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ORIGINAL ARTICLE

Shifts in the pelagic fishery dynamics in response to regional sea warming and fishing in the Northeastern Mediterranean

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Abstract

Understanding the dynamics of pelagic fish fluctuations is crucial to ecosystem well-being and sustainable fishery. Here, inter- and intra-annual landing dynamics of small and medium pelagic fish were delineated between 2000 and 2022 in the landlocked Sea of Marmara. Time series of environmental variables and fisheries landings were analyzed for their trends and inter-correlations. Results showed that variations in the landings of small and medium pelagic fish in the Sea of Marmara had strong seasonality and were very likely affected by fishing effort, and sea surface temperature regimes. During the study period, landings of anchovy, bonito and bluefish, and net primary production showed no significant trends. On the other hand, Mediterranean horse mackerel had a significant decreasing trend, while sardine landings and the sea surface temperature (0.05 ± 0.01 °C/ y^{-1}) had a significant increasing trend. Analysis of the duration of the fishing period in a given fishing season showed that reaching 90% of the landings (L_{90}) for anchovy, sardine, and Mediterranean horse mackerel shifted almost one month earlier, and for bonito, L_{90} showed no change for larger ones, but extended almost one month for small individuals. The multiple linear regression models indicated that the landing dynamics of small and medium pelagic fish were also influenced by the prey-predator relations in the food web. Exploiting anchovy stocks would likely have consequences on the dynamics of bonito and bluefish stocks, and exploiting bonito and bluefish stocks would have a cascading trophic impact on small pelagic fish catches. This study highlights the necessity of adaptive management measures for fisheries under regional sea warming conditions, and a one-and-a-half-month delay in the opening time of the fishing season, thus shortening its duration is strictly recommended.

Keywords Landing dynamics · Small pelagic · Climate change · Fishing season · Sea surface temperature · Sea of Marmara

Introduction

Climate change has a range of effects on marine ecosystems from changing water temperatures, modified circulation, or habitat conditions to effects occurring through altered pathways within biogeochemical cycles and food webs (Lima et al. 2022). Small pelagic fish such as anchovy and sardine are very sensitive to climatic fluctuations, and they can respond quickly through changes in their recruitment processes (Hunter and Alheit 1995; Pennino et al. 2020). The reproductive strategy of producing large quantities of pelagic eggs, which is present in pelagic fishes, makes their populations dependent on environmental conditions (Palomera et al. 2007; Giannoulaki et al. 2013). Overfishing and declining landings of small pelagic fish have been observed in the Mediterranean Sea, and decadal decreasing trends in landings of medium pelagic fish were also reported (Piroddi et al. 2017; Van Beveren et al. 2016; Ouled-Cheikh et al. 2022). Changes in pelagic fish populations, whether by fisheries or climate, affect the integrity of the marine ecosystem and economic stability (Cury and Shannon 2004; Alder et al. 2008; Coll and Libralato 2012). Therefore, delineating the landing dynamics of both small and medium pelagic fishes from regional to global scale can provide indispensable information to aid in developing management plans for ecosystem well-being and sustainable fishery.

The Sea of Marmara (SoM) is the northeastern most part of the Mediterranean Sea and is one of the seven marine

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ecoregions together with the Aegean Sea (Spalding et al. 2007). The SoM is a nearly enclosed basin that forms a transition zone between the Black Sea and the Mediterranean Sea via two narrow straits (the Bosphorus and the Dardanelles). It has a primarily east-west orientated movement corridor that may restrict the northward displacement of organisms (Philippart et al. 2007). The SoM fishery is predominantly pelagic. Its contribution to the overall Mediterranean pelagic fishery is nearly 10% (25,876 t to 268,178 t, respectively, FAO 2020). Anchovy (*Engraulis encrasicolus*) is the dominant species, accounting for approximately 70% of the total catch (FAO 2020), followed by Mediterranean horse mackerel (*Trachurus mediterraneus*), sardine (*Sardina pilchardus*), bluefish (*Pomatomus saltatrix*) and Atlantic bonito (*Sarda sarda*). Since bluefish and Atlantic bonito (bonito hereafter) are iconic fishes in Turkish culture, scientific research on their migration behavior in the SoM dates back to the 1950s. Large schools of bluefish and bonito migrate from the SoM to the Black Sea for spawning in the spring season and return to the SoM in late autumn (from August to October). This migration period of large bluefish and large bonitos through the Istanbul Strait (Bosphorus) was noted to be an important event and hence was a festive time for Istanbul residents (Ulman et al. 2020). However, their landings had decreasing trends since the onset of the 2000s. In the SoM, there are three main indirect approaches in force for fisheries management: (i) temporal industrial fishing ban from April 15 to September 1 every fishing season, (ii) minimum landing size (MLS) for certain species including small and medium pelagic fish, and (iii) geographical and structural gear restrictions. Annual temporal closures for industrial fishing are a regulation for protecting spring-summer spawners (such as anchovy, horse mackerel, and bonito) and have been applied since 1971. It is one of the longest (and permanent) closure periods for the industrial fisheries in the entire Mediterranean basin with a total of 135 days (Yıldız et al. 2020). Considering the importance of pelagic fishery, annual fishing ban is a very important management measure, because purse seiners constitute 80% of the total catch and only 5% of the 3500 active fishing boats in the SoM (Koyun et al. 2022).

In data-limited regions, such as the SoM, landing dynamics and its seasonality can be used as a proxy for fish stock status and level of its exploitation. Variation in landings, and its relation to environmental variables especially changes in the sea water temperature, are useful for understanding species interactions and their response to those changing condition. In this study, the inter- and intra-annual conditions in the landing dynamics of small and medium pelagic fish in the SoM were evaluated by considering regional sea warming, fishing effort, and prey-predator relations. Monthly basis landings of five pelagic fish and satellite-derived environmental variables from 2000 to 2022 were used. Specifically, decadal changes in the (i) seasonality of the environmental parameters, small and medium pelagic fish landings and fishing efforts, (ii) duration of the landing season for each species, (iii) the correlation between environmental parameters and landings of each species, and (iv) the relation between pelagic fish landings by means of prey-predatory interactions were analyzed.

Materials and methods

Data set

Monthly landings data of the small pelagic fish anchovy, horse mackerel, sardine, and medium pelagic fish bluefish, and bonito were obtained from the Istanbul Fish Market (IFM) of Istanbul Metropolitan Municipality (https://gida.ibb.istanbul/tarimve-su-urunleri-mudurlugu/su-urunleri-istatistikleri.html) where this kind of detailed dataset is only provided by. Data series spanned from 2000 to 2022. Earlier data were not used in the analysis because of the lack of certain environmental variables and intermittent monthly landing statistics. The small and medium pelagic fish species analyzed here are mainly subject to industrial exploitation and are caught by purse seiners, although a small part of their landings may have been derived from gillnets and trammel nets. The representativeness of the IFM landings data for the SoM by comparing it to Turkish Statistical Institute (TurkStat) annual catch statistics (https://biruni.tuik.gov.tr/medas/?locale=tr) were checked. The overall average ratio of annual landings data for five pelagic species by the IFM and TurkStat was 0.83 with ± 0.25 standard deviation which shows IFM landings data is acceptable to evaluate SoM pelagic fisheries. Bluefish and bonito are acknowledged for their different sizes and landings data were also provided separately for bonito and large bonito (> 35 cm), and small bluefish (< 25 cm) and bluefish (Table 1) which were used separately in the analyses as well.

The satellite data used for this study consisted of mean sea surface temperature (SST, °C) and net primary productivity (NPP, mg C m^{-2} d^{-1}). GlobColour monthly reprocessed NPP data product by ACRI-ST were used. SST data were a merged

Table 1 Different market sizes of Atlantic bonito and bluefish and their acknowledged Turkish names

Fish	TL (cm)	TW (g)	Acknowledged Turkish name	In this study
Bluefish	10–25	50–250	Çinekop	Small bluefish
	25–35	250–500	Lüfer	Bluefish
Atlantic bonito	30–35	600–900	Palamut	Bonito
	50–60	3000–4000	Torik	Large bonito

multisensory product by The Group for High Resolution Sea Surface Temperature (GHRSST), Met Office (National Meteorological Service for the UK), and Copernicus Marine Environmental Monitoring Service (CMEMS). All data were obtained from the CMEMS for the years 2000–2022. The data were spatially averaged for each fishing season prior to analyses.

Effort data based on fishing hours of purse seiners were obtained by the Global Fishing Watch (GFW) online tool between 2013 and 2022 to calculate landings per unit effort. The GFW is an international non-profit organization that provides global effort data by analyzing the positions of vessels tracked using Automatic Identification Systems (AIS) (Guiet et al. 2019). In the GFW system, once fishing vessels are identified and fishing positions detected in the AIS dataset, the apparent fishing effort can be calculated for the requested area by summarizing the “fishing hours” for all fishing vessels in that area. The effort estimates used in this study were expressed as the number of fishing vessel days for the whole SoM basin, calculated daily by summing the number of purse seine vessels fishing at least once in a given day, and were converted to monthly resolution.

All data were collated to conform to a fishing season that starts on the 1st of September in a given year and ends on the 15th of April in the succeeding year, covering seven-and-a-half-month period. A temporal fishing ban between the 15th of April and the 31st of August is applied for the industrial purse seiners operating in the SoM. Thus, to delineate the relationship between landings and environmental factors, one fishing season (fishing year) was set to eight different months from September to April (next year). Annual average values for both environmental and landings data were also calculated according to the fishing season.

Data analysis

Trend analyses were applied to the time series of satellite-derived SST and NPP data, and landings of each pelagic fish to determine the significant trends. The correlation between the entire time series of environmental variables and the landings of pelagic fish was detected by Pearson’s product-moment analysis following logarithmic transformation.

The changes in the fishing activity were analyzed both seasonally and inter-annually. Each pelagic species’ landings when reached 50% and 90% of the yearly landings was determined (L_{50} and L_{90} respectively). For each fishing season, the cumulative sum of the monthly landings was divided by the yearly total catch to set up a standardized time series of cumulative catches in the respective fishing season. A conditional bar table was generated to visualize the annual changes in the monthly duration of the fishery for each species from September 2000 to April 2022.

Landed catch is significantly related to the fishing effort exerted, hence, to uncover the relationships among environmental factors and trophic interactions, the landings-per-unit-effort (LPUE) values were calculated by dividing the monthly landings by the average monthly fishing effort. The calculated long-term averaged monthly fishing effort data from 2013 to 2022 were used to calculate monthly LPUE for 2000–2012 (Fig. 1b). Distributed-lag time series linear regressions were used to model the monthly LPUE of species using environmental (SST) and bio-optical and biotic (NPP and LPUE of other species) variables as predictors. The time series were subjected to reciprocal transformation prior to the regression analysis. The best model was selected using a stepwise approach, first including all the possible covariates in the model and then removing the ones with a p-value > 0.05 to minimize Akaike’s Information Criterion (Akaike 1974) score. Finally, the models that were statistically significant ($p < 0.05$) were chosen. Multicollinearity is an important concern in regression analysis when predictor variables are highly correlated to each other (Belsley et al. 2005). To assess the degree of multicollinearity, variance inflation factor (VIF) values were calculated for the predictors in the linear models and half of the suggested cutoff value (Midi and Bagheri 2010) were chosen. The skills of the statistically significant linear models in reproducing the time series LPUE values of species were analyzed using Taylor diagrams that encompassed information about the models’ correlations and standard deviations against observations (Taylor 2001).

Analyses were carried out with version 4.1.3 of R statistical software (R Core Team 2022) using packages “astsa” (Stoffer and Poison 2022), “olsrr” (Hebbali 2020), “caret” (Kuhn 2021), “zyp” (Bronaugh and Werner 2019), “xts” (Ryan and Ulrich 2020), “Hmisc” (Harrell 2022), and “corrplot” (Wei and Simko 2021).

Results

Inter- and intra-annual variations

According to the GFW data, the fishing effort peaked almost every year at the onset of the fishing season (September), and after exhibiting a sharp decrease in October remained mostly stable until late winter, and reached its lowest at the end of the season parallel to the landings’ pattern (Fig. 1b). Monthly variation of fishing effort in the time series was the lowest in October (CV = 0.21), indicating less variability in fishing effort. However, more variability was observed towards the end of the season (CV = 0.38–059). From 2013 to 2022, the total inter-annual fishing effort has almost halved (Fig. 1a). However, from 2000 to 2022, total landings did not differ significantly between the years ($p = 0.88$).

SST showed a significant positive trend of 0.05 ± 0.01 °C/ y^{-1} during the study period ($p < 0.01$). Monthly average

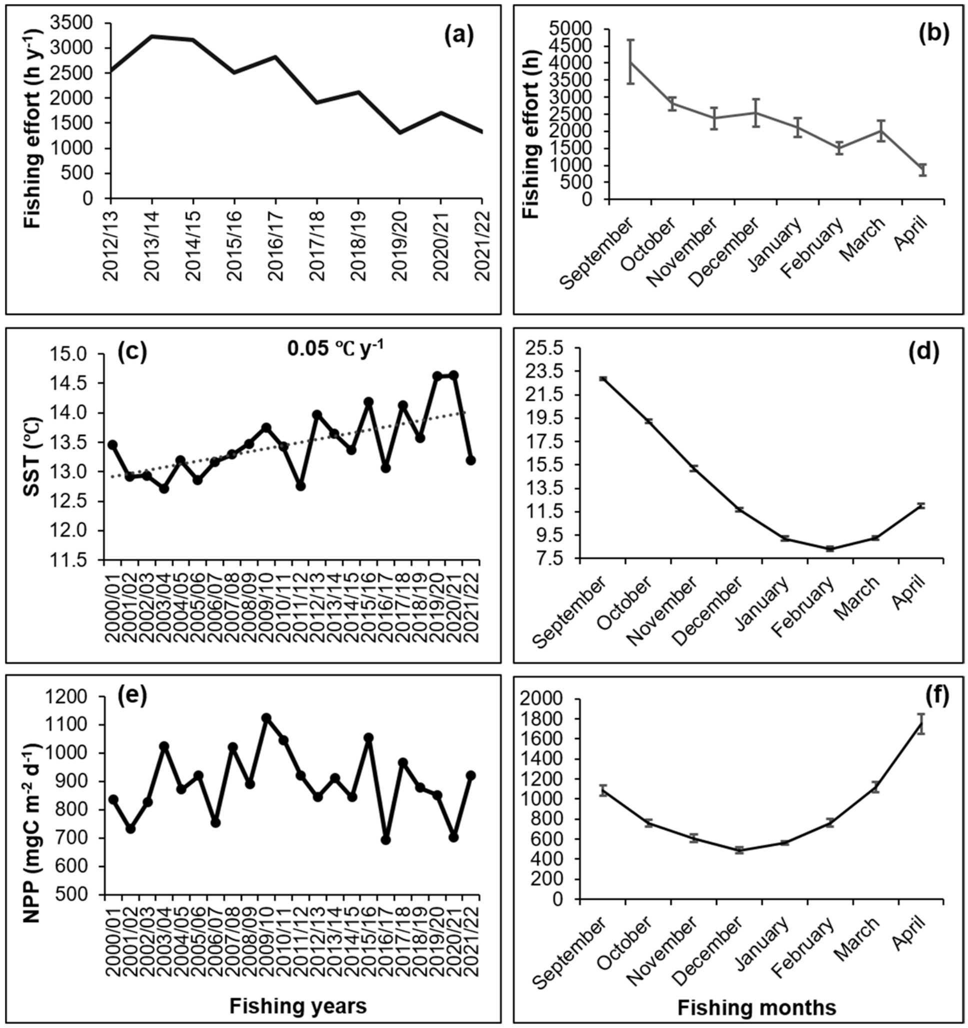

Fig. 1 Time series of **a** total fishing effort (h y^{-1}) between 2012/13 and 2021/22 fishing season, **b** average monthly fishing effort (**h**). Annual time series of **c** SST and **e** NPP between 2000/01 and 2021/22 fishing season. The values of the significant linear trends have been included (dashed black line). Average monthly cycle for the **d** SST and **f** NPP in the SoM. Error bars are the standard errors for each month of the fishing season

values indicated that the warmest month in a fishing season was September (22.85 ± 0.11 °C) and the coldest was February (8.23 ± 0.14 °C) (Fig. 1c, d). Contrary to the changes in SST, NPP values were stable and showed no significant trend. NPP reached a minimum in winter (December 327 ± 20 mg C m^{-2} d^{-1}), and increased to a maximum value in April (986 ± 83 mg C m^{-2} d^{-1}, Fig. 1e, f).

SST also showed an overall increase in the inner basin of the SoM between the initial (September 2000–April 2005) and final (September 2017–April 2022) five-year fishing seasons of the study period (Fig. 2). Much of the increase in SST occurred along the coastal areas and in the central basin. In addition, along the northeastern part and the Istanbul Strait, the SST increase was much higher than that in the southwestern part and the Çanakkale Strait.

Anchovy landings were relatively stable during the study period. Sardine landings increased with a significant trend ($p = 0.01$), but Mediterranean horse mackerel landings decreased with a significant trend ($p = 0.03$) (Fig. 3a). Bonito showed great fluctuations over the years, but no significant trends were found. Large bonito showed two distinct peaks in landings in 2002/2003 and 2016/2017 fishing season (578 and 695 tonnes, respectively). Both sizes of bluefish also showed large fluctuations in landings, and no significant trends were found. Similar to large bonito, bluefish showed two major peaks in landings, reaching up to 10 times the average value in the 2002/2003 and 2018/2019 fishing seasons (2324 and 2456 tonnes, respectively; Fig. 3a).

Average anchovy landings were maximum in November (3410 tonnes) and gradually decreased to a minimum in April (400 tonnes). Average sardine landings were the highest during the first months of the fishing season (September and October; 91 and 100 tonnes, respectively) and decreased to a minimum in November, then gradually increased and peaked in February (100 tonnes). Mediterranean horse mackerel landings showed a similar cycle to anchovy and were maximum in December (1072 tonnes), then gradually decreased and reached a minimum in April (Fig. 3b). Following the opening of the fishing season in September, bonito and large bonito landings were high

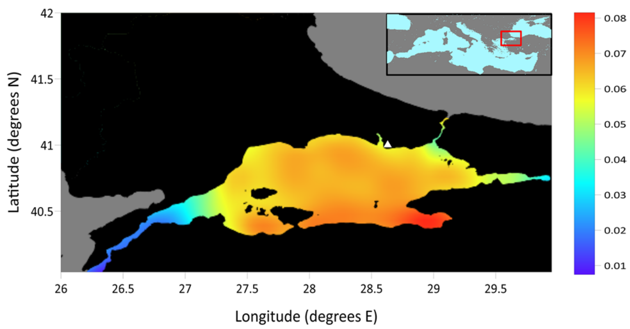

Fig. 2 Location of the Sea of Marmara and position of the Istanbul Fish Market (IFM, white triangle) in its northern coast where pelagic landings data were collected. Fractional change of sea surface temperature between the initial (September 2000–April 2005) and final (September 2017–April 2022) five-year fishing seasons of the study period

and reached a maximum in October (406 and 23 tonnes respectively), then sharply decreased to a minimum after November and remained very low until the end of the fishing season in mid-April. The average landings of small bluefish were minimum in September (35 tonnes), reached a maximum in November (1188 tonnes) and after a sharp decrease remained low until the end of fishing season. Average landing of bluefish reached a maximum in October (171 tonnes) and then gradually decreased to a minimum in April (3 tonnes) (Fig. 3b).

Average LPUE variations for medium pelagic fish had similar seasonality as the landings which were the highest during the first months, followed by sharp decreases and remained lowest in April, at the end of the fishing year (Fig. 3c). For the small pelagic fish, on the other hand, average LPUE variations showed different patterns than their landings. Contrary to the higher landings following the opening of the fishing season, LPUE values increased towards the end of the fishing year for sardine and Mediterranean horse mackerel. For anchovy, a similar pattern to that of medium pelagic fish was observed at the beginning of the fishing year, but LPUE remained stable during the rest of the fishing season (Fig. 3c). The fishing season started with high LPUE values first for bluefish, and both sizes of bonito in October, and continued with high LPUE values for anchovy and small bluefish in November once bonito LPUE started to decrease.

Shifts in the seasonality of pelagic fish landings

The standardized cumulative landing time series for each species displayed a similar shape for small pelagic and medium pelagic fish separately, which reflected the different phases of exploitation of those species during the fishing season (Fig. 4; Table 2). Thus, the indicator L_{90} displayed changes seperately during the initial and the final five-year fishing seasons of the study period (2000/2001 - 2004/2005 and 2017/2018 - 2021/2022, respectively). The L_{50} and L_{90} for anchovy, sardine, and Mediterranean horse mackerel shifted earlier, except for L_{50} of Mediterranean horse mackerel which remained stable (Fig. 4a, c; Table 2). The L_{50} and L_{90} were stable for bonito; however, L_{90} shifted almost one month earlier for large bonito (Fig. 4b, d; Table 2). The L_{50} and L_{90} were slightly delayed for small bluefish, and L_{50} was also slightly delayed for bluefish while L_{90} shifted slightly earlier (Fig. 4b, d; Table 2).

Relationships among variables

Both sizes of bonito and bluefish showed significant positive correlations with SST, and only small bluefish showed significant negative correlations with NPP (Fig. 5). The correlation between SST and bonito landings was also very high ($r > 0.60$). Anchovy and Mediterranean horse mackerel had a significant negative correlation with SST. To understand prey-predator interaction, the correlation between landings of medium and small pelagic fish was also detected. Anchovy landings were significantly correlated with horse mackerel and both sizes of bonito and bluefish. Mediterranean horse mackerel landings had a significant negative correlation with the landings of bonito, and had significant positive correlations with bluefish (Fig. 5).

The stepwise statistical linear modeling approach resulted in five statistically significant models for the LPUE of anchovy ($R^2 = 0.46$), sardine ($R^2 = 0.21$), horse mackerel ($R^2 = 0.28$), bonito ($R^2 = 0.54$), and bluefish ($R^2 = 0.65$). The models for sardine and horse mackerel explained less than 30% of the variability in their respective time series of LPUE, although both were statistically significant. However, models of anchovy, bonito, and bluefish had better skills in reproducing their respective time series of LPUE (Table S1). Taylor diagrams showed that the correlations of anchovy, sardine, horse mackerel, bonito, and bluefish models were 0.63, 0.15, 0.38, 0.76, and 0.78, respectively (Fig. S1a). The models of sardine and horse mackerel were statistically significant but had low explanatory power in reproducing the LPUE of the two species (Fig. S1b). The VIFs were close to unity, indicating that no important degree of multicollinearity that would hamper the outcomes of the regression analysis existed between the predictor variables in the models (Table S1).

Discussion

According to study results, variations in the landings of small and medium pelagic fish in the SoM had strong seasonality and were affected by fishing effort, prey-predator

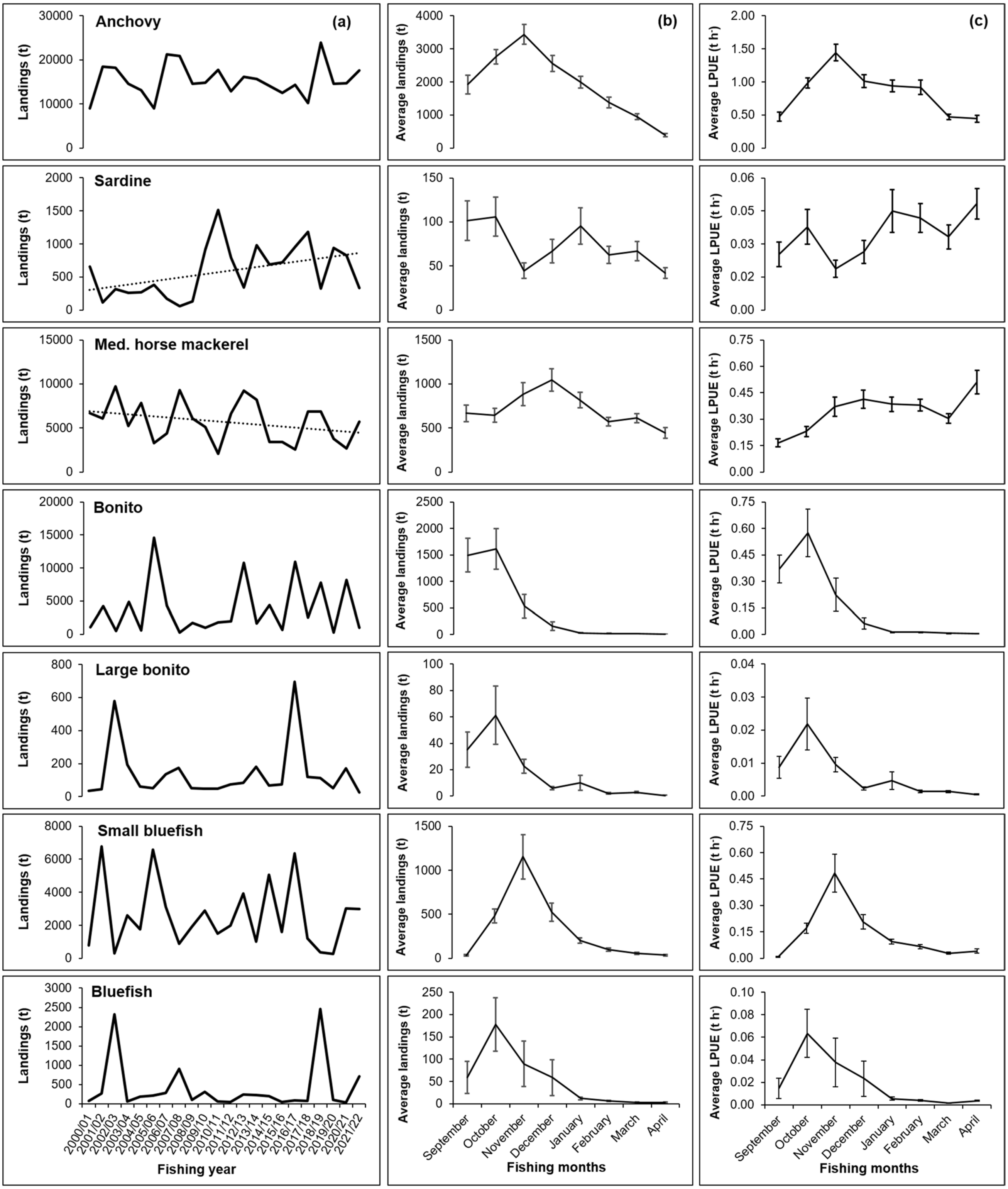

Fig. 3 Inter- and intra-annual dynamics of anchovy, sardine, Mediterranean horse mackerel, bonito, large bonito (> 35 cm), small bluefish (< 25 cm), bluefish. **a** Annual landings (tonnes per fishing year) between 2000/2001 and 2021/2022 fishing year. The values of the significant linear trends have been included (dashed black line). Average monthly cycle for **b** landings (tonnes), and **c** LPUE (tonnes per hour) of small and medium pelagic fish in the SoM. Error bars are the standard errors for each month of the fishing season

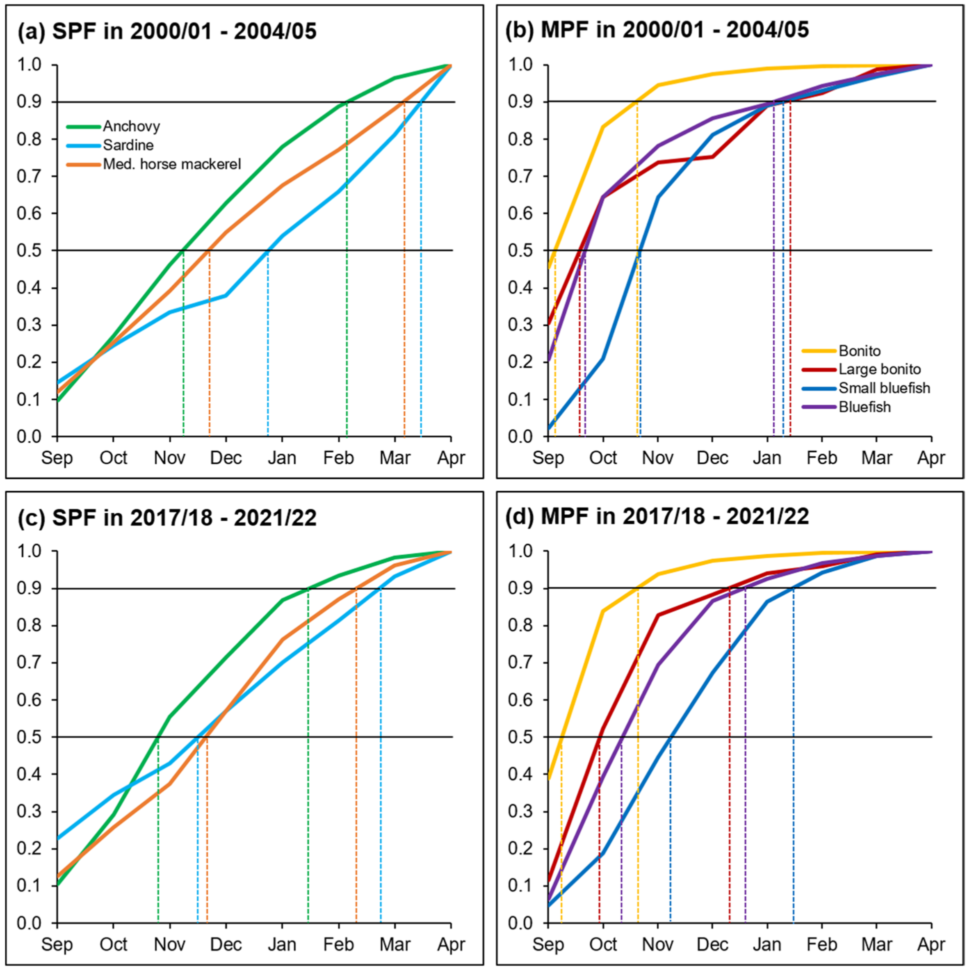

Fig. 4 Standardized cumulated monthly landings throughout the fishing season, indicating the months in which 50% (L_{50}), and 90% of the landings were completed (L_{50} and L_{90}, horizontal solid lines). **a**–**b** the initial (September 2000–April 2005) and **c**–**d** final (September 2017–April 2022) five-year fishing seasons of the study period. Colored vertical dashed lines show respective landings for each species at L_{50} and L_{90}. SPF: small pelagic fish, MPF: medium pelagic fish

Table 2 Changes in the duration of the fishing periods according to monthly landings of each pelagic fish between 2000/2001 and 2021/2022 fishing seasons in the Sea of Marmara. Colors indicate red for the shortest, yellow for the medium, and green for the longest fishing season for each species

Species	L90																					
	2000/01	2001/02	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10	2010/11	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19	2019/20	2020/21	2021/22
Anchovy	6	6	7	5	7	6	6	7	7	7	6	6	5	6	6	6	5	6	5	5	5	6
Sardine	7	8	8	8	8	8	7	7	7	6	6	7	7	7	7	7	7	7	8	7	6	7
Med. horse mackerel	7	8	8	7	8	8	8	7	7	7	7	7	7	7	7	7	7	7	7	6	7	7
Bonito	3	3	2	3	2	4	3	3	3	2	3	3	2	2	3	3	3	3	2	4	2	2
Large bonito	3	2	2	5	7	5	3	4	5	5	6	5	4	4	4	4	2	3	3	3	5	7
Small bluefish	5	6	7	5	6	5	4	5	5	4	6	6	5	5	5	5	4	5	7	5	6	5
Bluefish	5	3	3	7	5	4	5	4	4	3	4	5	4	4	5	6	4	6	4	5	6	4

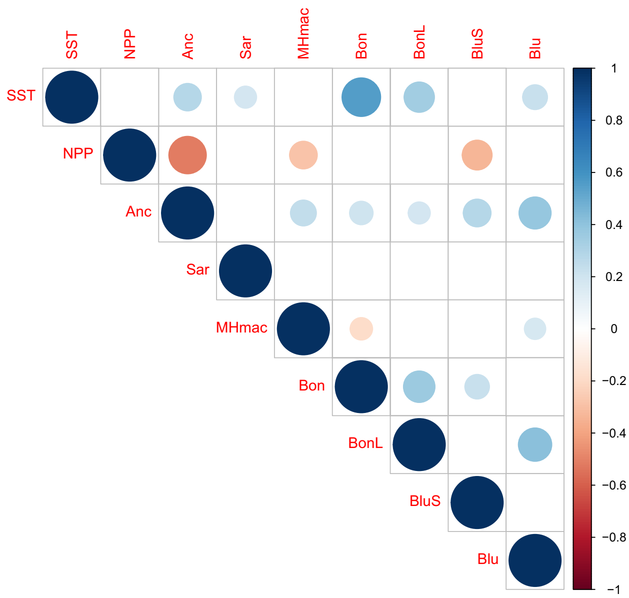

Fig. 5 Pearson correlation between landings of each pelagic species and environmental parameters. Colored circles indicate significant correlations at $p = 0.05$ whereas non-significant correlations are blank. Variables are as follows: SST: sea surface temperature, NPP: net primary production, Anc: anchovy, Sar: sardine, MHmac, Mediterranean horse mackerel, Bon: bonito, BonL: large bonito, BluS: small bluefish, Blu: bluefish. All variables were logarithmically transformed prior to analyses

dynamics, and SST regimes. During the study period, SST showed positive trends with 0.05 °C increase per annum from 2000 to 2022 in the SoM. Compared to neighboring seas with SoM, SST shows a slightly lower warming trend than the Black Sea (0.05–0.09 °C y^{-1}), but slightly higher than the Aegean and Mediterranean Seas (0.04–0.05 °C y^{-1} and 0.03–0.04 °C y^{-1}, respectively; Shaltout and Omstedt 2014; García-Monteiro et al. 2022). Other satellite-derived environmental variable, NPP, showed no clear trend over the years, but its seasonal variability was high as the spring season had the highest, and the winter season had the lowest productivity. Due to the fishing effort that concentrated at the onset of every fishing season, the landings of both small and medium pelagic fish were mainly aggregated in the autumn season and were the lowest in spring through the closing. Inter-annually, i.e., from 2000 to 2022, landings of anchovy, bonito, and bluefish showed no significant trends; on the other hand, sardine landings had a significant increasing trend, while Mediterranean horse mackerel had a significant decreasing trend.

Considering the bluefish and bonito according to their size, the landings of large individuals, which are already less than the small ones (3–5- and 4–10-folds, respectively), have become less frequent in two decades. This is defined as growth overfishing, which occurs when the catch size of the commonly caught species decreases over time (Pauly 1994). In addition to growth overfishing, recruitment overfishing is also detrimental to bluefish. Recruitment overfishing is defined as the rate of fishing above which the recruitment of a unit stock is significantly reduced and is characterized by a noticeable reduction in the spawning stock biomass and a decrease in the proportion of mature fish (Myers et al. 1994; Froese and Pauly 2023). Recently, bluefish smaller than 15 cm in length have been sold in Turkish fish markets, which signifies the likelihood of an imminent collapse of this fishery, as older mature fish now seem to be rare. Thus, the occurrence of both growth and recruitment overfishing is good predictors of impending future collapse of stocks. The general seasonal pattern of medium pelagic fish landings differed from that of small pelagic fish. Anchovy landings showed significant correlations with the landings of small and large bluefish. Both sizes of bonito landings had significant correlations with SST indicating migration patterns of both species. Bonito landings occurred mainly in autumn and extended to December in some years when bluefish landings were relatively low. Sabatés and Martin (1993) stated that bluefish had the potential to expand its range in the Mediterranean; therefore, there have been unusual occurrences and increasing abundance in different areas (the Ligurian and the Adriatic Sea) in the Mediterranean basin (Dulčić et al. 2005; Azzurro et al. 2019). Similarly, the sudden appearance of bonito in Nordic waters was assumed to be linked to a combination of favorable water temperatures and available prey species (Nøttestad et al. 2013).

The shift in L_{50} to almost one-month delay from 2000 to 2022 was hypothesized to be related to the variations in migration and the amount of bonito and bluefish. Schickele et al. (2021) highlighted that a potential mismatch between current fisheries areas and changes in the species climatic range of temperate-cold water species such as anchovy and sardine (bio-indicator species of climate-driven changes; Peck et al. 2013) could occur by the end of the century, implying a great loss of fisheries catch potential. Therefore, regarding future climate projections (Schickele et al. 2021) and the increasing SST trend in the SoM, adaptive management strategies must be considered. Our results may be an indication of a shift in spawning and migration cycles in these species through a subsequent decrease in recruitment success that will inevitably lead to shifts in species composition (Nunn et al. 2010; Moyano et al. 2023). Adjustment of the fishing season is inevitable in the management of pelagic fisheries when there are shifts in the life-history traits of stocks. Since there is no temporal fishing ban in the central Mediterranean, a very recent paper by Russo et al. (2022) highlighted that lockdown period reduced overall fishing hours during 2020 and had an immediate positive impact on fish biomass. They also suggest that temporal cessations of fishing activities should be implemented by limiting fishing effort and catches to benefit the fishery resources. Therefore, while underlining the importance of existing temporal closure regulation in the SoM, we also recommend a 45-day delay in the opening time of the fishing season, thus extending the duration of annual temporal closure for industrial fisheries by 45 days (180 days in total). Under recent climate change conditions, shifting the onset of the fishing season to mid-October instead of September in the SoM will help reduce conflicts between management priorities and ecological objectives. Climate change, specifically regional sea warming, has extremely likely impact on changes in the reproductive period (Fennie et al. 2023), traits (Canales et al. 2018), and spatial extent of species distribution (Pennino et al. 2020; Schickele et al. 2021). The duration of the temporal closure is not only crucial for conservation purposes of the fish population (Yıldız et al. 2020), but also to ensure the benefits of fisheries.

The activity of the purse seine fishery changed seasonally depending on the available fish species and their quantity. Because the fleet had an opportunistic nature and there was no restriction on the species and the volume of catch to be fished, they took advantage of the entire fishing season. The fishing effort had its peaks at the start of each fishing season, and the positive correlations between anchovy, small, and large bluefish landings could be an indirect consequence of the intensive fishing effort that yielded significant amounts of these fishes at the start of each fishing season. However, the reduced fishing period for anchovy also indicated that purse seiners preferred catching anchovy over other species at the beginning of each fishing season. As species distributions change in response to warming in sea waters (Azzurro et al. 2019), purse seiners may have more ability to adapt by following them. The fishing effort can be affected by the availability of target species (Maynou 2020), fishing strategy and tactics, legislation, market demands, and fuel prices (Tzanatos et al. 2013; 2014).

Anchovy is a critical food resource for the predatory species and transferring the energy from lower to higher trophic levels (Fennie et al. 2023), fluctuations in its populations construct ecosystem structure and functioning (Cury et al. 2000) while changes in environmental conditions might lead to the reconstruction of the interspecies relations. The linear model results showed a significant negative relationship between anchovy and bonito LPUE (as proxy of relative biomass) indicating prey-predator dynamics. If anchovy's relative biomass was low, the bonito's relative biomass was expected to be higher in two fishing seasons later. In other words, as per the anchovy model, the high relative biomass of bonito in the preceding fishing season can indicate a low relative biomass of anchovy in the succeeding fishing season. SST also played important roles in the landing dynamics of anchovy and bluefish, while NPP played a significant role in the landing dynamics of anchovy and bonito. The predatory species like bonito and bluefish exert a top-down trophic control on the food web, and resource competition with similar trophic level fish species on the variability of their LPUE. Daskalov et al. (2020) emphasized that bonito and bluefish are the main competitors for prey sources of small pelagic fish, as bluefish is the main predator of Mediterranean horse mackerel, whereas bonito prefers anchovy. This web of interactions indicated the presence of a possible cultivation effect between the two predatory fish species where the predation of bluefish on horse mackerel decreases the predation mortality on anchovy by horse mackerel, and hence, cultivated the bonito population and landings.

Impacts of the COVID-19 pandemic and mucilage outbreaks in the SoM

During the study period, three important events occurred which affected the whole SoM ecosystem and its components (Demirel et al. 2023). The SoM was challenged with two mucilage episodes in less than two decades. It was first observed throughout the basin between October 2007 and February 2008 (Yilmaz 2015). The second mucilage event was observed especially between March and August 2021. Furthermore, the year 2020 was the period of the COVID-19 global pandemic and lockdowns, and in Türkiye, countrywide lockdown occurred between April and June 2020. The time series of fisheries data included those three environmentally unusual years; i.e., 2007, 2020, and 2021. However, the closures and mucilage events, except that in 2007, took place towards the end of the industrial fishing season; the inter-annual comparison on the landings and fishing efforts showed no significant difference for those years. Although it is beyond the scope of this study, the impacts of mucilage events on ecosystem health, bio-ecology of pelagic fish species, and other pelagic system components, as well as socioeconomic processes namely small-scale fisheries are reported (Demirel et al. 2023) and they should soon be considered for better management decisions.

Conclusion

In this study, the intra- and inter-annual landing dynamics of pelagic fisheries in the SoM were examined from 2000 to 2022. High seasonality and annual variation were found in landing dynamics of small and medium pelagic fish. During the study period, the fishing season of anchovy, sardine, and horse mackerel has reduced and shifted by an average of one month. This seasonal shift illustrates both the concentration of fishing pressure on small pelagic fish and the impact of climate change on their life cycles. As a nearly enclosed basin, the renewal time of the water mass in the SoM is relatively shorter than that in open oceans; therefore, the SoM can respond quickly to the effects of climate change which is evident in the SST trend. If current fishing pressure continues on the anchovy stock, cascading trophic interactions in the food web can be soon expected, because prey-predator (anchovy-bonito) and predator-predator (bonito-bluefish) relationships are intertwined.

The current state of climate change in the SoM shows that serious cooperation among different stakeholders is necessary to build the ecosystem approach to fisheries management. Adaptive management strategies should be immediately considered to prevent amplified impacts of environmental factors and fishing from resulting in stock collapses (Jang et al. 2019). Thus, a one-and-a-half-month delay in the opening time of the industrial fishing season, thus shortening its duration, is strictly recommended as immediate adaptive management measures under regional sea warming conditions. The industrial fisheries, namely purse seine fishing sector in the SoM, are facing challenges to this climatic change, and the results clearly show that, in very near future, more radical decisions will be very likely necessary to protect this already altered, vulnerable, marginal sea's ecosystem, and remained coupled pelagic fish species.

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Data availability The data that support the findings of this study are available from the corresponding author, N.D., upon request.

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