variables that, although important, cannot alone entirely explain the expected distribution patterns. Indeed, the spatio-temporal distribution of marine species depends on many different variables (e.g., chemical-physical characteristics of the water, primary productivity, and community composition) for which no future projections exist, but which could have a determining role in influencing the estimated habitat suitability. Furthermore, the Adriatic Sea shows strong spatio-temporal variability in environmental conditions. It is in fact a continental basin, strongly influenced not only by the Mediterranean Sea circulation but also by the weather conditions, with a regular, mostly sandy and gently sloping western shore, while the eastern shore is more irregular, rocky and with a rapid increase in bathymetry [94]. The results of the present work were discussed considering the estimated habitat suitability, which is an average value for the central-northern Adriatic, but colonization by thermophilic species could occur heterogeneously, according to different possible patterns along the east coast compared to the west.

All this would suggest that instead of a meridionalization, the GSA17 is going to enter a phase characterized by tropical climatic conditions (i.e., tropicalization, according to the definition of [41]). In practice, the expected future climatic conditions seem to go beyond the 'simple' northward expansion of Southern Mediterranean species. The future conditions could be unsuitable also for Mediterranean thermophilic species and suitable for only tropical species, as the three tested in the present analysis (*E. coioides*, *S. ghobban* and *T. theraps*).

Due to its shallow depth, the Adriatic Sea, and the northern sub-basin in particular, is subject to strong temperature fluctuations, reaching extremely low temperatures in winter and warming up similar to the southern sub-basin in summer [94]. At the same time, since warming water near the seabed is much slower than at the surface, deeper areas could act as refuges for slower-dispersing species. However, in the case of the GSA17, the shallowness of the Northern and Central Adriatic Sea would prevent fish species from seeking refuge from climate change in deeper waters [86]. This variability can obviously influence the arrival of southern species in GSA17, perhaps favoring them in summer but preventing stable colonization of the area due to the cold winter temperatures. Therefore, the tropicalization of the Mediterranean Sea could deeply affect fisheries, as stocks of temperate/cold-affinity species will decline and will not necessarily be replaced by warm-affinity species of the same commercial value.

The GSA17 hosts one of the most important fishing fleets in the Mediterranean, where SSF plays a crucial role, both in terms of the number of vessels and their contribution to the local economy basin [95–99]. Indeed, the SSF sector consists of a large number of small, often individual, enterprises characterized by a low level of technology, offset by a certain versatility and adaptability [28]. SSF operators base much of their work on personal knowledge and experience. This knowledge, often handed down from generation to generation, enables fishermen to know and, above all, predict the behaviour and movements of the target species, thus maximizing catches. Therefore, SSF catches show a marked seasonality, often taking advantage of the approach to the coast by many marine species at certain times of the year. Indeed, target species vary locally and, more importantly, throughout the year.

This seasonality in catches, which represents one of the added values to SSF products, could however also represent a critical issue if, as expected, climate change would affect not only the distribution ranges but also the phenology and seasonality of the target species. In order to do this, SSF will need to harness its resilience and adaptability in order to manage the new conditions, finally putting aside the competition between fishers in favor of a cooperative approach. This would also lay the foundations for a management system capable of guiding consumers and, more generally, market demands. An example of this is the fishery of the blue crab, *C. sapidus*, a species unknown to GSA17 markets until a few years ago, which has rapidly become a target species for SSF before even establishing itself in local markets. At the moment, however, the possible ecological impacts on the native benthic communities remain still unclear, and so the medium terms modifications have to be still assessed.

The specificity, in terms of catches, shows the SSF as highly vulnerable to shifts in resources abundances and availability. This will be a problem if future habitat suitability will be lower than present for cold, temperate and warm-affinity species. SSF could prove itself to be resilient enough due to the short supply chain, but it lacks well-organized and structured distribution processes (also due to the absence of cooperation among fishers). Within this context, knowing future catch trends can provide useful management information to help manage resources and the market, perhaps favoring those species that are considered ancillary or occasional in the present but will become dominant in the future.

In this respect, we must not forget that the effects of climate change will not affect SSF alone but will also have more or less marked effects on all the other fishery sectors, even if it is not yet clear whether the diversity of the Mediterranean fleet in terms of catches and vessels will contribute to the adaptive capacity of these regions [32]. This will need to be accompanied by a series of actions and strategies aimed to focus on new target species, also adopting new techniques or modifying existing ones, therefore allowing the fishery sectors to adapt to changing environmental conditions. The analysis of trends showing a decreasing habitat suitability for many target species, and their likely replacement in the short to medium term by southern or tropical species, can be a tool not only for SSF operators but also for managers. Indeed, this kind of information can represent a useful tool on how to manage resources and the market in the near future, so as to increase the sustainability of SSF while maintaining their economic and social aspects. Indeed, efforts should focus on predicting vulnerability to invasions, providing the most at-risk areas with the tools to deal with these pressures [34,35]. Among the possible ways to combat the effects of climate change is through the establishment of marine protected areas. Indeed, the literature suggests that marine conservation can contribute to mitigating the effects of climate change in various ways, for example through carbon sequestration and the protection of coastal ecosystems, while at the same time increasing catches and fishers' earnings [100].

Therefore, it is essential to implement a management of fish stocks that could be climate resilient [101–103], able to integrate tools and policies at different spatial and temporal scales with trans boundaries management plans ([2] and citation therein). The results of this work aim at contributing to a body of knowledge of fundamental importance for a sea such as the Mediterranean [93], among the most invaded marine regions in the world [9,13], which is warming faster than the global average [40].

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/fishes8010009/s1.

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