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Warming and salinization effects on the deep-water rose shrimp, *Parapenaeus longirostris*, distribution along the NW Mediterranean Sea: Implications for bottom trawl fisheries

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ABSTRACT

The deep-water rose shrimp is a main resource for the GSA 6 bottom trawling fleet. In the last decade, landings have increased without a clear understanding of the causes. This study aims to analyze this trend, potentially related to changes in environmental conditions. Results showed an increase in the species' landings, which spread northwards along the GSA 6. GAM models detected a significant effect of location, time, and depth on the distribution of the deep-water rose shrimp, as did for temperature and salinity. Similar values between landings and LPUE were found throughout, suggesting no effects of fishing effort in time. ANOVA tests showed a significant increase of sea bottom temperature and salinity in time, which were correlated with increasing LPUE values. Then, the trend seems to be related to environmental changes rather than changes in fishing effort. Further research is needed to implement management plans that ensure the resource sustainability.

1. Introduction

The Mediterranean Sea is under severe fishing pressure caused by different types of fishing modalities and gears. Fishing activities have reduced the productivity of commercial stocks, being most of them currently overexploited (FAO, 2022), altering the ecosystems production and functioning (Colloca et al., 2017). This fragile condition has caused an increasing concern on the status of the Mediterranean ecosystems, demonstrating the need for a new management approach based on rebuilding overexploited stocks (Colloca et al., 2013; Vasilakopoulos et al., 2014). The already damaged ecological status of the Mediterranean Sea is also affected by other issues such as climate change (e.g., oceanic warming and acidification), which are added to overfishing (Lacoue-Labarthe et al., 2016; Tzanatos et al., 2014). In fact, both factors combined can worsen the fishing stocks of the commercial species (D'Onghia et al., 2012). Despite that most Mediterranean fishing stocks exhibit overfishing conditions, some species show opposite trends, either with an increase in biomass or in average individual size such as the deep-water rose shrimp, *Parapenaeus longirostris* (Lucas, 1846), in southern Adriatic waters (Ungaro and Gramolini, 2006). In this case, stock renewal may result from alterations in the environment at the ecosystem level, being favored by increases in water temperature (Ungaro and Gramolini, 2006).

The Mediterranean Sea has been described as a significant hotspot for climate change, turning into a region where both environmental and human-induced impacts can have far-reaching consequences (Giorgi, 2006). Several changes have been observed in this region, including warming and salinization (Adloff et al., 2015; Schroeder et al., 2017). Particularly, starting in 2014, an abrupt rise in sea water temperature was reported in the NW Mediterranean, aligned with global warming changes (Bahamon et al., 2020; Margirier et al., 2020). These environmental trends may alter the spatial distribution of marine species and represent one of the most perceptible outcomes of climate change, affecting commercial fisheries and biodiversity (Bellard et al., 2012; Perry et al., 2005). Hastings et al. (2020), suggested that latitudinal shifts in marine species abundance will continue to be driven by

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anticipated sea temperature increases, which may have repercussions of socioeconomic significance. As an example, the deep-water rose shrimp, increased its presence and abundance in the central and eastern Mediterranean Sea becoming a target species for some fisheries whereas it was still found in very low densities in the western basin (Abelló et al., 2002). The stocks of this species seem to be favored by the tropicalization of the Mediterranean Sea (Benchoucha et al., 2008; Ungaro and Gramolini, 2006) but other factors may have also influenced the species' dynamics. Nonetheless, the deep-water rose shrimp is increasing its economic importance becoming one of the most caught crustaceans of the Mediterranean bottom trawling fishing fleet and, at present, being the fourth commercial species with the highest revenue in some Mediterranean subregions (Geographical Sub Areas, GSAs) (FAO, 2022).

The deep-water rose shrimp is a demersal decapod crustacean with a wide geographic distribution in both Mediterranean and Atlantic waters (Sobrino et al., 2005). The species is found in the Mediterranean and adjacent seas, in the East Atlantic, from Portugal to Angola, and in the West Atlantic, from the north coast of the USA (i.e., Massachusetts) to French Guiana (Holthuis, 1980). The species inhabits the bottom mud or muddy sand between 20 m and 750 m (Holthuis, 1980; Tom et al., 1988), although its maximum abundance varies between 150 and 400 m depth (FAO, 2023). In the Mediterranean Sea, the studies on the deep-water rose shrimp determine that the species is more abundant in the eastern and central basins (Abelló et al., 2002), related to an increase in sea surface temperature (Colloca et al., 2014; Ligas et al., 2011). Moreover, some studies show increasing landings for the deep-water rose shrimp, which may be determined by a decrease in fish abundances (Cartes et al., 2009) and an increase in trawlers moving from other resources to target crustaceans (Colloca et al., 2017).

Landings of the deep-water rose shrimp have been reported since 1980 with a total worldwide catch of 26,278 t in 2020 (FAO, 2023). In NW Mediterranean waters, fisheries have a traditional and cultural heritage, which is fundamental for the socio-economy of the coastal communities (Farrugio et al., 1993). The abundance of the targeted resources has changed over time, forcing the fishing activity and market to adapt to resources availability. For example, the decrease in catches of the Norway lobster, *Nephrops norvegicus* (Linnaeus, 1758) (European Union, 2019), forced to adopt new commercial strategies, including the exploitation of the deep-water rose shrimp, a resource present in the area, with a lower abundance than other commercial crustaceans (Abelló et al., 1988). As a consequence of the increasing interest to exploit the deep-water rose shrimp, the aim of this work was to disclose the anthropic and environmental factors driving the temporal changes in its spatial distribution in the GSA 6 over more than one decade (i.e., 2008–2020). This work evaluates the spatial and depth distribution of Landings Per Unit of Effort (LPUE). Moreover, the LPUE of the deep-water rose shrimp are compared with those of the Norway lobster, an endobenthic territorial species (Aguzzi et al., 2023b). This species may be a potential competitor for the substrate when both species, the deep-water rose shrimp and the Norway lobster, show overlapping crepuscular and nocturnal activity patterns (i.e., maximum catches as proxy for copresence on the substrate) (Aguzzi et al., 2009, 2015). Finally, the LPUEs from the deep-water rose shrimp are correlated with environmental variables. Overall, the goal is to understand the evolution of the deep-water rose shrimp LPUE and the reasons behind it.

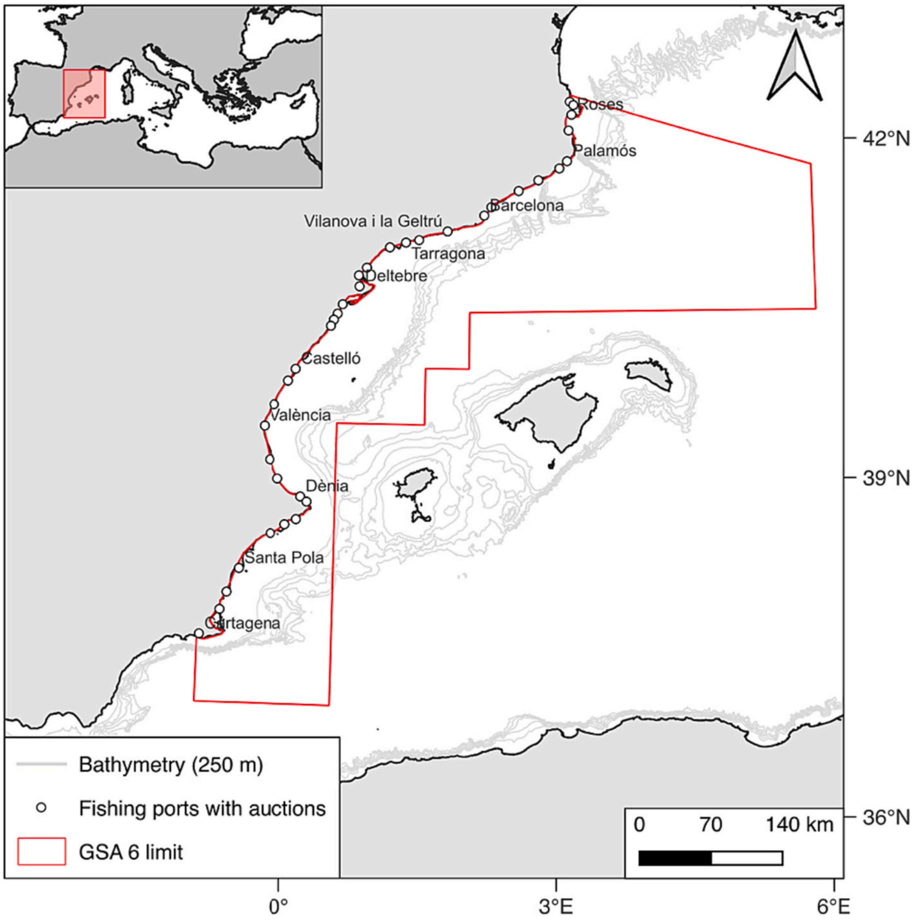

Fig. 1. Study area indicating the geographical limits of the GSA6. White dots indicate fishing ports with daily fish auctions. Bathymetry isobaths indicated in 250 m depth intervals, with the maximum at 1250 m.

2. Materials and methods

2.1. Area of the study

The study area considers the FAO geographical subarea 6 (GSA 6), as defined by the General Fisheries Commission of the Mediterranean (GFCM) (Fig. 1) comprising 175,686 km^2 (Muñoz et al., 2023). The GSA 6 contains 42 fishing ports with daily auctions (Fig. 1), which conduct a daily register of the species landed by each vessel.

2.2. Dataset

2.2.1. Landings

In the Spanish Mediterranean, the trawling fishing fleet is allowed to fish between 50 and 1000 m depth, within the 5 weekdays and a maximum of 12 h per day, landing all catches daily. In relatively shallow areas, such as the Ebre Delta, trawling is prohibited at $<$3 nautical miles off the coast despite the authorization to fish above 50 m depth (EC 1626/1994; EC 1967/2006).

Landings are sold fresh daily by a descending bidding system at the fishing auctions where the local fishers' guilds register the economic value and total amount of the landed species. All these data are sent daily to the regional administrations databases and gathered by the Spanish Fisheries Secretariat (Spanish Government). The Catalan Research Institute for the Governance of the Sea (*Institut Català de Recerca per la Governança del Mar*, ICATMAR) processes this data for the GSA 6 and uses it to provide scientific advice to the regional and Spanish fishery administrations. The information on landings is used to create a dataset recorded for each fish market and filtered by fishing type (bottom trawling). Moreover, this dataset has an identifying track code, unique for each fishing trip (by day and vessel), which enables to discern and quantify the different landed species.

2.2.2. Vessel Monitoring System (VMS)

Georeferenced vessel trajectories and fishing times per vessel were used to assess the landings distribution of the deep-water rose shrimp in the GSA 6. For that, VMS data were analyzed together with the landings dataset. VMS is a satellite-based monitoring system that provides data at regular time intervals, at least once every two hours, specifying the location, course, and speed of each vessel (Sala-Coromina et al., 2021). This system was implemented in 2006 for vessels longer than 15 m and later, in 2012, the mandate was modified to include vessels longer than 12 m. VMS transfers data to a satellite, which sends it to a receiving station on land, from where the information is transmitted to the corresponding administration (Spanish Fisheries Secretariat, Spanish Government) to be used for the control of fishing activities.

For spatial data processing, the same protocol described in Sala-Coromina et al. (2021) was applied on this study. VMSbase R package (Russo et al., 2014) was used to remove duplicate registers or points on land, as described by Russo et al. (2011). Then, the point frequency was increased by interpolating points at 10 min resolution. VMS records of the vessels' tracks were identified with a unique track code for each fishing trip (day and vessel). These VMS data obtained were introduced in a PostgreSQL (14.1 version) - PostGIS (3.2 version) database for further analyses. A speed filter, being the trawling speed range between 1.5 and 4.5 knots, was used to subset data points corresponding to vessels on fishing activity and, thus, excluded the trip to fishing ground and inactive moments. Additionally, a depth filter was applied to remove points out of the fishing zones ($>$1000 m). Finally, the total fishing time (in hours) was calculated for each filtered track.

The subset VMS data were joined to the daily landings dataset by their identifying track codes to obtain a final dataset, which included the total fishing time and landings equally distributed among all fishing positions by day and vessel. Then, all the dataset variables were yearly aggregated in a 1 km^2 grid (EPSG 4326) on the GSA 6 area for further analyses.

2.2.3. Sea bottom temperature and salinity

Monthly sea bottom temperature and salinity data were extracted from the Regional Oceanic Modeling System (ROMS) (Shchepetkin and McWilliams, 2005) implemented on the NW Mediterranean Sea from years 2008 to 2020. A description of the model implementation and validations are provided in Clavel-Henry et al. (2021).

The model has a spatial resolution of ~2 km and a vertical discretization of 40 sigma layers, with outputs of the water properties recorded daily. The realignment process involved that ROMS data were averaged into the landing grid cell which overlapped with ROMS grid cells. When the overlapping did not cover the whole surface area of ROMS grid cells, weights were applied in the calculations. Thus, the weight was the percentage of the grid cell surface area overlapped by the landings grid cells. Finally, the spatially distributed landing values were aggregated yearly and joint with gridded temperature and salinity values from ROMS.

2.3. Data analyses

The biological and physical datasets were yearly aggregated from years 2008 to 2020 at a 1 km^2 grid resolution. The geographical Landings Per Unit Effort (LPUE) distribution of the deep-water rose shrimp was mapped with yearly aggregations along the GSA 6 area, using QGIS software 3.30 version (QGIS Development Team, 2022). LPUE (kg h^{-1} km^{-2}) are understood as the total kilograms landed (kg km^{-2}) of deep-water rose shrimp by the number of hours (h) spent fishing by each vessel, a.k.a. effort (Bishir and Lancia, 1996; Lancia et al., 1996; Seber, 1982). In this study, LPUE are considered the same than CPUE (Catches Per Unit of Effort) because the discarded fraction of the species from the total catch is negligible (for more information see data from https://icatmar.cat database).

Then, to understand the reasons behind the spatial distribution of the species and its LPUE yearly variability, different parameters were examined including landings, the interaction with Norway lobster (*Nephrops norvegicus*) LPUE, and the interaction with sea bottom temperature and salinity. Additionally, LPUE and landing trends were plotted with the total biomass index data (kg km^2) obtained from the Mediterranean International Trawl Surveys (MEDITS). These plots allowed to characterize the trends observed with fishery-dependent and independent data.

LPUE for the Norway lobster was obtained following the same procedures applied to the deep-water rose shrimp. The yearly distribution of LPUEs of the deep-water rose shrimp and Norway lobster were used as a proxy for the species abundance assuming that both LPUE trends follow the changes in their stock abundances (Leitão et al., 2022; Maunder and Punt, 2004).

Sea bottom temperature and salinity values obtained from the ROMS model (Clavel-Henry et al., 2021) were used to plot the mean values of these environmental variables at a depth range of 100–400 m, which is the deep-water rose shrimp optimal range distribution (Fortibuoni et al., 2010; Sobrino et al., 2005). These values were used to detect changes and potential correlations between the environmental variables and deep-water rose shrimp LPUE. Moreover, detailed heatmaps were plotted to illustrate the evolution of temperature and salinity from the sea surface to 400 m depth for the GSA 6 during the study period. Tests on the analysis of the variance (i.e., ANOVA) were conducted to assess the significance of the environmental changes over time and depth.

2.4. Generalized Additive Models (GAM) and correlation tests

The effect of spatial, temporal, depth, and environmental variability in the LPUE of the deep-water rose shrimp was determined fitting Generalized Additive Models (GAMs) (Hastie and Tibshirani, 1990) with Gaussian distribution and an identity link. GAM modeling was applied with *mgcv* package (Wood, 2017) from R Studio (R Core Team, 2022) using *bam* function (Wood et al., 2015), which is used to apply GAMs with very large datasets. The analysis was performed using data aggregated yearly in a 5 km^2 grid. The bathymetric data used in the models were obtained from the GEBCO (General Bathymetric Chart of the Oceans) portal with a spatial resolution of 15 arc *sec*. A bathymetric filter was applied to include bottom depths between 100 and 600 m depth, which is also within the shrimp species' depth range distribution obtained from the landings distribution of this study and from Holthuis (1980). The response variable was LPUE (kg h^{-1} km^{-2}), log-transformed with log$_{10}$ (LPUE+1) to approximate to a normal distribution. The fitted GAMs followed the function:

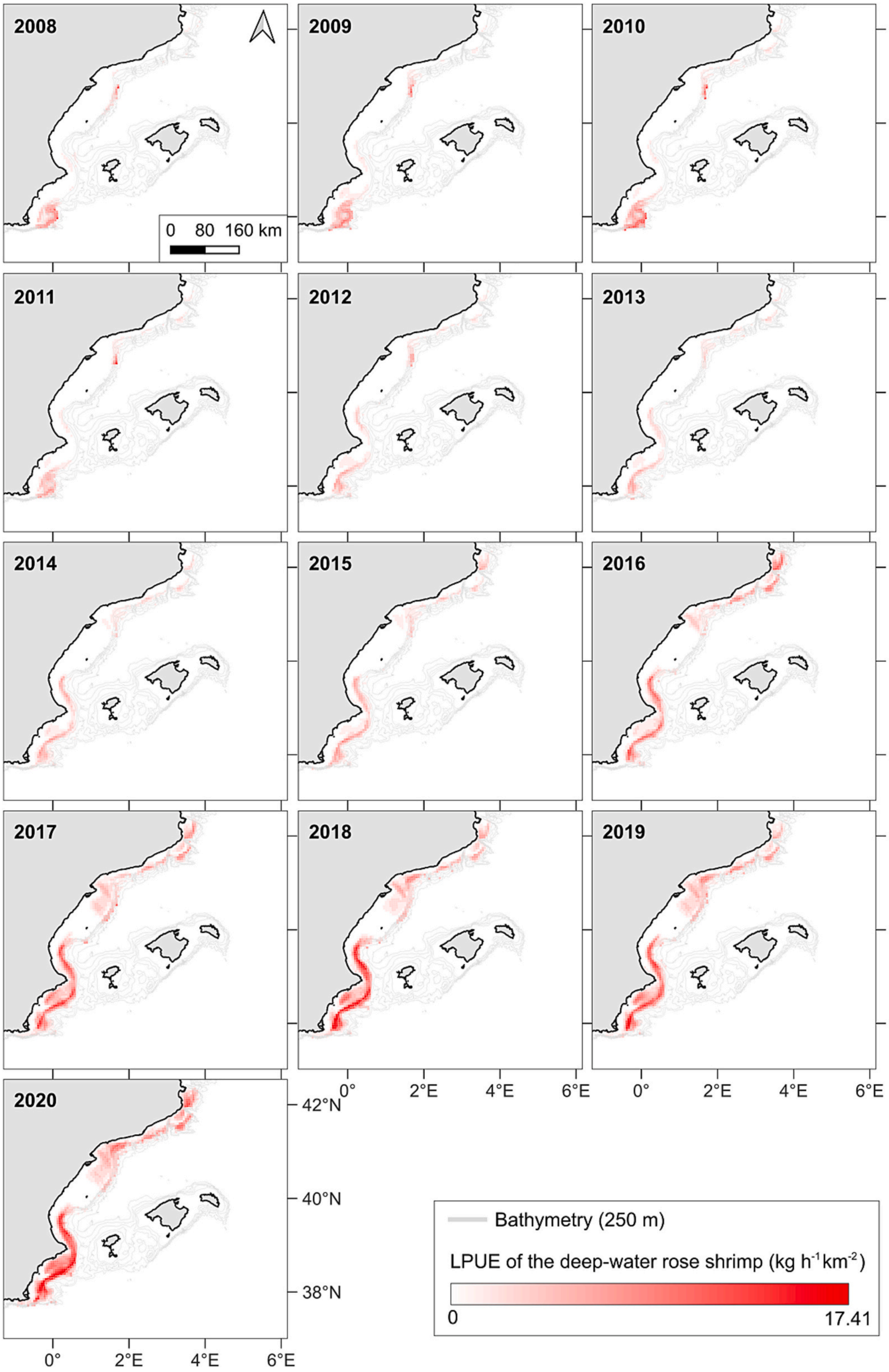

Fig. 2. Evolution of the deep-water rose shrimp yearly Landings Per Unit of Effort (LPUE, kg h^{-1} km^{-2}) from 2008 to 2020. LPUE are represented in red. Bathymetry is shown in 250 m depth intervals. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$$G(Y) = \beta_0 + T_i + s_{i,i+1}(x_i, x_{i+1}) + s_{i+2}(x_{i+2}) + \ldots + s_{i+z}(x_{i+z}) + \varepsilon$$

where G is the Gaussian link function between the species LPUE (Y) and the explanatory variables (x_i). β_0 represents the intercept, T_i is the sampling year (from 2008 to 2020), s_i is the smoother spline function for each one of the covariates (x_i to x_{i+z}), including the interaction between the LPUE's location (latitude and longitude), and the individual effects of depth, sea bottom temperature, and sea bottom salinity. The method of forward stepwise selection of the covariates was followed. The model with the lowest Akaike Information Criterion (AIC) and highest deviance explained was selected as the best model to fit the data. Additionally, the evolution of the optimal depth range per year of the deep-sea rose shrimp LPUE, was evaluated using the following GAM function:

$$G(Y) = \beta_0 + s_{i+2}(x_{i+2}) + \varepsilon$$

Finally, potential significant relationships between yearly LPUE of deep-water rose shrimp and temperature, and LPUE and salinity, were tested using Pearson correlations.

3. Results

3.1. Spatial distribution of LPUE

There was a steady increase of the deep-water rose shrimp landings with the time period of the study (i.e., from year 2008 to 2020) along with a spread of the resource from south to north along the GSA 6 (Fig. 2). In 2008, the deep-water rose shrimp was mostly landed in the southern ports of the study area. Later, in 2014, the LPUE spread northwards along the GSA 6, with a maximum of 3.78 kg h^{-1} km^{-2}. This trend increased later on, in 2016, when the LPUE reached maximums of 7.79 kg h^{-1} km^{-2} at some ports over the continental margin. In 2020, LPUE reached its highest value, 17.41 kg km^{-2}.

3.2. Time series of LPUE, landings and total biomass

The evolution of the deep-water rose shrimp yearly landings (kg km^{-2}) and LPUE (kg h^{-1} km^{-2}) from 2008 to 2020 showed a similar trend (Fig. 3A). The similarities were also observed in the spatial evolution, as shown in Figs. 2 and S1. That is, between 2008 and 2013, the yearly aggregated values remained relatively low, with landings between 47,758 and 92,365 kg km^{-2} and LPUE between 0.11 and 0.19 kg

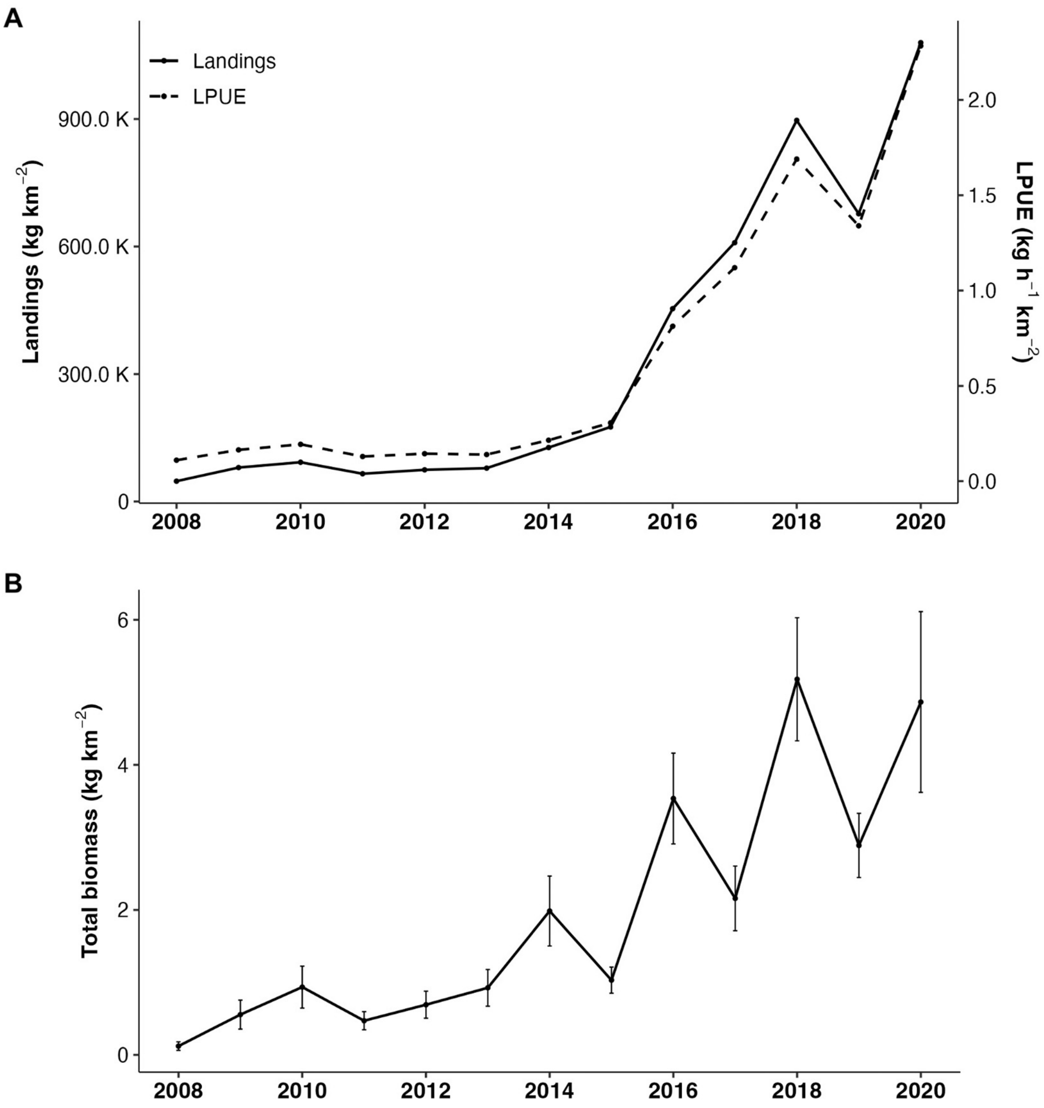

Fig. 3. Evolution of the deep-water rose shrimp total yearly landings (solid line; kg km^{-2}) and LPUE (dotted line; kg h^{-1} km^{-2}) (A) and total biomass (±SD; kg km^{-2}) (B) from years 2008 to 2020 for the GSA6.

h^{-1} km^{-2}. However, in 2014, they began to increase and, in 2020, both landings and LPUE peaked with 1,079,690 kg km^{-2} and 2.29 kg h^{-1} km^{-2}, respectively.

The evolution of the yearly total biomass index (kg km^{-2}) from the period of study showed an increasing trend (Fig. 3B), similar than that observed in Fig. 3A, with both LPUE and landings data. Between 2008 and 2013, the total biomass varied between 0.12 and 0.93 kg km^{-2}. From 2014 onwards, values followed an oscillating pattern characterized by high and low peaks every 2 years. The biomass reached its highest value in 2018, with 5.18 kg km^{-2}. The relatively wide error bars may be explained by the type of survey.

3.3. *Deep-water rose shrimp and Norway lobster LPUE*

The LPUE evolution of the deep-water rose shrimp and the Norway lobster between 2008 and 2020 showed opposite trends (Fig. 4). Whereas the highest LPUE of the Norway lobster was recorded from 2008 to 2014, with values between 0.58 and 0.72 kg h^{-1} km^{-2}, the deep-water rose shrimp had very low landings, with values ranging 0.11 and 0.21 kg h^{-1} km^{-2}. In 2014, the landings started to decrease for the Norway lobster, opposite to the landings for the deep-water rose shrimp, which increased from that year on. In 2020, the deep-water rose shrimp reached its highest peak, with 2.29 kg h^{-1} km^{-2}. On the contrary, the Norway lobster reached its lowest value, with 0.38 kg h^{-1} km^{-2}. However, the LPUE variability was much higher for the deep-water rose shrimp, which ranged from 0.11 to 2.29 kg h^{-1} km^{-2}, whereas the Norway lobster LPUE variability was only from 0.38 to 0.76 kg h^{-1} km^{-2}. Therefore, despite the opposite trends observed, the LPUE for the Norway lobster was much less variable than that for the deep-water rose shrimp.

The LPUE evolution for the deep-water rose shrimp, between 2008 and 2020, showed an increase in depth during the second half of the period studied (Figs. 5A and S3). The highest LPUE values were observed between 2018 and 2020, within the range of 100 m and 400 m depth, with the highest value for LPUE obtained at around 200–225 m depth in 2020. In contrast, the Norway lobster showed a decreasing trend in the LPUE along the period studied and its global depth range distribution (Fig. 5B). Maximum LPUE were recorded between 2009 and 2014, within 200 m and 500 m depth. Landings at the optimal depth range for the Norway lobster narrowed progressively over time with the highest LPUE being found between 350 m and 400 m depth.

3.4. *Sea water temperature and salinity trends*

Yearly variation of sea bottom temperature and salinity at 100–400 m depth during the studied period showed similar trends (Fig. 6). Generally, the temperature varied between 2008 and 2013, but it increased progressively from 2013 onwards, peaking first in 2016, and later on in 2020. Salinity showed fluctuating values until 2014, when peaked. However, in 2016 salinity started to increase progressively until 2020, when it reached its highest. Temperature values varied between 13.71 °C in 2010 and 14.03 °C in 2020 (Fig. 6A) whereas salinity changed between 38.14 PSU in 2011 and 38.21 PSU in 2020 throughout the studied period (Fig. 6B).

Heatmaps considering depths until 400 m are shown in Fig. S2. The shallower depths (40–100 m) exhibited a range of temperatures between 15.0 °C and 16.0 °C, with the highest temperature observed in the shallowest layers, approximately at 50 m depth (Fig. S2A). The lowest temperatures (13.5 °C) were found in the deepest depths analyzed, ≈400 m depth. In 2014, there was a temperature increase across the entire area and throughout the entire depth range, which was also observed in 2016, reaching 16.0 °C in the surface. The general increase experienced in 2016 persisted over time. Sea temperature values between shallower and deeper layers exhibited fluctuations of approximately 2.5 °C. The results of the ANOVA test confirmed the statistically significant differences of these changes ($p < 0.001$), highlighting the importance of temperature shifts in the studied area.

There were small differences in the evolution of sea bottom salinity with depth over time (Fig. S2B). Generally, salinities remained relatively low in the shallower depths (40–100 m depth), ranging from 37.25 to 37.75 PSU. The maximum salinity value observed (38.50 PSU) was recorded at the maximum depth, about 500 m depth. In 2014, there was an average salinity increase across the entire depth range. Salinity values in depth fluctuated no >1.25 PSU, with small variations over the time (Fig. S2B). However, ANOVA tests showed statistical significance of these changes ($p < 0.001$) within the GSA 6.

3.5. *Relationship between the deep-water rose shrimp LPUE and sea bottom features*

Among the four tested GAMs, the model considering all variables (Table 1), including yearly spatial location, depth, and environmental variables (i.e., temperature and salinity), was the best to fit the data, with the deviance explained and the AIC reaching values of 64.4 % and 5299.5, respectively. All variables were significantly different ($p < 0.001$), except for the period between 2009 and 2011, which presented lower values of significance (p values between 0.01 and 0.05; Table S1).

The yearly GAMs show the evolution of the deep-water rose shrimp LPUE in depth, between 2008 and 2020 (Fig. S3). At the beginning of the time series, the LPUE were distributed around 200–300 m depth and increased progressively until 2016 at these depths. From that year on, the depth distribution of the species' LPUE was clearly defined between

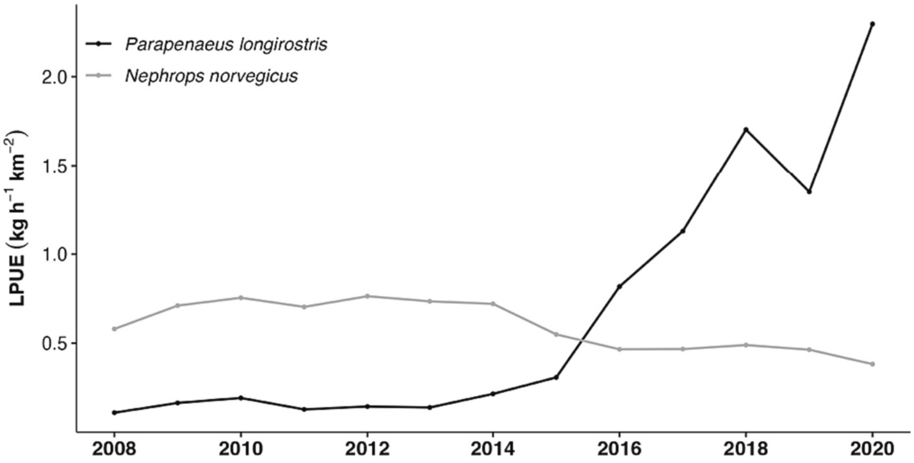

Fig. 4. Evolution of the LPUE (kg h^{-1} km^{-2}) for the deep-water rose shrimp (black line) and the Norway lobster (grey line) from year 2008 to 2020.

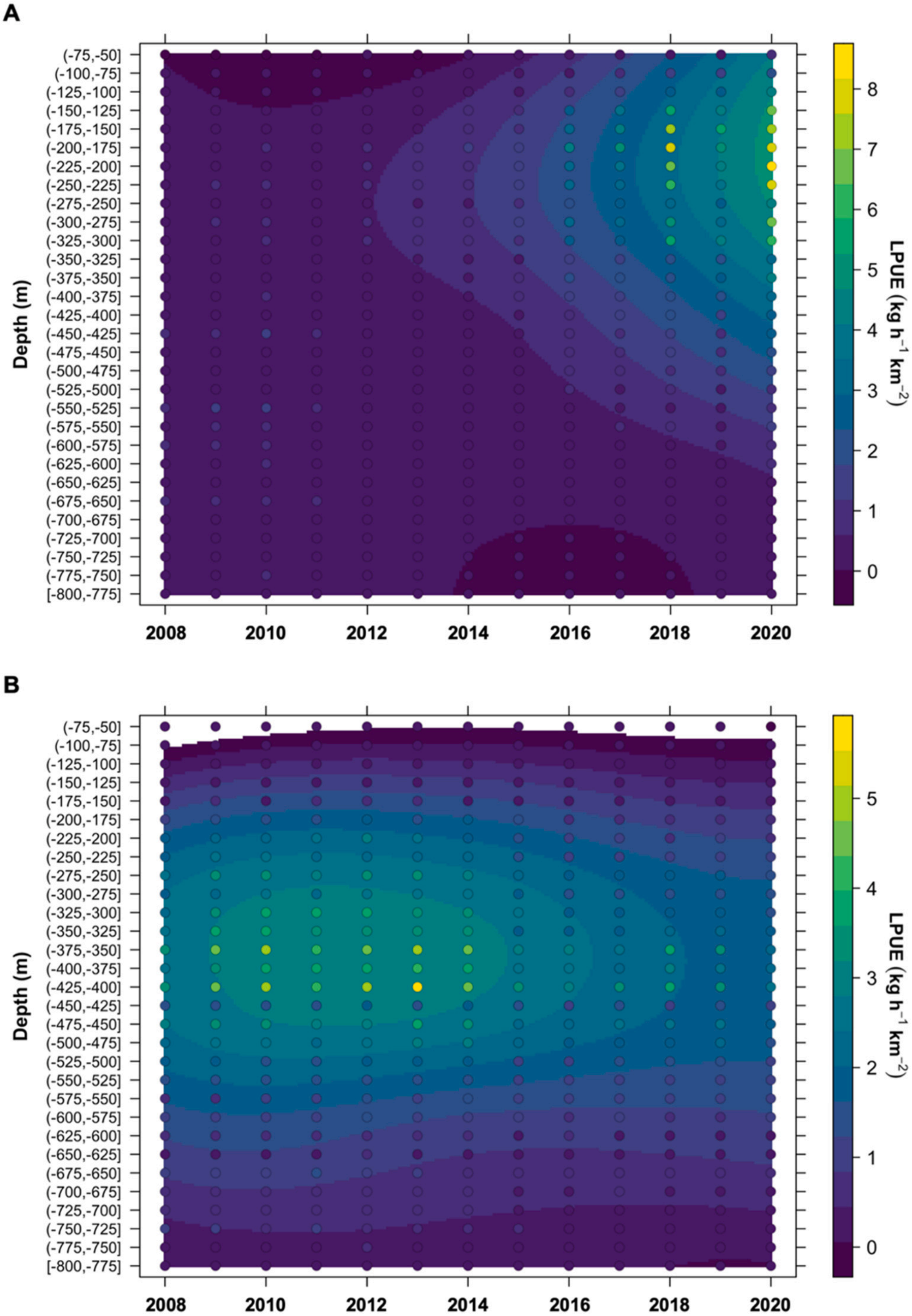

Fig. 5. Deep-water rose shrimp (A) and Norway lobster (B) bathymetric evolution of LPUE (kg h^{-1} km^{-2}) from years 2008 to 2020.

100 m and 300 m. Both response variables in the GAMs (spatial location and fishing depth) were significant for all years except for 2008, with no statistical significance in depth ($p > 0.05$; Table S2). The uncertainty of these models relied on the amount of data for each depth range. Therefore, at the maximum distribution range of the deep-water rose shrimp, where the resource was less caught, the uncertainty increased (Fig. S3).

Additionally, correlation tests showed significant positive correlation between the LPUE of the deep-water rose shrimp and both temperature ($r = 0.8291, p = 0.0004$) and salinity ($r = 0.8097, p = 0.0007$).

4. Discussion

This study reports that the deep-water rose shrimp has increased in the GSA 6 in the last decade, both in LPUE and geographic distribution. Fishing resources are subject to environmental characteristics, which are changing rapidly as a consequence of climate variability (IPCC, 2023). In agreement, the increasing trends found for the deep-water rose shrimp are related to a deep water increase in temperature and salinity. These findings highlight that climate change is also influencing deep-sea fishery resources, whose depth range of distribution is partially below the Mediterranean thermocline (200 m threshold) (Houpert et al.,

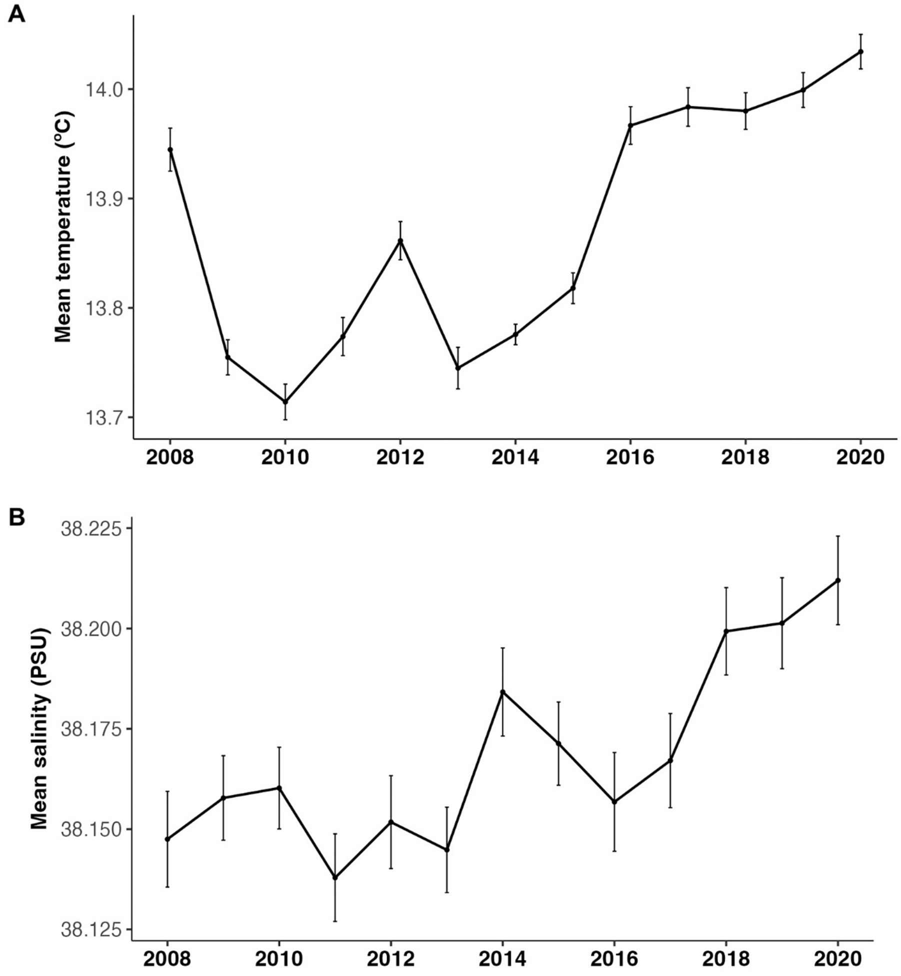

Fig. 6. Evolution of mean sea bottom temperature (A) and bottom salinity (B) at 100–400 m depth interval (depth range coincides with the deep-water rose shrimp optimal range), between 2008 and 2020. Bars represent standard deviation of the mean.

Table 1
GAM results for the LPUE (kg h^{-1} km^{-2}) of the deep-water rose shrimp. AIC is the Akaike Information Criterion. The best model is in bold writing.

Model	AIC	Dev. expl. (%)
log(LPUE + 1) ~ as.factor(year) + s(lat, lon) + s(depth)	5694.2	62.0
log(LPUE + 1) ~ as.factor(year) + s(lat, lon) + s(depth) + s (temperature)	5518.8	63.1
log(LPUE + 1) ~ as.factor(year) + s(lat, lon) + s(depth) + s (salinity)	5443.2	63.5
log(LPUE + 1) ~ as.factor(year) + s(lat, lon) + s(depth) + s (temperature) + s(salinity)	**5299.5**	**64.4**

2015).

The deep-water rose shrimp has gained importance as a fishing resource in the Mediterranean Sea with a global catch increasing from 17,545 t in 2008 to 26,278 t in 2020 (FAO, 2023). In addition, Sbrana et al. (2019) reported an expansion of the deep-water rose shrimp in the Mediterranean from 1998 to 2015, and predicted a further expansion of the species in areas where it was not yet abundant, as demonstrated in the present study. This northern spread of species has been named as “meridionalization” (Bianchi and Morri, 1993), coinciding with regions where water temperature is higher than the average (Azzurro, 2008). The reasons behind this increase in in catch and northward distribution can be diverse and may include environmental and fishing traits.

Water temperature is a key environmental characteristic that defines the survivorship of the species in a specific habitat, which changes may determine the expansion or reduction of the species distributions (Waldock et al., 2018). Global warming of all ocean surfaces has been recorded since 1880 (NOAA, 2014). In detail, in the NW Mediterranean, higher temperatures have been recorded since 2014 (Bahamon et al., 2020; Margirier et al., 2020), coinciding with what observed for deep sea temperature in the current study. Within the Mediterranean, in the North Tyrrhenian–Ligurian Sea, the number of landings for the deep-water rose shrimp increased, driven by warm water temperatures (Colloca et al., 2014), as reported hereby. In fact, this species prefers warm waters (Abelló et al., 2002) so the ongoing warming of the upper and intermediate water layers of the western Mediterranean (Vargas-Yáñez et al., 2009) could be influencing the abundance of this species, and consequently the increase of its landings. This is supported by Cartes et al. (2009), who hypothesized that low rainfall regimes, high water temperatures and fewer river discharges could be a possible explanation for the preservation of deep-water benthic communities, such as the deep-water rose shrimp. Moreover, Aguzzi et al. (2013) suggested that climate change effects on crustaceans could also be related to changes in the photic niche of species due to modifications in the primary productivity/flux of organic matter. The increase in deep-water shrimp landings is also related to a higher sea bottom salinity, as previously reported by Margirier et al. (2020) for the Levantine intermediate water in the Ligurian Sea. It has been described that the maximum spawning for the species is strongly related to salinity, with higher salinities influencing positively to reproduction, as observed in Morocco (Benchoucha et al., 2008). Then, the combination of higher temperatures and salinities, as demonstrated with the GAM outputs of this present study, seem to be both influencing positively the deep-water rose shrimp abundance and catchability.

Another factor that has been reported to change the catches of commercial stocks is the time dedication of a specific fleet to target a resource. In this sense, it has been reported that the decline in catches of other crustaceans, such as the Norway lobster (*N. norvegicus*), has caused the redirection of the crustacean fleet efforts to the deep-water rose shrimp grounds (Sobrino et al., 2005). However, the observed differences of LPUE of the deep-water rose shrimp and the Norway lobster found in this study, can be understood as different responses to environmental drivers such as sea bottom temperature, related to life history traits of the species (Sbrana et al., 2019), rather than the redirection of the fleet effort. According to Aguzzi et al. (2009, 2015) the deep-water rose shrimp is a nektobenthic species whereas the Norway lobster is endobenthic. Despite that both species can be captured by trawling, which means that they are co-present at least on the seabed, both species seem to inhabit different habitats. The deep-water rose shrimp inhabits the water column layers nearby the seabed, within a depth range of between 20 and 700 m as reported in this study and previously observed in other Mediterranean and Atlantic waters (Sobrino et al., 2005; Colloca et al., 2014), with maximum abundances at 200–225 m depth (data of this study). In contrast, the Norway lobster inhabits burrows built in muddy bottoms, with a wide bathymetric distribution, ranging from a few meters down to 900 m (Aguzzi et al., 2023a; Johnson and Johnson, 2013) and maximum abundances between 350 and 400 m depth (data of this study). Furthermore, the reproductive strategy of these two species is different. During the egg-incubation period (4–6 months) of the Norway lobster, the berried females spend most of their time in burrows (Aguzzi et al., 2003), which contributes to the protection of the most sensitive life-stages (Ligas et al., 2011) while reducing its exposure to the fishing gears. These differences, along with the increase in deep-water rose shrimp landings during the second half of the studied period, seem to indicate a lack of competition between habitats or fishing interests.

In the Mediterranean Sea fisheries, from a bioecological and economic standpoint, one of the most important target species is the deep-water rose shrimp. This species seems to be favored by the environmental changes, following a large-scale redistribution of the global catch, with increases in high-latitude regions, and decreases in the tropics (Cheung et al., 2010). However, the lack of knowledge regarding its biology may affect the output of stock assessment models and difficult the development of efficient management plans (Perdichizzi et al., 2022). Sobrino et al. (2005) suggested that studies focused on creating spatio-temporal fishing bans, along with experiments with more selective gears, would be important for the management of the deep-water rose shrimp and avoid a potential future collapse of the stock. Therefore, proper and dynamic management strategies are especially important in a global change scenario, where commercial species could experience distribution shifts in the future (Ben Lamine et al., 2023). Currently, the European Commission has developed multiannual plans (MAPs) for western Mediterranean Sea demersal stocks to ensure their sustainable exploitation, including the deep-water rose shrimp. The measures contain the reduction of the fishing pressure by diminishing the number of days and vessels at sea (EU 2019/1022). Despite these management pressures, scientific monitoring and further studies are still needed for this species to avoid its over- or full exploitation, as has happened in other Mediterranean areas (Sobrino et al., 2005).

5. Conclusions

Between 2008 and 2020, the landings of the deep-water rose shrimp increased from south to north throughout the GSA 6. Such increase was correlated with sea bottom warming and salinization, instead of the increase in sea surface temperature or surface salinity. The reported trend was particularly observed since 2014 onwards, at the starting of the northward spread of the resource in the area. The LPUE followed the exact same trend as landings over time, indicating that the resource increased in abundance rather than being subjected to an increased fishing effort. The different life traits and LPUE evolution of the deep-water rose shrimp and the Norway lobster, reinforced the hypothesis that there was no interaction between both fishing resources. It is important to note that the methodology followed in this study, with fishery dependent data, can be replicated with other commercial species to obtain information on the stocks' variation, which can be very useful to develop sustainable management plans, especially when studying a whole management area such as the GSA 6. Scientific monitoring and further studies are necessary to ensure accurate management measures currently implemented, being the deep-water rose shrimp one of the most targeted species of the Mediterranean bottom trawl fisheries.

CRediT authorship contribution statement

Mireia G. Mingote: conceptualization, methodology, formal analysis, writing (original draft), writing (review and editing).

Eve Galimany: conceptualization, writing (original draft), writing (review and editing), supervision.

Joan Sala-Coromina: conceptualization, methodology, formal analysis, writing (review and editing).

Nixon Bahamon: methodology, formal analysis, writing (review and editing).

Jordi Ribera-Altimir: methodology, formal analysis, data curation, writing (review and editing).

Ricardo Santos-Bethencourt: validation, writing (review and editing).

Morane Clavel-Henry: methodology, data curation, writing (review and editing).

Joan B. Company: conceptualization, writing (review and editing), supervision.

Declaration of competing interest

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Data availability

Data can be accessed through ICATMAR's website (www.icatmar.cat). You can contact us through a form (data service) to request more specific information.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2023.115838.

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