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Deepening our perspective about the small and medium pelagic fish: case study in the Canary Islands (NW Africa, Spain)

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Research Article

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Abstract

Small and medium pelagic fish (SMPF, i.e. *Scomber colias*, *Trachurus* spp, *Sardina pilchardus*, and *Sardinella* spp) in the Canary Islands are mainly targeted by the artisanal purse-seine fleet. The waters in the archipelago (located in the coastal transition zone of the Canary Current Eastern Boundary Upwelling System) are monitored since the late nineties by a hydrographic section (RAPROCAN) designed to study the temporal variability of the eastern subtropical gyre. In this study we analyse the relationship between the SMPF abundance assumed from official sale notes (reported since 2007) and several oceanographic parameters obtained for the outermost water layer (Sea Surface Temperature, SST, and concentration of chlorophyll *a*, Chla) and from the 200–800 m depth waters (Sea Temperature, ST_200–800, and salinity, Salinity_200–800). Except for SST, statistically significant correlations occur between environmental variables and SMPF landings when one-year time-lag is considered, matching with the time period necessary for these species to attain legal catchable sizes and, hence, being catchable by the fishery. However, in the GLM only Chla resulted a significant explaining variable for the SMPF landings during the following year, probably because this strong correlation overshadows the ST_200–800 influence. Keeping the monitoring systems is crucial to understand, foresee and anticipate potential variations in the fishery resources and to aim the sustainable exploitation of the SMPF populations, even more challenging in the current climate change scenario.

Introduction

Small and medium pelagic fish (SMPF) are important species for commercial fisheries worldwide and are key elements for the food security and for the functioning of marine ecosystems linking lower and upper trophic level species (Cury *et al.*, 2000; FAO, 2020). Thus, variations in their populations can impact the dynamics of the whole ecosystem structure and promoting large ecological and socioeconomic consequences (Pita *et al.*, 2014). In addition, these species are known to be highly sensitive to the environmental conditions throughout their life history, with specific tolerance windows for temperature, salinity, oxygen and pH (among others), which define their bioclimatic envelope (Sekadende *et al.*, 2020). Therefore, due to their short generation times and tight coupling to lower trophic levels, populations of SMPF display large boom-and-bust dynamics that are closely linked to climate variability, promoting different responses by species and stocks (Peck *et al.*, 2021; Ma *et al.*, 2022). In this context, climate change and fishing are the two dominant processes by which humans affect marine life, which have not stopped increasing for last century (FAO, 2022; Mann, 2024). In particular, the pelagic zone (i.e. the largest living space of the planet) holds half of the global primary production and sustains most of the animal biomass on Earth, including SMPF and, of course, their forage (Ariza *et al.*, 2022). Numerous researchers investigate the SMPF responses (which vary depending on species and areas) in a scenario where, although fisheries' catches are unlikely to increase much beyond current levels, the earth will warm, the oceans will acidify and hydrology will continue changing (Checkley *et al.*, 2009, 2017; Alheit *et al.*, 2019; Albo-Puigserver *et al.*, 2022).

In the research of describing the influence of environmental conditions on the abundance and biomass variability in marine organisms, Sea Surface Temperature (SST and their anomalies) and primary production proxies (such as chlorophyll *a* concentration) are commonly the most used environmental variables. Probably because these data can be obtained indirectly from satellite images, and are freely available from several open libraries such as NASA-EarthData (https://www.earthdata.nasa.gov/) or IRI/LDEO Climate Data Library (https://iridl.ldeo.columbia.edu/). In particular, the relationship between SMPF and temperature has been a subject of extensive scientific research because it affects their growth, reproduction, distribution, and overall abundance. Regarding geographic distribution shifts, northward expansion of SMPF has been described for several thermophilic species in the northeast Atlantic Ocean (such as *Scomber colias* and *Sardinella aurita*), which are being monitored since beginning 2000 as study cases of the global warming effect on SMPF (Houssa *et al.*, 2013; ICES, 2021; among others). Obviously, they alter their geographic distribution following the latitudinal change of sea temperature, occupying waters masses where they can develop their normal metabolic and biological cycles in accordance to their temperature tolerance limits (Schickele *et al.*, 2020). Consequently, as waters warm, SMPF may migrate poleward, but also to deeper waters in search of suitable temperatures (Sekadende *et al.*, 2020). Moreover, during their life span and linked to breeding/feeding purposes, SMPF sometimes reach quite deep waters (Froese and Pauly, 2023), as has been observed for *Trachurus picturatus* and *S. colias* in the Azorean surroundings (Arkhipov *et al.*, 2002).

The Canary Islands is an Atlantic archipelago composed by eight islands in NW African waters, located in the coastal transition zone of the Canary Current Eastern Boundary Upwelling System and, hence, influenced by the major Canary Current, the NW African upwelling and the eddies and currents among islands. The Canary Islands are characterized by a narrow oceanic shelf, with great depth among islands surrounded by oligotrophic waters, leading to a general low productive marine system (Figure 1) (Barton *et al.*, 1998; Brito *et al.*, 2002). Increasing trends in calibrated SST have been registered in the north of the Canary Islands since the 1980' (Vélez-Belchí *et al.*, 2015). Regarding fisheries in the Canary Islands, after tuna fish, SMPF are the second group in importance on landings. They are mainly caught by the artisanal purse-seine fleet, which generally perform daily fishing trips in close waters to landing ports. Based on the official sale notes, most of the activity is concentrated around the main islands, i.e. Tenerife and Gran Canaria. Much effort has been paid to the characterization of this fishery in the archipelago, but only some works have analysed the influence of environmental variables on the biomass and life history traits of the SMPF inhabiting Canary waters (Brochier *et al.*, 2008, 2009, 2018; Jurado-Ruzafa *et al.*, 2019, 2022).

The link between changes on the abundance, distribution and biological traits of SMPF and environmental and climatic conditions is a crucial topic to foresee variations which could strongly impact the marine ecosystems functioning as well as food security worldwide. However, although several monitoring programmes exist the Canary Islands, few interdisciplinary studies have been performed in the study area so far. In the present study we aim to investigate the potential relationship between the annual landings of SMPF in the Canary Islands with the SST, chlorophyll *a* concentration in the sea surface and, for the first time, with variables in deep waters.

Materials and methods

Fishery and environmental data

The most common SMPF species caught in the Canary Islands are (in order of importance in landings): *S. colias*, *Trachurus* spp, *Sardinella* spp and *Sardina pilchardus*. In the present work, we used the total landings of SMPF using the official sale notes from 2007 (when the official reporting system was implemented) to 2021. Effort data have not been considered, due to many shortfalls having been described for this fishery, and subsequent indices (such as landings per unit of effort, LPUE) should not be taken as reliable (Quinzán and Jurado-Ruzafa, 2021).

Annual mean values of SST and concentration of chlorophyll *a* (Chla) were obtained for the study area (between 27–29.5°N and 13–18.5°W) from the NASA database GIOVANNI (Acker and Leptoukh, 2007). Sea temperature and salinity in the 200–800 m depth water layer (ST_200–800 and Salinity_200–800) were taken in the framework of the RAPROCAN Program, which include a 'Deep hydrographic section around the Canary Islands' and whose aim is to establish the decadal and/or subdecadal variability in the eastern margin of the subtropical gyre. When possible, two hydrographic cruises per year (spring and fall), including a deep hydrographic section along the North of the archipelago (http://www.oceanografia.es/pedro/research_IROC2018_Canary.html) (Figure 1). Later, data is processed with the software SBE Data Processing from Sea-Bird Scientific following the recommendation given in Duarte *et al.* (2012), and MATLAB is used for the data analysis. For the present study, the data used from the RAPROCAN Program (time period: 2007–2021) was averaged for the selected depth layer, selected to avoid the influence of the seasonal thermocline, which spreads out to a depth of 170 to 200 metres (Villanueva and Ruiz, 1994).

Statistical analyses

Linear correlations between the environmental variables and the SMPF landings in the Canary Islands (for the total and by species) were tested using the ρ-Pearson correlation coefficient. Likewise, correlation between the environmental variables was

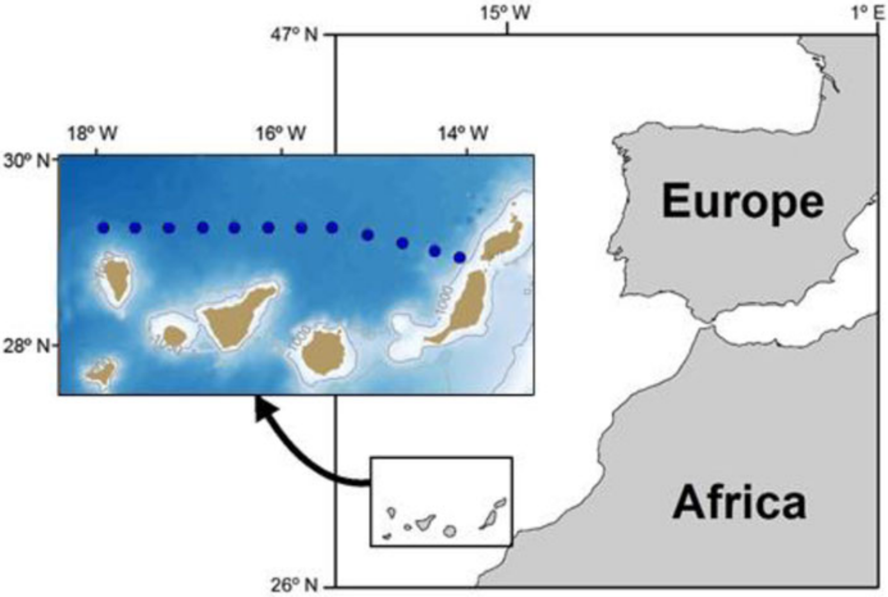

Figure 1. Map showing the Canary Islands allocation. Blue points represent the RAPROCAN stations for the acquisition of oceanographic data used in the present study.

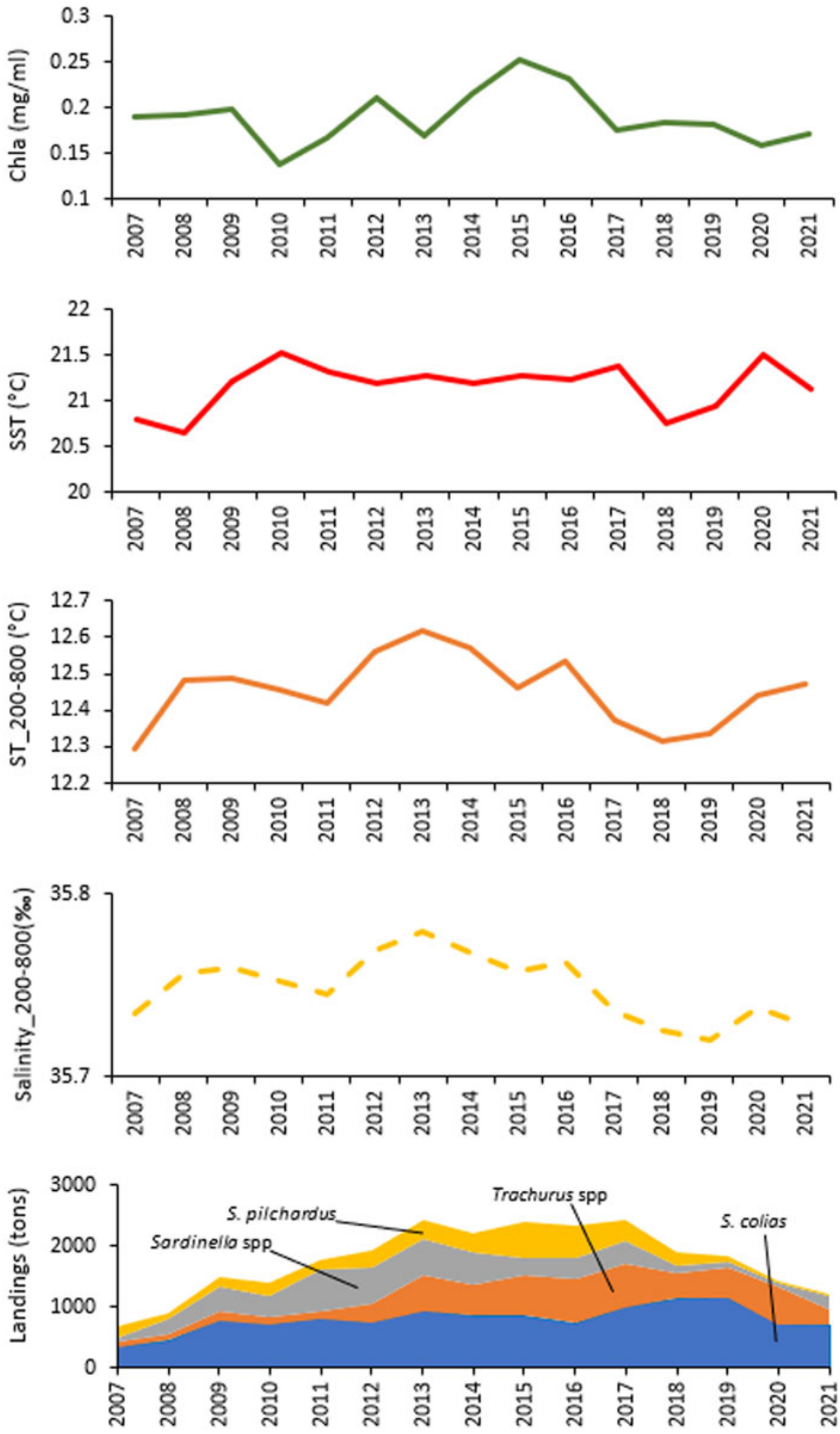

Figure 2. Annual mean values of chlorophyll *a* concentration (Chla), Sea Surface Temperature (SST), Sea Temperature and Salinity in the water layer between 200 and 800 m depth (ST_200–800 and Salinity_200–800, respectively) and landings of small pelagic fish in the Canary Islands. Time period: 2007–2021.

tested. For these statistical analyses and plots representations, IBM® SPSS® Statistics v. 25 and Microsoft Excel 2019 were used.

Analyses were also performed considering one-year lag to match SMPF landings with the environmental variables occurring the previous year (SMPF_landings$_{-1}$). This additional analysis is based on the growth patterns of the species analysed, since catchable sizes are attained approximately one year later from the fish birth (Santamaría, 1993; Lorenzo and Pajuelo, 1996; Jurado-Ruzafa and Santamaría, 2018; Jurado-Ruzafa *et al*., 2020, 2021).

Once correlated variables with the SMPF_landings$_{-1}$ were identified (based on ρ-Pearson correlations), the significance of these relationships was investigated for the whole time series using a Generalized Linear Model (GLM) using the R-package *glm2* (Marschner, 2011; R Core Team, 2023).

Results

The environmental data collated as well as the SMPF landings reported in the Canary Islands from 2007 to 2021 are represented in Figure 2. Regarding the ρ-Pearson correlation coefficients obtained (Table 1), significant correlations were only found when one-year time lag was considered between SMPF landings and the environmental variables, with the exception of SST, which was not correlated with landings in any case.

Table 1. Results of the ρ-Pearson correlation coefficient between the annual mean values of the environmental variables (SST, Sea Surface Temperature; ST_200–800, averaged sea temperature at 200–800 m depth; Salinity_200–800, averaged salinity at 200–800 m depth; Chla, chlorophyll *a* concentration) and the SMPF total landings, both for the corresponding year and assuming a 1-year time lag (SMPF_landings$_{-1}$)

Variable	SMPF_landings	SMPF_landings$_{-1}$	SST	Chla	ST_200–800	Salinity_200–800
SMPF_landings						
ρ-Pearson correlation	1	0.769**	0.367	0.309	0.252	0.355
P-value	–	0.001	0.162	0.244	0.365	0.194
SMPF_landings$_{-1}$						
ρ-Pearson correlation	0.769**	1	0.296	0.531*	0.540*	0.531*
P-value	0.001	–	0.284	0.042	0.038	0.042
SST						
ρ-Pearson correlation	0.367	0.296	1	−0.233	0.433	0.236
P-value	0.162	0.284	–	0.386	0.107	0.397
Chla						
ρ-Pearson correlation	0.309	0.531*	−0.233	1	0.254	0.475
P-value	0.244	0.042	0.386	–	0.360	0.074
ST_200–800						
ρ-Pearson correlation	0.252	0.540*	0.433	0.254	1	0.806**
P-value	0.365	0.038	0.107	0.360	–	0.000
Salinity_200–800						
ρ-Pearson correlation	0.355	0.531*	0.236	0.475	0.806**	1
P-value	0.194	0.042	0.397	0.074	0.000	–

***bilateral significance *P*-value < 0.01; *bilateral significance *P*-value < 0.05

On the one hand, ρ-Pearson correlation coefficient between ST_200–800 and Salinity_200–800 was 0.806, with a *P*-value < 0.0001, confirming the expected strongly correlation between salinity and temperature (Stewart, 2008). For this reason, Salinity_200–800 was excluded from subsequent analyses. On the other hand, no significant correlation exist between ST_200–800 and Chla ($t = 1.049$, *P*-value = 0.3149).

Finally, regarding the GLM results (Table 2 and Figure 3), significant correlation was found only between SMPF_landings$_{-1}$ and the concentration of Chla. The missing significant correlation with ST_200–800 may be explained because the shortness of the time series, or for the great contribution of the Chla to explain SMPF landings. Anyway, although the contribution to the model is not significant when Chla is considered, ST_200–800 is significantly correlated with the SMPF landings performed during the next year.

Discussion

Understanding the relationship between water temperatures (in the surface, but also in deep layers) and SMPF abundance is crucial for predicting how these fish populations might respond to climate change. It involves complex interactions between oceanographic processes, food web dynamics, and the behavioural patterns of these species, making it a subject of extensive scientific research and monitoring.

Table 2. Results of the Generalized Linear Model (GLM) between the annual mean values of the selected environmental variables (ST_200–800, sea temperature at 200–800 m depth; Chla, chlorophyll *a* concentration) and the SMPF the total landings assuming a 1-year time lag (SMPF_landings-$_1$)

Coefficients	Estimate	SD Error	*t*-value	*P*-value
Intercept	− 21,230.9	13,022.0	−1.630	0.1313
ST_200–800	169.9	106.2	1.601	0.1378
Chla	9294.8	3961.0	2.347	0.0387*

**P*-value < 0.01.

In the Canary Islands, the available data about biomass and/or abundance of small SMPF estimated from fishery-independent information correspond to outdated studies which, in addition, did not covered the whole archipelago (González, 2008). In the present study, fishery dependent data (derived from official SMPF landings) was used to assess the potential influence of several environmental variables in the SMPF biomass. In this sense, numerous authors (Grbec *et al.*, 2002; Ormaza-González *et al.*, 2016; Teixeira *et al.*, 2016; Olmos *et al.*, 2023; among others) have proven that although climate-dependence analyses of a fish population should be derived from biomass data, in its absence, landing data are useful as a first approximation. Indeed, catch statistics are recognized to be linked to fishing and environmental pressures (Borges *et al.*, 2003; Gamito *et al.*, 2015; Fortibuoni *et al.*, 2017; Olmos *et al.*, 2023) and Pilling *et al.* (2009) demonstrated the usefulness of using data derived from official sale notes to describe and analyse patterns in fish populations. Indeed, in a previous works in the region (Jurado-Ruzafa *et al.*, 2019, 2022), this data source has served to find out seasonal patterns in small pelagic landings. Even when the shortness of the time series and the biomass proxy used (subject to several shortfalls related to the official data collection system [González, 2008; Quinzán and Jurado-Ruzafa, 2021]) made the possibility of finding any correlation with environmental variables improbable, Chla has resulted a good indicator of the SMPF landings produced the following year in the Canary Islands. In addition, this one-year time lag correlation has been observed for the ST_200–800 and the Salinity_200–800, supporting the necessity of keeping the monitoring system. As commented in the 'Introduction' section, much of the SMPF species reach greater depths in different

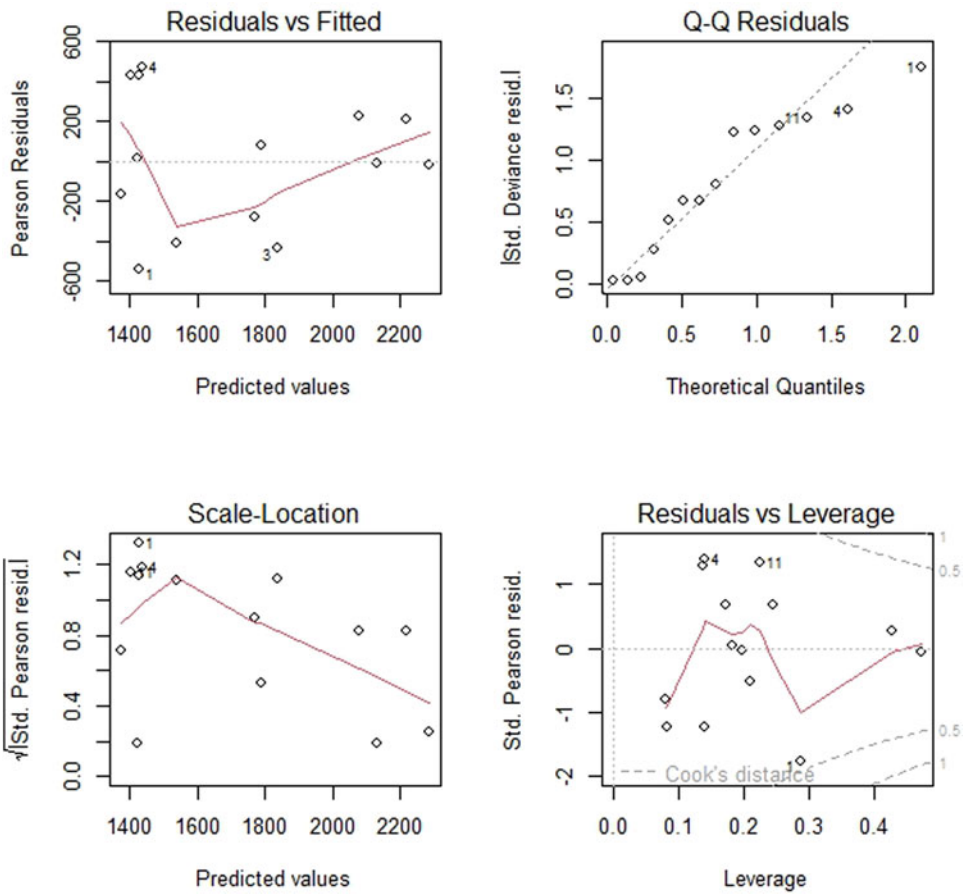

Figure 3. Plotted results of the Generalized Linear Model (GLM) between the annual mean values of the selected environmental variables (ST_200–800: sea temperature at 200–800 m depth; Chla: chlorophyll *a* concentration) and the SMPF the total landings assuming a 1-year time lag (SMPF_landings-$_{1}$).

ontogeny stages and related to feeding/reproduction and, hence, the conditions from 200 to 800 m could influence the recruitment success of these species. Usually, relationship between marine pelagic species and environmental variables are performed using the conditions in the outermost water layer, which can be freely and easily obtained from open databases. Nevertheless, while in the present analysis in the Canary Archipelago no correlations between annual landings and SST were found in any case, statistically significant and positive correlation between the SMPF landings and the sea temperature in the 200–800 m layer one-year time-lag. Therefore, conditions in the water layer 200–800 m depth seem to influence SMPF landings' trends in the Canary Islands. This layer is less affected by atmosphere variations and probably influences on success of the SMPF spawning, the eggs and larvae survival and recruitment processes. In fact, legal catchable sizes are approximately attained by one-year-old individuals, explaining the one-year time-lag. Since most of the studies investigating this kind of relationships find significant influence of the environmental conditions in surface waters (Fernandes *et al.*, 2020; Pennino *et al.*, 2020; Ramírez *et al.*, 2021; 2022; Selvaraj *et al.*, 2022, among others), this is a highlightable finding. However, as commented, the availability of data routinely got for specific areas, and not derived from satellite images, is unusual and expensive information to obtain. There exist initiatives such as the ARGO Programme (https://www.aoml.noaa.gov/proj/argo/), but the drifting profiling floats position (and, hence, the data available) is dependent on the ocean currents drifting the buoys.

In the current climate change scenario, in which water warming in the Canary area has been proven (Vélez-Belchí *et al.*, 2015), the possibility of SMPF-schools migration following cooler waters to northern latitudes (Walther *et al.*, 2002) or to deeper waters (Sekadende *et al.*, 2020) should be monitored. On the one hand, latitudinal expansion of *S. colias* and *S. aurita* (Zardoya *et al.*, 2004; Sabatés *et al.*, 2006; Zeeberg *et al.*, 2008; Blanchet *et al.*, 2019; ICES, 2021; among others). On the other hand, the presence of bigger individuals of *S. colias* and *T. picturatus* has been observed in deep waters around seamounts surrounding other Atlantic archipelagos (Jesus, 1992; Arkhipov *et al.*, 2004; Menezes *et al.*, 2006). So much so that there are longline fisheries specialized in capturing this fraction of the populations (Jesus, 1992; Garcia *et al.*, 2015). However, this point has not been verified in the Canary Islands so far. These kinds of behaviour changes may substantially reduce the catchability of these fish by the artisanal fishers with simple gear and boats (Sekadende *et al.*, 2020). Since this movement can affect local fisheries and disrupt established ecosystems, understanding the relationship between global warming and small pelagic fish is crucial not only for the conservation of these species but also for the communities and industries that depend on them.

Ecosystem and population models have found that temperature and primary production (here represented by Chla) are often the main drivers of change in SMPF distribution and abundance at global and regional scales, being precise and realistic to inform long-term fisheries management (Fernandes *et al.*, 2020). In this sense, much effort must be done to truly understand the intricate processes driving the primary production in Canary waters and the linkages with SMPF distribution and abundance. In general, it is assumed that a certain water warming should promote the primary production in marine waters (Liu *et al.*, 2019), but in the oligotrophic waters surrounding the archipelago, other factors should be analysed to understand the Chla decreasing trend recorded during the last decade. For example, in the Mediterranean Sea, important effects on future trends of anchovy and sardine have been related to other factors such as river discharge or climate-driven changes in water currents (advection/retention dynamics) which impact on survival of the pre-recruitment stages (Lloret *et al.*, 2004). Based on an extensive review by Peck *et al.* (2013), few studies have examined the direct effects of salinity, temperature and/or light on growth, feeding and survival in juveniles' stages of SMPF; however, the results obtained in the present analysis support the fact that, mainly primary production, but also temperature in deep waters seem to play a pivotal role in the juveniles' survival of the SMPF in the archipelago.

Scientific community is conscious that, although more information is needed to make reliable predictions regarding the future state of marine ecosystems, there exist evidences about sensitivity and vulnerability of pelagic species and ecosystems to climate change (Checkley *et al.*, 2009). It is worth to note that the Canary Islands are under the influence of one of the major Eastern Boundary Upwelling Systems in the world, which seem to make the region a 'thermal refugia' from global warming for the marine organisms inhabiting these waters (García-Reyes *et al.*, 2023). However, climate change challenges fisheries management and requires adaptive strategies able to incorporate changes in the distribution and abundance of these species. At present, the stock status of the SMPF in the Canary Islands remains not assessable using the available mathematical models (Quinzán and Jurado-Ruzafa, 2021). To achieve reliable scientific advice, improvement on data consistency is needed. But studies to understand the population structure of the SMPF in the Central and Northeast Atlantic (including the Macaronesian archipelagos) and their potential changes are also necessary, as well as to investigate spatial migration processes and monitor distribution patterns shifts. Since sustainable fishing practices must ensure human wellbeing by safeguarding the integrity of marine life-supporting systems, a significant challenge to fisheries management is that sustainable fishing levels can decline, often synergistically, by co-occurring with climate-driven environmental stressors (Ramírez *et al.*, 2021). Due to disentangling climatic and fishing (human)-induced impacts on marine populations is probably impossible, making interdisciplinary studies becomes crucial.

To conclude, keeping the monitoring programmes both on the ecosystem communities and the environmental conditions is critical to understand, foresee and anticipate potential variations in the fishery resources and to aim the sustainable exploitation of the SMPF populations, especially to face the climate change challenges.

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Competing interest. None.

Ethical standards. This research was not covered by any regulation and formal ethical approval was not required.

Data availability. Data availability on request from the authors.

References

Acker JG and Leptoukh G (2007) Online analysis enhances use of NASA Earth science data. *Eos, Transactions American Geophysical Union* **88**, 14–17.

Albo-Puigserver M, Bueno-Pardo J, Pinto M, Monteiro JN, Ovelheiro A, Teodósio MA and Leitão F (2022) Ecological sensitivity and vulnerability of fishing fleet landings to climate change across regions. *Scientific Reports* **12**, 17360.

Alheit J, Lorenzo ED, Rykaczewski RR and Sundby S (2019) Drivers of dynamics of small pelagic fish resources: environmental control of long-term changes. *Deep Sea Research Part II* **159**, 1–3.

Ariza A, Lengaigne M, Menkes C, Lebourges-Dhaussy A, Receveur A, Gorgues T, Habasque J, Gutiérrez M, Maury O and Bertrand A (2022) Global decline of pelagic fauna in a warmer ocean. *Nature Climate Change* **12**, 928–934.

Arkhipov AG, Kozlov DA, Shnar VN and Sirota AA (2002) Structure of waters and distribution of fish at different ontogenetic stages around seamounts of Central-Eastern Atlantic Ocean. *ICES CM* 2000/M:03.

Arkhipov AG, Sirota AA, Kozlov DA and Shnar VN (2004) Observations on hydrographic structures, ichthyoplankton and fish populations around seamounts of the central-eastern Atlantic. *Archive of Fishery and Marine Research* **51**, 201–214.

Barton ED, Arístegui J, Tett P, Cantón M, García-Braun J, Hernández-León S, Nykjaer L, Almeida C, Almunia J, Ballesteros S, Basterretxea G, Escánez J, García-Weill L, Hernández-Guerra A, López-Laatzen F, Molina R, Montero MF, Navarro-Pérez E, Rodríguez JM, van Lenning K, Vélez H and Wild K (1998) The transition zone of the Canary Current upwelling region. *Progress In Oceanography* **41**, 455–504.

Blanchet M-A, Primicerio R, Smalås A, Arias-Hansen J and Aschan M (2019) How vulnerable is the European seafood production to climate warming? *Fisheries Research* **209**, 251–258.

Borges MF, Santos AMP, Crato N, Mendes H and Mota B (2003) Sardine regime shifts off Portugal: a time series analysis of catches and wind conditions. *Scientia Marina* **67**(Suppl. 1), 235–244.

Brito A, Pascual PJ, Falcón JM, Sancho A and González G (2002) Peces de las Islas Canarias. Catálogo comentado e ilustrado. Francisco Lemus, Arafo.

Brochier T, Ramzi A, Lett C, Machu E, Berraho A, Fréon P and Hernández-León S (2008) Modelling sardine and anchovy ichthyoplankton transport in the Canary Current System. *Journal of Plankton Research* **30**, 1133–1146.

Brochier T, Colas F, Lett C, Echevin V, Cubillos LA, Tam J, Chlaida M, Mullon C and Fréon P (2009) Small pelagic fish reproductive strategies in upwelling systems: a natal homing evolutionary model to study environmental constraints. *Progress In Oceanography* **83**, 261–269.

Brochier T, Auger P-A, Pecquerie L, Machu E, Capet X, Thiaw M, Cheikh Mbaye B, Braham C-B, Ettahiri O, Charouki N, ene NdawO S, Werner F and Brehmer P (2018) Complex small pelagic fish population patterns arising from individual behavioral responses to their environment. *Progress In Oceanography* **164**, 12–27.

Checkley D, Alheit J, Oozeki Y and Roy C (eds) (2009) *Climate Change and Small Pelagic Fish*. Cambridge: Cambridge University Press.

Checkley D, Asch RG and Rykaczewski RR (2017) Climate, Anchovy, and Sardine. *Annual Review of Marine Science* **9**, 469–493.

Cury P, Bakun A, Crawford RJM, Jarre A, Quiñones RA, Shannon LJ and Verheye HM (2000) Small pelagics in upwelling systems: patterns of interaction and structural changes in "wasp-waist" ecosystems. *ICES Journal of Marine Science* **57**, 603–618.

Duarte C, Vélez P, Fraile-Nuez E, Álvarez M, Dachs J, Navarro N, Blanco J, Arrieta J, Gasol J and González-Gordillo J (2012) Expedición de Circunnavegación MALASPINA 2010: Libro blanco de métodos y técnicas de trabajo oceanográfico.

FAO (2020) Report of the Working Group on the Assessment of Small Pelagic Fish of Northwest Africa. Casablanca, Morocco, 8–13 July 2019. *FAO Fisheries and Aquaculture Report* 1309. FAO, Rome.

FAO (2022) *The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation*. Rome: FAO.

Fernandes JA, Frölicher TL, Rutterford LA, Erauskin-Extramiana M and Cheung WWL (2020) Changes of potential catches for North-East Atlantic small pelagic fisheries under climate change scenarios. *Regional Environmental Change* **20**, 116.

Fortibuoni T, Giovanardi O, Pranovi F, Raicevich S, Solidoro C and Libralato S (2017) Analysis of long-term changes in a Mediterranean marine ecosystem based on fishery landings. *Frontiers in Marine Science* **4**, 1–16.

Froese R and Pauly D (2023) FishBase. World Wide Web electronic publication [Online]. Available at www.fishbase.org

Gamito R, Teixeira CM, Costa MJ and Cabral HN (2015) Are regional fisheries' catches changing with climate? *Fisheries Research* **161**, 207–216.

Garcia A, Pereira JG, Canha Â, Reis D and Diogo H (2015) Life history parameters of blue jack mackerel *Trachurus picturatus* (Teleostei: Carangidae) from north-east Atlantic. *Journal of the Marine Biological Association of the UK* **95**, 401–410.

García-Reyes M, Koval G, Sydeman WJ, Palacios D, Bedriñana-Romano L, DeForest K, Montenegro Silva C, Sepúlveda M and Hines E (2023) Most eastern boundary upwelling regions represent thermal refugia in the age of climate change. *Frontiers in Marine Science* **10**, 1158472.

González JA (ed.) (2008) Memoria científico-técnica final sobre el Estado de los Recursos Pesqueros de Canarias (REPESCAN). Instituto Canario de Ciencias Marinas, Agencia Canaria de Investigación, Innovación y Sociedad de la Información, Gobierno de Canarias, Telde.

Grbec B, Dulcic J and Morovic M (2002) Long-term changes in landings of small pelagic fish in the eastern Adriatic possible influence of climate oscillations over the Northern Hemisphere. *Climate Research* **20**, 241–252.

Houssa R, Kifani S, Tojo N, Lakhigue A and Charouki N (2013) Spatial dynamics of sardine (*Sardina pilchardus*) and sardinella (*Sardinella aurita*), two small pelagic fishes in the Canary Current System. *GIS/Spatial Analyses in Fishery and Aquatic Sciences* **5**, 119–132.

ICES (2021) Second workshop on Atlantic chub mackerel (*Scomber colias*) (WKCOLIAS2). *ICES Scientific Reports* **3**, 1–231.

Jesus GT (1992) Study of the growth and reproduction of *Trachurus picturatus* (Bowdich, 1825) in Madeira. Madeira. Direcçáo Regional das Pescas Doc. N° **1991/03**.

Jurado-Ruzafa A and Santamaría MTG (2018) Age, growth and natural mortality of blue jack mackerel *Trachurus picturatus* (Carangidae) from the Canary Islands, Spain (NW Africa). *African Journal of Marine Science* **40**, 451–460.

Jurado-Ruzafa A, González-Lorenzo G, Jiménez S, Sotillo B, Acosta C and Santamaría MTG (2019) Seasonal evolution of small pelagic fish landings index in relation to oceanographic variables in the Canary Islands (Spain). *Deep Sea Research Part II* **159**, 84–91.

Jurado-Ruzafa A, Hernández E, Duque-Nogal V, Pascual-Alayón PJ, Carrasco MN, Sancho A and Santamaría MTG (2020) Life history parameters of the round sardinella *Sardinella aurita* in the Central East Atlantic off north-west Africa. *Journal of the Marine Biological Association of the United Kingdom* **100**, 997–1009.

Jurado-Ruzafa, A, Sotillo B, Santana-Arocha Z, Mañé BG, Estil·las C, González-Lorenzo G and Perales-Raya C (2021) Reproductive behavior of the main small pelagic fish caught in the Canary Islands (Spain, NW Africa). V SIBECORP, online, 11–15 October [Spanish].

Jurado-Ruzafa A, Canal G, Quinzán M, Sotillo B, Santana-Arocha Z, Estil·las C, Mañé BG, González-Lorenzo G and Perales-Raya C (2022) Influence of environmental variability on population traits of small pelagic fish in the Canary Islands (NW Africa, Spain). ICES/PICES Small Pelagic Fish, Lisbon, 2–7 November.

Liu Z, Chen L, Smith NG, Yuan W, Chen X, Zhou G, Alam SA, Lin K, Zhao T, Zhou P, Chu C, Ma H and Liu J (2019) Global divergent responses of primary productivity to water, energy, and CO_2. *Environmental Research Letters* **14**, 124044.

Lloret J, Palomera I, Salat J and Sole I (2004) Impact of freshwater input and wind on landings of anchovy (*Engraulis encrasicolus*) and sardine (*Sardina pilchardus*) in shelf waters surrounding the Ebre (Ebro) River delta (north-western Mediterranean). *Fisheries Oceanography* **13**, 102–110.

Lorenzo JM and Pajuelo JG (1996) Growth and reproductive biology of chub mackerel *Scomber japonicus* off the Canary Islands. *South African Journal of Marine Science* **17**, 275–280.

Ma S, Tian Y, Li J, Ju P, Sun P, Ye Z, Liu Y and Watanabe Y (2022) Incorporating thermal niche to benefit understanding climate-induced biological variability in small pelagic fishes in the Kuroshio ecosystem. *Fisheries Oceanography* **31**, 172–190.

Mann ME (2024) Global warming. Encyclopedia Britannica. Available at https://www.britannica.com/science/global-warming

Marschner IC (2011) Glm2: fitting generalized linear models with convergence problems. *The R Journal* **3/2**, 12–15.

Menezes GM, Sigler MF, Silva HM and Pinho MR (2006) Structure and zonation of demersal fish assemblages off the Azores Archipelago (mid-Atlantic). *Marine Ecology Progress Series* **324**, 241–260.

Olmos M, Ianelli J, Ciannelli L, Spies I, McGilliard CR and Thorson JT (2023) Estimating climate-driven phenology shifts and survey availability using fishery-dependent data. *Progress In Oceanography* **215**, 103035.

Ormaza-González FI, Mora-Cervetto A, Bermúdez-Martínez RM, Hurtado-Domínguez MA, Peralta-Bravo MR and Jurado-Maldonado VM (2016) Can small pelagic fish landings be used as predictors of high-frequency oceanographic fluctuations in the 1–2 El Niño region? *Advances in Geosciences* **42**, 61–72.

Peck MA, Reglero P, Takahashi M and Catalán IA (2013) Life cycle ecophysiology of small pelagic fish and climate-driven changes in populations. *Progress In Oceanography* **116**, 220–245.

Peck MA, Alheit J, Bertrand A, Catalán IA, Garrido S, Moyano M, Rykaczewski RR, Takasuka A and van der Lingen CD (2021) Small pelagic fish in the new millennium: a bottom-up view of global research effort. *Progress In Oceanography* **191**, 102494.

Pennino MG, Coll M, Albo-Puigserver M, Fernández-Corredor E, Steenbeek J, Giráldez A, González M, Esteban A and Bellido JM (2020) Current and future influence of environmental factors on small pelagic fish distributions in the northwestern Mediterranean sea. *Frontiers in Marine Science* **7**, 622.

Pilling GM, Apostolaki P, Failler P, Floros C, Large PA, Morales-Nin B, Reglero P, Stergiou KI and Tsikliras AC (2009) Assessment and management of data-poor fisheries. In Payne A, Cotter J and Potter T (eds), *Advances in Fisheries Science*. Oxford: Blackwell Publishing Ltd, pp. 280–305.

Pita C, Silva A, Prellezo R, Andrés M and Uriarte A (2014) Socioeconomics and management. In Ganias K (ed.), *Biology and Ecology of Sardines and Anchovies*. Florida: CRC Press, pp. 335–366.

Quinzán M and Jurado-Ruzafa A (2021) Exploratory assessments of small pelagic fish in the Canary Islands using data-limited methods. Presented at FAO/CECAF Working Group on the Assessment of Small Pelagic Fish of Northwest Africa. 21–25 June 2021, online.

R Core Team (2023) *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing. Available at https://www.R-project.org/

Ramírez F, Pennino MG, Albo-Puigserver M, Steenbeek J, Bellido JM and Coll M (2021) SOS small pelagics: a safe operating space for small pelagic fish in the western Mediterranean sea. *Science of The Total Environment* **756**, 144002.

Ramírez F, Shannon LJ, van der Lingen CD, Julià L, Steenbeek J and Coll M (2022) Climate and fishing simultaneously impact small pelagic fish in the oceans around the southernmost tip of Africa. *Frontiers in Marine Science* **9**, 1–11.

Sabatés A, Martín P, Lloret J and Raya V (2006) Sea warming and fish distribution: the case of the small pelagic fish, *Sardinella aurita*, in the western Mediterranean. *Global Change Biology* **12**, 2209–2219.

Santamaría MTG (1993) Actividad de la flota sardinal española en África Occidental. Aspectos biológicos de la sardina (Sardina pilchardus

(Walbaum, 1792)), dinámica y evaluación del recurso (PhD Thesis). Universidad de La Laguna, San Cristóbal de La Laguna, Spain.

Schickele A, Leroy B, Beaugrand G, Goberville E, Hattab T, Francour P and Raybaud V (2020) Modelling European small pelagic fish distribution: methodological insights. *Ecological Modelling* **416**, 108902.

Sekadende B, Scott L, Anderson J, Aswani S, Francis J, Jacobs Z, Jebri F, Jiddawi N, Kamukuru AT, Kelly S, Kizenga H, Kuguru B, Kyewalyanga M, Noyon M, Nyandwi N, Painter SC, Palmer M, Raitsos DE, Roberts M, Sailley SF, Samoilys M, Sauer WHH, Shayo S, Shaghude Y, Taylor SFW, Wihsgott J and Popova E (2020) The small pelagic fishery of the Pemba Channel, Tanzania: what we know and what we need to know for management under climate change. *Ocean & Coastal Management* **197**, 105322.

Selvaraj JJ, Rosero-Henao LV and Cifuentes-Ossa MA (2022) Projecting future changes in distributions of small-scale pelagic fisheries of the southern Colombian Pacific Ocean. *Heliyon* **8**, e08975.

Stewart RH (2008) *Introduction to Physical Oceanography*. USA: Department of Oceanography, Texas A & M University, Melville. pp. 260.

Teixeira CM, Gamito R, Leitão F, Murta AG, Cabral HN, Erzini K and Costa MJ (2016) Environmental influence on commercial fishery landings of small pelagic fish in Portugal. *Regional Environmental Change* **16**, 709–716.

Vélez-Belchí P, González-Carballo M, Pérez-Hernández MD and Hernández-Guerra A (2015) Oceanographic and biological features in the canary current large marine ecosystem. In Valdés L and Déniz-Gonzaléz I (eds), *IOCT Series* 115. Paris: Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO), pp. 299–308.

Villanueva P and Ruíz A (1994) Oceanographic characteristics of the Canary Islands waters. *The International Hydrographic Review* **71**, 67–78.

Walther G-R, Post E, Convey P, Menzel A, Parmesan C, Beebee TJC, Fromentin J-M, Hoegh-Guldberg O and Bairlein F (2002) Ecological responses to recent climate change. *Nature* **416**, 389–395.

Zardoya R, Castilho R, Grande C, Favre-Krey L, Caetano S, Marcato S, Krey G and Patarnello T (2004) Differential population structuring of two closely related fish species, the mackerel (*Scomber scombrus*) and the chub mackerel (*Scomber japonicus*), in the Mediterranean sea. *Molecular Ecology* **13**, 1785–1798.

Zeeberg J, Corten A, Tjoe-Awie P, Coca J and Hamady B (2008) Climate modulates the effects of *Sardinella aurita* fisheries off Northwest Africa. *Fisheries Research* **89**, 65–75.