**DOMESTICATING THE WILD: THE INFLUENCE OF AQUACULTURE ESCAPES ON TWO ICONIC MEDITERRANEAN SPECIES**

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**Abstract**

Extractive fisheries and marine aquaculture share space and target species. Several regional-scale examples exist of escapees entering wild fisheries landings, yet no study has assessed the influence of aquaculture on landings at an ecosystem scale. We examined the effects of farmed fish escapes on fisheries using FAO data and published escape rates for Gilthead seabream (*Sparus aurata*) and European seabass (*Dicentrarchus labrax*). Seabream landings were significantly correlated with the estimated biomass of escaped seabream entering the wild. There was a similar pattern for seabass until 2005, but the overall relationship between landings and escapes was not significant due to the dramatic drop in catches in recent years. We argue that seabass escapees’ relatively high mortality, lower capturability, and minor ‘leaking’ from farms may obscure their influence on landings. Significant positive fisheries regime shifts were detected for both species, matching the onset of aquaculture in the Mediterranean and the period when escapees from aquaculture surpassed landings. Our results suggest that fish escapes of these two iconic species may mask wild stock overexploitation, confound stock assessments, alter genetic diversity, increase the risk of spreading pathogens and parasites, and compete with wild conspecifics.

**Keywords:** *European seabass, Gilthead seabream,* escape events, stock assessments, small-scale fisheries, fisheries landings.

**Running page head:** Mediterranean farmed fish escapes

1. **INTRODUCTION**

Extractive fisheries are suffering a worldwide decline in landings (Pauly & Zeller 2016) caused by depletion and overfishing, which affects 68% of fish stocks (Costello et al. 2016). Despite declining wild catches, human fish consumption is expected to rise significantly in the following decades (Costello et al. 2020, Naylor et al. 2021). Aquaculture is viewed by many as vital to fill much of the unmet demand (Naylor et al. 2021, Boyd et al. 2022) and has grown 6.7% annually since 1990 (FAO 2022). These global patterns are largely mirrored in the semi-closed Mediterranean Sea, considered the world’s second most overexploited fishing area, with 63.4% of stocks fished at unsustainable levels (FAO 2022). Overfishing, combined with other human stressors (e.g. habitat loss, exotic species), are the main drivers of fish stock declines in the Mediterranean (Vasilakopoulos et al. 2014). In contrast, aquaculture in the region has rapidly grown over the past decades, heavily relying on high and medium trophic level species (i.e. finfish), leading to the process of ‘farming up’ marine food webs (Stergiou et al. 2009). Fisheries and aquaculture in the Mediterranean share the same target species. Gilthead seabream (*Sparus aurata*) and European seabass *(Dicentrarchus labrax*) are the most farmed and of high commercial interest to the fishing sector. Combined annual aquaculture production now exceeds 440,000 tonnes, while wild fisheries catches were ca. 7,500 tonnes in 2020 (FAOSTAT 2022). It has been estimated that approximately 400-500 million fish of each species are held in over 20,000 floating cages across the Mediterranean (Trujillo et al. 2012).

In areas where farmed populations coexist with wild conspecifics, the risk of potential interactions due to escape events exists (Arechavala-Lopez et al. 2018, Atalah & Sanchez-Jerez 2020). Specifically, i) trophic interactions with wild fish assemblages (Lorenzen et al. 2012), ii) influence on the genetic structure of wild conspecific’s populations (Glover et al. 2013) and iii) potential role as a vector of parasites and diseases (Madhun et al. 2015) have been described as the main interactions of escaped fish in the wild. Some of these interactions have already been reported for the Mediterranean Sea. For instance, escaped seabream is known to exploit natural resources once in the wild (Arechavala-Lopez et al. 2012), and both wild seabream and seabass genetic structure may be influenced by escapees in the Adriatic Sea (Šegvić-Bubić et al. 2017, Žužul et al. 2019). Yet there is a knowledge gap on the role of escaped fish as vectors for parasites and diseases in the Mediterranean (Arechavala-Lopez et al. 2013b).

While the extent of escapes across the Mediterranean is unknown, evidence suggests that escape events are widespread and significantly contribute to wild stocks (Dimitriou et al. 2007a, Glamuzina et al. 2014, Brown et al. 2015, Izquierdo‐Gómez et al. 2017). Jackson et al. (2015) estimated that 7.65 million juvenile and adult fish had escaped across three Mediterranean countries over three years. The magnitude of accidental restocking deriving from escape events is substantial enough to alter the trajectories of fisheries landings at the local scale. The latter occurred in some areas where catches of escaped individuals represented between 20 and 70% of the total catch (Brown et al. 2015, Izquierdo‐Gómez et al. 2017). Such scenarios might scale up after massive escape events due to extreme climatic events when the escaped biomass is significantly higher (Toledo‐Guedes et al. 2014). What is more, the landed biomass of reared species is exclusively represented by escapees in areas where such species are locally absent (Toledo‐Guedes et al. 2014, Izquierdo-Gomez & Sanchez-Jerez 2016). In the long term, Dimitriou et al. (2007) revealed that landings of seabream doubled in the Messolonghi lagoon (Greece), since the production began in the area. Whether the local effects of accidental restocking of wild populations through escape events are also perceptible at a Mediterranean-scale is still unknown. Therefore, this study aims to assess if fisheries’ landings are influenced by the recapture of escaped fish at the ecosystem level, using historical landing data from the Mediterranean. Additionally, we assessed whether changes in landings over time have contributed to fisheries regime shifts associated with aquaculture development and subsequent changes in escaped fish biomass.

1. **MATERIAL AND METHODS**

***2.1 Study area and datasets***

We used the FAO time series data on aquaculture production and fisheries landings of seabream and seabass in the Mediterranean and the Black Sea area between 1950 and 2020 (FAOSTAT 2022). This area was selected because it is an extensive semi-closed system (i.e., escaped fish would not emigrate from the system in significant numbers) and is the most critical area for seabass and seabream aquaculture (FAOSTAT 2022). Because fishing effort data was unavailable for the entire Mediterranean, we extracted yearly fleet sizes for six states with complete records (Spain, France, Slovenia, Greece, Malta, and Cyprus) from the European Union fleet register (Maritime Affairs and Fisheries 2022). Italy was excluded from analyses due to a significant anomaly in the catch records detected between 2004 and 2005. Specifically, Italian seabream reported landings dropped from 3,318 tonnes in 2004 (61% of the Mediterranean total) to 156 tonnes in 2005. Similarly, reported seabream landings dropped from 3,349 (46% of the Mediterranean total) to 265 tonnes. During subsequent years reported landings for both species remained at comparatively low levels, providing evidence of significant disruption in the data time series from 2005 onwards because of changes in the Italian data collection system (FAO 2022). For the countries (i.e., Malta, Cyprus, and Slovenia) that entered the fleet register in 2005, the number of vessels was extended back to avoid the noise created when a significant number of vessels entered the census, which artificially raises the number of vessels.

The small-scale vessel fleet is the most crucial fleet targeting seabream and seabass, mainly using trammel nets and gill nets as fishing gears. Escapees most influence this fleet since 80% of farms are within 10 km of shore (Trujillo et al. 2012), and escapees of both species disperse into natural coastal habitats (Arechavala-Lopez et al. 2011, Arechavala-Lopez et al. 2012). Thus, trawlers and purse seiners were excluded, and only data associated with small-scale vessels based in Mediterranean home ports were retained for the study, using fleet size (i.e. number of boats) as a fishing effort proxy. Then, landings of the six countries (Spain, France, Slovenia, Greece, Malta, and Cyprus) were pooled by species and divided by the total number of boats to obtain landings per unit of effort (hereafter LPUE in kg of fish/boat). The latter dataset comprised 30 years, from 1990 to 2020.

***2.2 Estimated rates of escape***

Rates of escape across the Mediterranean Sea are difficult to estimate as there are no specific requirements to report escapes across most farming countries, which means long-term estimates do not exist as in salmon-producing countries (e.g. Norway; Jensen et al. 2010). However, some estimates have been made through research projects across several countries for both bass and bream, which we have used to estimate a long-term annual escape rate.

Escape rates were derived from Jackson et al. (2015), who investigated escape events across three major Mediterranean seabream and seabass-producing countries (Spain, Greece and Malta) between 2009 and 2012. Fifty-two reported escape events led to 6.84 million escaped seabreams, while 15 events resulted in 0.6 million escaped seabass. Using the production data for these three countries, we estimated 9.6% and 0.6% annual escape rates for seabream and seabass, respectively. This suggests many more seabreams escape than seabasses. However, over 5 million of the 6.84 million seabass that escaped during Jackson et al.’s (2015) three-year study period did so in only two escape incidents where major storms broke down entire farms. Seabream and seabass farms are typically co-located in the same farming areas with similar levels of exposure and use the same farming technology (Papageorgiou et al. 2021). This means that, over the long term, large-scale escape incidents due to storms are equally as likely for both species. Supporting this, Toledo-Guedes (2014) estimated that the escape rate of seabass in the Canary Islands reached 5 % in years when large storms caused mass escape events (Toledo‐Guedes et al. 2014). Therefore, for the analyses, we used an escape rate of 5% for both species.

Jackson et al.’s (2015) escape rates are likely under-estimates for several reasons. First, the study surveyed fish farmers on escapes and data reported was volunteered by producers. This contrasts with several salmon-producing countries, where reporting every escape incident is mandatory (e.g. Norway, Scotland). Second, most escapees reported were caused by farm structure failure during storms when large and prominent escape events occur. Jackson et al.’s (2015) estimates do not fully account for difficult-to-detect ‘leaky escape’ events when fish escape through small holes in the nets. Third, Jackson et al.’s (2015) escape estimates do not account for the similarly difficult-to-detect process of ‘escape through spawning’, which is a significant source of entry to the wild of farmed seabream (Somarakis et al. 2013).

***2.3 Statistical analyses***

We assessed temporal trends of seabream and seabass aquaculture production, escaped biomass and fisheries landings in the Mediterranean. We used Granger’s Causality Test to seek relationships between the escapes and landings and escapes and LPUE time series, separately for seabream and seabass. The Granger Causality test determines whether or not a predictor time series helps forecast a response time series, conditional to the autocorrelation in the response (Granger 1969). We used a regime shift index (RSI) combined with an automatic sequential algorithm (Rodionov 2004) to assess the existence, timing, and significance (α=0.05) of abrupt changes in standardised anomalies in landings and LPUE data. Anomalies were calculated for each yearly value by subtracting the mean and dividing by the standard deviation for the analysed period. This is a sequential processing technique; for each new observation, the test examines the validity of a null hypothesis: the existence of a regime shift. The absolute value of RSI represents the magnitude of the shift(s), while its sign (+ or -) indicates an increase or decrease between regimes (Rodionov 2004). Trends in stock abundances are usually detected by analysing catch or landings per unit of effort rather than pure catch or landings data (Watson & Pauly 2001). However, it has been argued that trends in catch data are consistent with biomass trends (Froese et al. 2012). Using landings data from all the Mediterranean countries guarantees that the patterns detected are not an artefact produced by the sampling scheme or records changes for a specific country. Regarding fishing efforts, the present analysis assumes that there have not been significant inter-annual changes in species targeting the respective fleets.

1. **RESULTS**

Seabass landings rapidly increased from 100 - 200 t in the early 1970s, when the first records were available, to 3,287 t in 2006 (Figure 1 and Figure 2a). After 2006, the landings dropped significantly below 1,000 t in the late 2010s and recovered to 1,538 tonnes in 2020 (Figure 1). Meanwhile, seabream landings have steadily increased from 100 - 200 t in the 1950s to 5,346 t in 2020 (Figure 1 and Figure 2a). Large fluctuations in seabass LPUE were observed between 1990 and 2020, with significant peaks in 1994, 2006 and 2020 (0.05, 0.07 and 0.06 t per vessel, respectively, Figure 2b). Seabream LPUE increased from ca. 0.025 t per vessel in the early 1990s to 0.12 t per vessel in 2020 (Figure 2b). Since the onset of aquaculture in the late 1970s, production of both species has grown exponentially, from below 100 t to a maximum of ca. 220,000 t by 2020 (Figure 1). Based on an escape rate of 5%, we estimate that more than 127,000 t of seabass and 138,000 t of seabream escaped from Mediterranean aquaculture farms between 1970 and 2020. Estimated seabass escapees (641 t) surpassed landings (612 t) for the first time in 1994 (Figure 2a) and have continued to do so every year since 1996. From the mid-2000s onwards, the estimated biomass of escaped seabass was significantly higher than landings. In 2020, escaped biomass was seven times higher than caught biomass (Figure 2a). Neither seabass landings nor LPUE was significantly correlated with escaped biomass (F = 1.04 and F = 0.1, respectively and *P*>0.05).

For seabream, estimated escaped biomass (3,527 t) exceeded landings (3,393 t) for the first time in 2000 (Figure 2a). Between 2000 and 2010, escaped and fisheries seabream biomass were similar; however, after 2010, the escaped biomass was much higher than the fisheries biomass. By 2020, escaped biomass was twice as large as landings (10,842 and 5,346 t, respectively, Figure 2a). Seabream landings and LPUE correlate with escaped biomass (Granger test, F = 12.7 and F = 15.4, respectively, *P*<0.001 in both cases).

Regime shift analysis detected four positive shifts in standardised seabass landings anomalies: in 1982 (+0.40), 1999 (+1.06), 2002 (+0.64), and 2020 (+0.84), and two negative shifts: in 2011 (-1.07) and 2015 (-0.63, Figure 3). Similarly, two positive shifts in LPUE anomalies were detected, one in 2004 and one in 2020 (+0.77 and + 1.00, respectively) and another negative shift in 2008 (-0.58, Figure 3). For seabream, significant positive shifts in landing anomalies were detected in 1958 (+0.94), 1964 (+0.07), 1975 (+0.68), 1992 (+0.29), 1999 (+0.65) and 2005 (+0.94, Figure 3). Additionally, a slight negative shift was detected in 1979 (-0.14, Figure 3). Positive shifts in seabream LPUE anomalies were detected in 2000 (+1.04), 2008 (+0.73), 2016 (+1.81) and 2020 (+1.81, Figure 3).

1. **DISCUSSION**

Our Mediterranean-level analysis provides solid correlative evidence that landings of seabream, an iconic fish species, are now driven by aquaculture. A landings-per-unit-of-effort (LPUE) proxy, using data from six Mediterranean EU member states, also showed significant correlations with seabream escapes, suggesting that aquaculture continues to influence landings after accounting for fishing effort. However, despite a similar pattern being evident for seabass until 2005, the relationship between landings and escapes for this species was not significant, mainly due to a large drop in landings in the last five years. We argue that relatively higher mortality rates post-escape, lower capturability by the artisanal fleet, and minor 'leakage' of farmed seabass compared to seabream may prevent the detection of escapees’ effect on landings for this species. Given the substantial declines (30%) in fisheries landings across all species in the Mediterranean (FAO 2020, 2022) and the downward trend in the number of fishing vessels across the Mediterranean and the Black Sea area over the last decades (-37% for the studied fleets since 1990), the most parsimonious explanation for the recent and rapid increase in seabass and sea bream landings is that escaped fish from aquaculture boost wild populations. Our results have significant implications for fisheries stock assessments, which escapees will continuously confound, and the genetic diversity of these species in the wild. High connectivity levels between wild and farmed populations may also contribute to epidemics of pathogens or parasites and competition for food and habitat (Arechavala-Lopez et al. 2013b, Arechavala-Lopez et al. 2018).

Globally, fish escapes are common in farming regions, including the Mediterranean Sea and the Black Sea, two of the ecoregions at most risk from farmed fish escapes (Atalah & Sanchez-Jerez 2020). Every year millions of fish escape from fish farms into Mediterranean natural coastal habitats, and the leading cause of escape incidents (>90%) is farm structural failure due to extreme weather events (Jackson et al. 2015). The situation has worsened over recent years due to record-breaking storms that hit the Mediterranean (Amores et al. 2020), and escapees continue to be one of the main concerns of both farmers and fishermen (Akyol et al. 2019).

Available evidence suggests that seabream are more prone to escape than seabass (Glaropoulos et al. 2012). Seabream actively bite farm nets when visually attracted by worn and loose threads or even biofouling organisms (Papadakis et al. 2013, Glaropoulos et al. 2014). At the same time, seabass do not display a net-biting or induced-escape behaviour as marked as seabream (Glaropoulos et al. 2014). In addition, recapturing escaped seabass is more challenging than seabream because of their better swimming and dispersion abilities and more pelagic behaviour, which would hinder recapture by artisanal fisheries using bottom gillnets and trammel nets (Arechavala-Lopez et al. 2013c, Toledo‐Guedes et al. 2014). There is little data on escaped fish survival in natural coastal habitats, but seabass escapees are more susceptible to stress due to reduced food intake and growth, resulting in a higher mortality rate in acute stress moments (e.g. escape events) compared to seabream (Samaras et al. 2018). Additionally, ‘escape through spawning’, where farmed fish reach sexual maturity and spawn in sea cages, is an additional route of escape (Uglem et al. 2012). One million 1-year-old seabream were estimated to recruit to wild populations in Greece via this escape route in 2012 (‘escape through spawning’, Somarakis et al. 2013), although the wider extent of this process through space and time in the Mediterranean is unknown. Thus, different pre- and post-escape behaviours among the two species and seabream ‘escape through spawning’ may explain the differences in the relationship between escaped biomass and landings.

Theoretically, aquaculture could alter fisheries captures in two ways: (1) fish escapes enhance conspecific wild stocks, thus maintaining and increasing captures; and (2) cheaper farmed fish flood the market, rendering wild fisheries non-profitable and thus relaxing fishing pressure (Villasante et al. 2013). However, wild and farmed fish behave as two different, unrelated products (Villasante et al. 2013). The latter together with the multi-specific nature of Mediterranean fisheries (Lleonart & Maynou 2003), prevent the flooding effect. However, the evidence points that aquaculture escapees increase landings at a regional scale (Dimitriou et al. 2007b, Glamuzina et al. 2014, Toledo‐Guedes et al. 2014, Arechavala‐Lopez et al. 2015, Izquierdo‐Gómez et al. 2017). Our analysis reflects the additive effect of many local cases across the Mediterranean Sea. Although seabream and seabass stocks are currently not formally assessed in the Mediterranean and the Black Sea area, they are essential demersal fisheries, highly vulnerable and heavily exploited (Osio et al. 2015, Froese et al. 2018). Before the introduction of aquaculture, seabream stocks were fished at levels above sustainable yield (Farrugio et al. 1994), and it is unlikely that this situation has improved (FAO 2020, 2022). In this context, escapees could mask the overexploitation of wild stocks (Hansen et al. 1999, Tsikliras et al. 2015), promoting misleading stock assessments.

The biomass of species reared in floating cages in the Mediterranean massively surpasses that of wild populations, and estimated escapees are well above fisheries’ landings. This also happens, for instance, with Atlantic salmon (*Salmo salar*) but at a scale several orders of magnitude larger (Naylor et al. 2005). Positive regime shifts in landings were detected in the early 1980s and 2000s, matching the onset of aquaculture in the Mediterranean and when estimated escapees vastly surpassed landings of both species, respectively (Figure 3). Stock assessments of Atlantic salmon are reliable because it is relatively easy and accurate to distinguish between wild and escaped fish (Fiske et al. 2005). However, since the available tools for identifying the origin of seabream and seabass are not implemented, escapees could sustain landings regardless of the state of wild stocks (Arechavala-Lopez et al. 2013a, Warren-Myers et al. 2015). Aside from the multi-specific nature and wide variety of gears used in Mediterranean fisheries, stock assessments and fisheries management occur at both regional and national levels, adding to the complexity of dealing with escapees (Smith & Garcia 2014). For the first time, we show that escapees can influence landings at a pan-Mediterranean scale, highlighting the urgent need to identify wild and escaped stocks and adjust catch records accordingly (Hansen et al. 1999).

Most restocking programs use wild broodstock to produce fish that will be released (Araki et al. 2007); thus, escape events may be defined as ‘unplanned restocking actions’ because they represent an unintentional and non-controlled release of cultured fish coming from selectively bred broodstock. How suitable farmed fish are for maintaining and improving wild populations remains unclear (Araki & Schmid 2010). Some studies point out that using farmed fish with low genetic diversity to restock small wild populations can cause introgression and loss of local adaptations, which could end in local extinctions due to genetic drift and bottlenecks (Youngson et al. 2001, Baskett et al. 2013). Both seabream and seabass are well established in the Mediterranean; in the case of seabass, its population is divided into three main genetic groups: the North-Eastern Atlantic, the Western Mediterranean and the Eastern Mediterranean (Haffray et al. 2007). However, Mediterranean haplotypes have been detected as far as the Thames estuary and Norway (Coscia & Mariani 2011), which is explained by the common use of Mediterranean hatchery strains in the Atlantic. Genetic admixture is evident between wild and farmed seabass in Cyprus, where at some locations, escapees represent up to 70% of individuals captured in the wild (Brown et al. 2015). For seabream, some genetic differentiation exists between Atlantic and Mediterranean populations (Sola et al. 2007), and genetic admixture between farmed escapees and wild populations occurs at the regional level (Šegvić-Bubić et al. 2014). Continuous escape-mediated replenishment of wild populations could affect the genetic landscape and dilute local adaptations in both species, which may compromise the sustainability of wild stocks in the long term (Youngson et al. 2001). However, for seabass, the oldest domesticated stocks have been bred in captivity for only eight generations without input from wild stocks (Chavanne et al. 2016), and most seabream broodstocks are genetically similar to wild ones (Maroso et al. 2021), which may limit the extent of genetic effects of farmed fish over wild populations. Finally, unlike proper restocking, parasites and diseases are not monitored during escape events, posing a transmission risk to wild populations (Toledo-Guedes et al. 2012, Arechavala-Lopez et al. 2013b).

Consumers have concerns that aquaculture escapees are not labelled correctly (Luque & Donlan 2019). Mislabelled escapees are sold as wild fish in local markets because discriminating tools are not applied (Arechavala-Lopez et al. 2013a). Food security could be compromised due to the antibiotic concentration that recent escapees, previously subjected to treatment, could carry (Juan‐García et al. 2007). Conversely, commercial and recreational fisheries can benefit from escape events, which can be seen as positive events in the short term. Escapees provide extra income for commercial fishers, enhancing the fishing experience and boosting recreational fishers' capture (Lorenzen et al. 2012). Together with natural mortality, both professional and recreational fisheries can play an important role in removing escapees from the wild (Toledo‐Guedes et al. 2014). Although the overall impact may be low (Dempster et al. 2018), the inclusion of recapture actions in future contingency plans could boost the effectiveness of fisheries in preventing the entrance of farmed fish labelled as wild in the markets.

While technical standards in farm designs have been implemented in Norway and Scotland (Jensen et al. 2010); there is a clear need to implement these standards to prevent escapes in Mediterranean countries, to avoid impacts on the functioning and structure of marine ecosystems and promote the industry's sustainable development. Mitigation measures, including monitoring plans aiming to identify escaped fish both in the wild and within fisheries landings, are needed to address the fishing actions contained in a contingency plan removing escapees from the wild or to label escaped fish entering the food chain correctly. These measures would, in turn, improve the reliability of wild stock assessments for the correct resource management and food safety.

1. **ACKNOWLEDGEMENTS**

KT-G was supported by a postdoctoral tenure program, Juan de la Cierva Formación (FJCI-2014-20100) and Juan de la Cierva Incorporación (IJCI-2017-34174), funded by Spanish National Research Agency. A Maria Zambrano Grant financed by the Spanish Government through the European Union NextGenerationEU fund supported JA. PA-L was supported by a postdoctoral tenure program, Juan de la Cierva Incorporación (Ref. IJCI-2015-25595) and Ramon y Cajal (Ref. RYC2020-029629-I), funded by Spanish National Research Agency. The study was funded by the project “GLObal change Resilience in Aquaculture-2 (GLORiA2),” supported by the Biodiversity Foundation of the Spanish Ministry for the Ecological Transition and Demographic Challenge through the Pleamar Program and co-financed by the European Maritime and Fisheries Fund (EMFF). The study also forms part of the LIFE IP INTEMARES Project “Integrated, innovative and participatory management of the Natura 2000 Network in the Spanish marine environment”, and the ThinkInAzul programme, which MCIN supports with funding from European Union NextGenerationEU (PRTR-C17.I1) and by Generalitat Valenciana (THINKINAZUL/2021/044-TOWARDS).

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1. **FIGURE CAPTIONS**

Figure 1. Temporal trends in fisheries landings (blue lines) and aquaculture production (red lines) in the Mediterranean and Black Sea area for seabass (Dicentrarchus labrax, left panel) and seabream (Sparus aurata, right panel). Data source FAO 2022.

Figure 2. Temporal trends in a) fisheries landings (red lines),b) landings-per-unit-of-effort (LPUE) vs estimated fish escapes biomass from aquaculture farms (blue lines)in the Mediterranean Sea and Black Sea for seabass (*Dicentrarchus labrax,* left panels) andseabream (*Sparus aurata*, right panels)*. F*and *P*-values for Granger’s causality tests are shown in the respective panel.

Figure 3. Regime shift index (dotted lines) for the standardised fisheries landings anomalies (solid blue lines) and standardised landings-per-unit-of-effort (LPUE, solid red lines) for seabass (*Dicentrarchus labrax,* left panels) andseabream (*Sparus aurata*, right panels) in the Mediterranean Sea and Black Sea.

Chart, line chart

Description automatically generated

Figure 1.

Chart

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Figure 2.

Chart, histogram

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Figure 3.