SCIENTIA MARINA 88 (4)
December 2024, e089
ISSN-L: 0214-8358, eISSN: 1886-8134
https://doi.org/10.3989/scimar.05546.089

Influence of climate drivers and fishing effort on fish stock condition using dynamic factor analysis: a case study from the Caspian Sea

Hasan Fazli [1], Gholam Reza Daryanabard [1], Akbar Pourgholami [2], Seyed Abbas Hoseini [3], Mohammad Reza Mirzaei [4], Parto Bahreini [5]

[1] Caspian Sea Ecology Research Centre, Iranian Fisheries Science Research Institute, Agricultural Research, Education and Extension Organization (AREEO), Sari, Iran.
(HF) (Corresponding author) E-mail: h.fazli@areeo.ac.ir. ORCID iD: http://orcid.org/0000-0003-1172-105X
(GRD) E-mail: daryanabard@gmail.com. ORCID iD: http://orcid.org/0000-0002-5099-9196
[2] Inland Waters Aquaculture Research, Iranian Fisheries Science Research Institute, Agricultural Research, Education and Extension Organization (AREEO), Anzali, Iran.
(AP) E-mail: pourgholami_yas@yahoo.com. ORCID iD: http://orcid.org/0000-0002-5020-7523
[3] Inland Water Stocks Research Centre, Iranian Fisheries Science Research Institute, Agricultural Research, Education and Extension Organization (AREEO), Gorgan, Iran.
(SAH) E-mail: ab_hossaini@yahoo.com ORCID iD: https://orcid.org/0000-0003-3650-2945
[4] Offshore Fisheries Research Centre, Iranian Fisheries Science Research Institute, Agricultural Research, Education and Extension Organization (AREEO), Chabahar, Iran.
(MRM) E-mail: mirzaei.mr@gmail.com. ORCID iD: https://orcid.org/0000-0003-0885-162X
[5] Colangelo College of Business, Grand Canyon University, Phoenix, Arizona, USA.
(PB) E-mail: parto.bahreini97@gmail.com. ORCID iD: http://orcid.org/0009-0000-1476-2020

Summary: We explored the potential impact of climate-driven factors [East Atlantic-West Russian pattern, sea surface level (SSL), sea surface temperature (SST) and river discharge] alongside fishing effort (E) on shifts in aquatic species demographics. Dynamic factor analysis (DFA) was employed for indices of annual catch (Cat), Abundance (Abu), fingerlings released, spawning stock biomass (SSB), percentage of immature (Imm), mega spawners and relative condition factor from datasets of *Chelon aurata* and *Rutilus kutum* over 30 years. Of 324 DFA models, the optimal model for both species included a "diagonal and unequal" R matrix with SST, SSL and E as exploratory covariates, revealing one common trend for *C. aurata* and SST and SSL and two common trends for *R. kutum*. Within the common trend for *C. aurata*, Abu and SSB displayed a strong positive correlation with trend 1. In the case of *R. kutum*, the first common trend showed a positive correlation with Cat, Abu, and SSB and a negative one with Imm. Also, rising SST and decreasing SSL negatively affect species' health. This study emphasizes integrated monitoring and management to sustain fish species and the ecosystem, advocating adaptive strategies to counter environmental stressors and anthropogenic effects.

Keywords: Abundance, condition factor, overfishing indicators, climate-driven, fishing effort, dynamic factor analysis, coastal waters.

Influencia de los factores climáticos y del esfuerzo pesquero en la condición de las poblaciones de peces mediante el análisis factorial dinámico: un estudio de caso del mar Caspio

Resumen: Exploramos el impacto potencial de factores climáticos (patrón Atlántico Este-Oeste de Rusia EA_WR, nivel de la superficie del mar SSL, temperatura de la superficie del mar SST, descargas fluviales RD) junto con el esfuerzo pesquero E en los cambios en la demografía de las especies acuáticas. Se empleó el análisis factorial dinámico (DFA) para los índices de captura anual Cat, abundancia Abu, alevines liberados FR, biomasa del estoc reproductor SSB, porcentaje de inmaduros Imm, mega-reproductores Meg y factor de condición relativa Kn de los datos de *Chelon aurata* y *Rutilus kutum* recogidos durante 30 años. De 324 modelos DFA, el modelo óptimo para ambas especies incluyó una matriz R "diagonal y desigual" con SST, SSL y E como covariables exploratorias, revelando una tendencia común para *C. aurata* y SST y SSL con dos tendencias comunes para *R. kutum*. Dentro de la tendencia común para *C. aurata*, Abu y SSB mostraron una fuerte correlación positiva con la tendencia 1. En el caso de *R. kutum*, la primera tendencia común mostró una correlación positiva con Cat, Abu y SSB, y una relación negativa con IMM. Además, el aumento de SST y la disminución de SSL afectan negativamente la condición de las especies. Este estudio enfatiza el monitoreo y la gestión integrados para sustentar las especies de peces y el ecosistema, abogando por estrategias adaptativas para contrarrestar los factores de estrés ambiental y los efectos antropogénicos.

Palabras clave: Abundancia, factor de condición, inmaduros, grandes reproductores, factores impulsados por el clima, esfuerzo pesquero, análisis factorial dinámico, aguas costeras.

Citation/Como citar este artículo: Fazli H., Daryanabard G.R., Pourgholami A., Hoseini S.A., Mirzaei M.R., Bahreini P. 2024. Influence of climate drivers and fishing effort on fish stock condition using dynamic factor analysis: a case study from the Caspian Sea. Sci. Mar. 88(4): e089. https://doi.org/10.3989/scimar.05546.089

Editor: J. Salat.

Received: May 16, 2023. **Accepted:** August 12, 2024. **Published:** February 25, 2025.

INTRODUCTION

Climate change and human disturbance have significantly impacted the Caspian Sea (CS) over recent decades (Karpinsky et al. 2005). In addition to occurring over a range of spatial and temporal scales, these effects alter marine ecosystem structure and function under a combination of local and global pressures (Mackinson and Daskalov 2007). Sea surface level (SSL) and rising sea water temperatures are two environmental factors driving changes in the Caspian ecosystem that affect the fish abundance and community structure (Beyraghdar Kashkooli et al. 2017, Fazli et al. 2021, 2022a).

The ichthyofauna of the whole Caspian basin includes 159 species (Naseka and Bogutskaya 2009), of which 119 species belong to 63 genera that were reported in the southern CS basin (Esmaeili et al. 2018). In this region, *R. kutum*, *C. aurata*, and other bony fishes such as *Cyprinus carpio*, *R. rutilus*, *Vimba vimba* and *Alburnus chalcoides* are the most frequently caught species using the beach seine method (Fazli et al. 2022a). During the last three decades, the annual catch of bony fishes ranged from 10910 t to 23800 t. The species *R. kutum* and *C. aurata* are among the most important commercial fish, comprising 60.5% and 21.7% of the total catch, respectively, and together accounting for more than 90% of total income.

R. kutum is a migratory anadromous fish endemic to the sea and spreads throughout the Caspian basin, mainly in the southern CS (Valipour and Khanipour 2006, Fazli et al. 2022a). Its spawning occurs in April (Daryanabard et al. 2020). This bottom-feeding species consumes a variety of prey items, primarily bivalves and cirripeds (Afraei Bandpei et al. 2009).

C. aurata, identified as the second important species (Fazli et al. 2022a), was introduced as an exotic species from the Black Sea between 1930 and 1934. Being euryhaline and eurythermic, *C. aurata* feeds on periphyton, detritus and invertebrates found throughout the CS. During spring, it tends to migrate to the northern regions, while in autumn, it moves towards the southern regions (Probatov and Tereshchenko 1951, Fazli et al. 2013). Unlike *R. kutum*, *C. aurata* is catadromous and spawns mainly in October and November (Fazli et al. 2008). During the past two decades, both *C. aurata* and *C. saliens* have experienced severe disease outbreaks, resulting in high mortality rates. A nodavirus-like agent has been isolated from both species, exhibiting clinical signs such as severe abdominal distention, abnormal swimming and hyperinflation of the swim bladder (Zorriehzahra et al. 2005, Soltani et al. 2010, Ghiasi et al. 2016).

Time series studies of population biological data for aquatic species are critical for managing the related ecosystems. These studies are valuable in several ways, including the fact that they can help establish baselines and provide insights into the patterns and factors that influence population patterns and their effects. Understanding how environmental variability and anthropogenic stressors affect long-term population dynamics will enable us to manage better and conserve ecosystems and species. Long-term changes in populations can be comprehended by employing multivariate time series analyses. Dynamic Factor Analysis (DFA) is a valuable tool for examining ecological time series data and identifying common population trends. DFA can also be utilized to evaluate the covariance among multiple ecological time series (Zuur et al. 2003). Furthermore, numerous studies have utilized DFA to assess the influence of environmental variables on ecological indices (Jorgensen et al. 2016, Barber et al. 2019, Bitetto et al. 2019). In a recent study in the southern CS, DFA was used to determine the impact of environmental variables on sturgeon populations (Fazli et al. 2022b), but DFA has never been applied to the two main Caspian benthopelagic fish stocks (*C. aurata* and *R. kutum*) in this ecosystem.

The objective of the present study was to analyse the trends of biological indicators for *C. aurata* and *R. kutum* in the southern CS. We used DFA to assess the relative synchrony of total catch and abundance, spawning stock biomass (SSB), percentage of immature and mega spawners, and relative condition factor. Also, for *R. kutum* the seventh response variable “fingerling released” was added to the models. The aims of the study were i) to analyse the trends of biological indicators, ii) to investigate the influence of environmental factors [SSL, seawater surface temperature (SST), the East Atlantic-West Russian pattern and river discharges], and anthropogenic activity (fishing effort) on the variability of *C. aurata* and *R. kutum* bio-indicators over the past three decades. These findings will help to better understand the Caspian ecosystem and aid in the formulation of effective fisheries management strategies.

MATERIALS AND METHODS

Study area and sampling

The CS is generally divided into northern, middle and southern parts. The present study focuses on the deeper southern part of the CS, specifically Iranian waters, where more than 120 Iranian beach seine fishing cooperatives are engaged in fishing activities targeting bony fishes, especially *R. kutum* and mullets (Fig. 1). The beach seines have not undergone major technological improvements during the study period. Each seine is about 1200 m long and 10–20 m high, with a cod-end bag consisting of mesh sizes of 30 and 33 mm. The net height of the seines depends on the slope conditions of the sea bed, with the shortest seines being used in the eastern area. The hauling is conducted by a vessel with a length of approximately 16 m and a tonnage of approximately 20 t. Mean hauling times are about 3 hours, and the number of hauls range from 1 to 6 per day (mostly 2 to 3). The catch occurs from early morning until nighttime (about 9 p.m.). The fishing season commences in October with a mean SST of 22.6±0.8°C and concludes in April with a mean SST of 14.1±1.21°C (Fazli et al. 2022a; Fig. 2). The fish samples were collected between 1991 and 2020. Archival data of a total of 117476 *C. aurata* and 166006 *R. kutum* specimens were obtained from the Iranian Fisheries Science Research Institute (IFSRI) and used as input data. Each individual was measured to the nearest 1 cm in fork length and the nearest 10 grams of body weight.

Biological variables

Six response variables of stock indices, including total catch (Cat) and abundance (Abu), SSB, percentage of immature (Imm) and mega spawners (Meg), and relative condition factor (Kn) of *C. aurata* and *R. kutum*, as well as fingerlings released (FR) for *R. kutum* from 1991 to 2020, were surveyed in this study (Table 1). The Kn was calculated to assess the condition of different fish species. Kn was calculated by using the formula W_o/W_c, where Wo is the weight observed, and Wc is the weight calculated based on the length-weight relationship (Table 2). According to Froese (2004), the percentages of Imm and Meg serve as stock condition indicators, defined respectively as the frequency of fish samples with a length lower than $L_{m50\%}$ (mean lengths at 50% maturity) and the frequency of fish with a length greater than L_{opt} (optimum length)+10% (Table 2). The maturity ogive for *C. aurata* females was 0.20, 0.63, 0.88 and 0.97 at ages 3, 4, 5 and 6 (Fazli et al. 2008), and for *R. kutum* it was 0.08, 0.60 and 0.90 for ages 3, 4 and 5, respectively (Afraei et al. 2009). The older ages of both species were the age at full maturity. The time series data of Abu and SSB were obtained from studies on the stock assessment of bony fishes conducted by the IFSRI using cohort analysis (Pope 1972). By multiplying the biomass with the female's maturity index (Fazli et al. 2008; Afraei et al. 2009), SSB estimations were generated in metric tons from the biomass. The Cat and FR provided by the Iranian Fisheries Organization were used as input data.

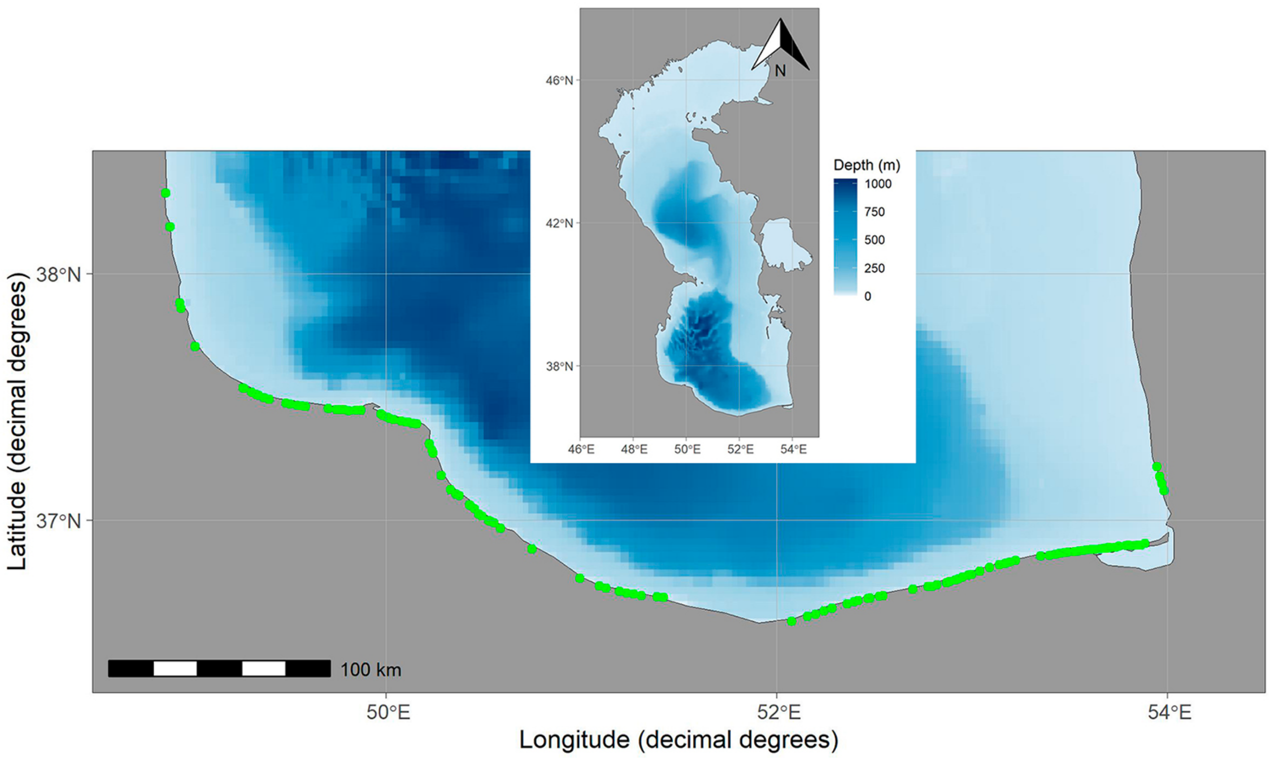

Fig. 1. – Map of the study area. The green-filled circles show the beach seine locations.

Table 1. – Summary of the biological indices and source of data.

Variable		Period	Source
Cat	Catch	Monthly	Iranian Fisheries Organization
FR	Fingerlings released	Annually	
Abu	Abundance	Annually	Produced by the authors, using the archival data from the Iranian Fisheries Science Research Institute
SSB	Spawning stock biomass	Annually	
Imm	Percentage of immature	Annually	
Meg	Percentage mega spawners	Annually	
Kn	Relative condition factor	Annually	

Table 2. – The length-weight relationship values, $L_{m50\%}$ and L_{opt}, were used to estimate the relative condition factor and percentage of immature and mega spawners for two benthopelagic fish species in the Caspian Sea.

Species	*a* (constant)	*B* (slope)	$L_{m50\%}$ (cm)	L_{opt} (cm)	Reference
Rutilus kutum	1.0104	3.043	*37.8	**44.0	*Afraei Bandpei 2009; **Fazli et al. 2012
Chelon aurata	0.0251	2.749	*26.0	35.3	*Fazli et al. 2008

Table 3. – Summary of the monthly environmental variables and source of data.

Scale	Variable		Source
Global	EA-WR	East Atlantic-West Russian	https://catalog.data.gov
Regional	SST	Sea surface temperature	https://neo.sci.gsfc.nasa.gov
	SSL	Sea surface level	Caspian Sea National Research Centre
Local	RD	River discharge	Caspian Sea National Research Centre
	E	Fishing effort	Iranian Fisheries Organization

Explanatory variables

The effects of four environmental variables on the long-term trends in fish stock indices of *C. aurata* and *R. kutum*, including one global variable with large-scale influence, the East Atlantic-West Russian pattern (EA_WR), two regional variables, SST and SSL, one local variable, the sum of river discharges of Sefidrood, Polrood, Chalos and Haraz (RD), and one anthropogenic activity, beach seine hauling (E), were analysed over the period 1991 to 2020. In order to calculate the regional index for the period 1991 to 2020, monthly averaged SST data with resolution 0.1° × 0.1° (obtained from the NOAA website, https://neo.sci.gsfc.nasa.gov) was used. The monthly averaged SSL and RD data from the Caspian Sea National Research Centre, EA_WR obtained from https://catalog.data.gov, and E from the Iranian Fisheries Organization were used in this study (Table 3).

Univariate analysis

Analyses were conducted for annual time series data of each fish stock condition and environmental variables. The trend of the variables was analysed after smoothing with the LOESS method. The breakpoints technique was applied to annual data using the "strucchange" package of R software, and an algorithm was employed to test for structural changes and investigate interannual variabilities. The determination of the optimal number of segment partitions was based on the Bayesian information criterion, which allowed for the identification of the most significant changes (Zeileis et al. 2002). Also, a Pearson correlation matrix was calculated between the three-decade time series of the response variables and five explanatory parameters using the "corrplot" package of R software for both species.

Dynamic factor analysis

The DFA model consists of four components: common trends (M), explanatory variables, a level parameter and a noise component (Zuur et al. 2003). In this study, four hypotheses related to the covariance matrix (R) of the observation error were tested: diagonal-equal, diagonal-unequal, equalvarcov and unconstrained. Additionally, various DFA models were employed, incorporating up to three common trends (1, 2 and 3). The response data Cat and Abu were log-transformed to attempt to normalize their distribution. All response and explanatory variables were standardized to have a zero mean and unit variance.

The configuration of the DFA model, considering six response variables and three common trends, was expanded by incorporating five explanatory variables with varying numbers of covariates (ranging from 0 to 5) for each fish species, resulting in 324 tested models. The environmental variables for both species were SSL, SST, RD, E, and EA_WR. The efficiency of the models was evaluated using the Akaike information criterion corrected for small sample size, following the guidelines of Burnham and Anderson (2002), Zuur et al. (2003) and Holmes et al. (2021).

To determine whether a series was associated with a trend, an arbitrary cutoff level of 0.2 was selected for loadings, as suggested by Zuur et al. (2003). The assumptions of normality and independent observation errors for the residuals of the selected models were assessed to validate the obtained models (Figs S1 and S2). For univariate analyses, the R software (R Core Team, 2020) was utilized along with the strucchange (Zeileis et al. 2002), corrplat (Wei and Simko, 2021), and ggplot2 (Wickham 2016) R libraries. The MARSS R library (Holmes et al. 2021) was employed for the DFA analysis.

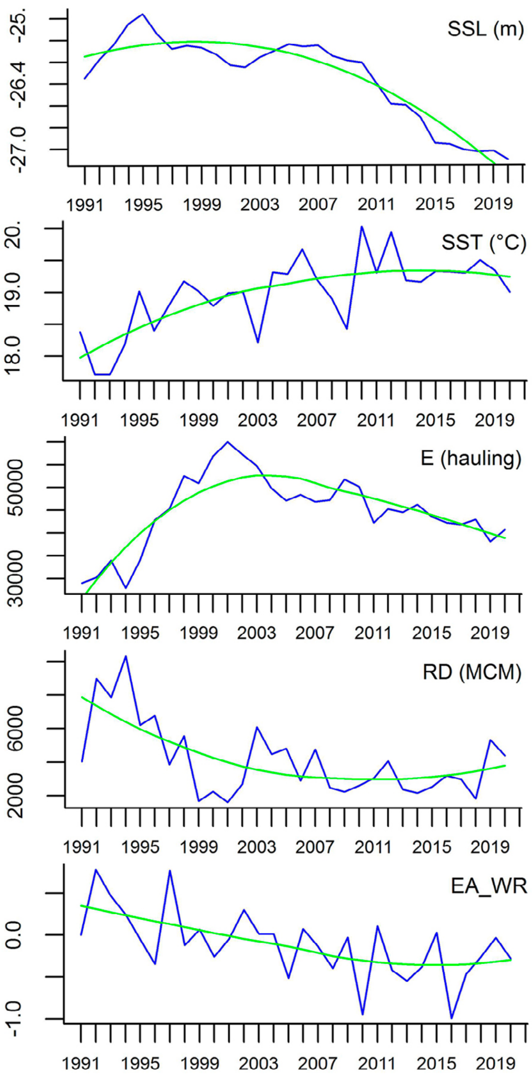

Fig. 2. – Time series environmental parameters of sea surface level (SSL), sea surface temperature (SST), fishing effort (E), river discharge (RD), and East Atlantic-West Russian pattern (EA_WR) in the period 1991-2020. The green curve is the loess-smoothed trend.

RESULTS

Environmental variables

In Figures 2, 3 and 4, the corresponding environmental variables and multispecies biological time series data indicate large annual fluctuations. For environmental data, the summarized statistics (average ± sd) for SSL, SST, E, RD, and EA_WR were -26.3±0.40 m, 19.0±0.57°C, 44837.8±8178.2 hauls, 4135.2±2210.51 million cubic metres and -0.11±0.40. The annual SSL time series showed a clear decrease from 1994 (Fig. 2). The annual SST displayed an increasing trend over the entire period. The E increased to the highest in 2002 and then followed a decreasing trend. RD and EA_WR displayed a negative long-term trend (Fig. 2).

Biological time series data

For biological data, the summarized statistics for Cat, Abu, SSB, Imm, Meg and Kn of *C. aurata* were 3277.0±1332.2 t, 63.4±18.99 10^6 ind, 7880.4±3119.1t, 11.9±4.76%, 19.2±6.83% and 1.02±0.04, respectively, and the Cat, Abu, FR, SSB, Imm, Meg and Kn of *R. kutum* were 9943.2±2931.0 t, 123.30±32.27 10^6 ind, 188.20±63.81 10^6 ind, 26202.4±6904.8 t, 45.2±6.71%, 7.4±2.09% and 1.06±0.06, respectively (Figs 3 and 4).

For *C. aurata*, Cat attained the maximum at 6599 t in the year 2002 and the minimum at 1425 t in the year 1994, indicating two breakpoints in 1998 and 2008. The maximum Abu and SSB were observed to be 97.1 10^6 ind and 12583 t in 2001 and 2000, respectively, while the minimum Abu and SSB were 38.3 10^6 ind and 2925.2 t in 2015 and 2019, respectively. Four discontinuities were detected for Abu (in 1998, 2004, 2008 and 2012), and SSB showed four breakpoints in 1997, 2003, 2007 and 2012 (Fig. 3).

For *R. kutum*, the maximum Cat was 17196 t in 2007, Abu was 193.0 10^6 in 2006, and SSB was 37624 t in 2006. The minimum recorded values were 6133 t for Cat, 57.2 10^6 ind for Abu, and 14552 t for SSB, in 2020. Four breakpoints were detected for Cat (1997, 2006, 2009 and 2015), Abu showed four breakpoints in 1995, 2003, 2012 and 2017, and SSB showed three breakpoints in 1996, 2005 and 2015 (Fig. 4). The maximum and minimum of FR were 400 10^6 ind in 2009 and 97 10^6 ind in 1992, with three breakpoints in 2001, 2009 and 2013.

The maximum and minimum of Imm were 24.0% in 1994 and 3.9% in 2009, with two breakpoints in 2002 and 2017 for *C. aurata* and 56.5% in 2017 and 31.3% in 2014 for *R. kutum*, with two breakpoints in

2010 and 2015. The Meg ranged between 8.5% in 2015 and 31.9% in 1999, averaging 11.9±4.8% for *C. aurata* and between 3.5% in 2008 and 13.0% in 1991, averaging 45.2±6.7% for *R kutum*. Two discontinuities were detected for *C. aurata* in 1996 and 2012, and *R kutum* in 2003 and 2008, respectively. For both species, Kn time series data displayed a clear decreasing trend and showed three breakpoints in 1995, 2005 and 2010 for *C. aurata* and in 1997, 2002 and 2010 for *R. kutum* (Figs 3 and 4).

Correlation analysis

The Pearson correlation coefficient showed several weak correlations among explanatory variables (Figs 5 and 6). Among the six response time series data of *C. aurata*, one of the Cat, SSB, Meg and Kn had a positive significant correlation with at least one of the SSL, E, and SST environmental variables (except for the correlation of Kn and SST, which was negative; Fig. 5). In the case of *R. kutum*, the only correlations were Kn with SSL, SST, RD, and FR with SST (Fig. 6).

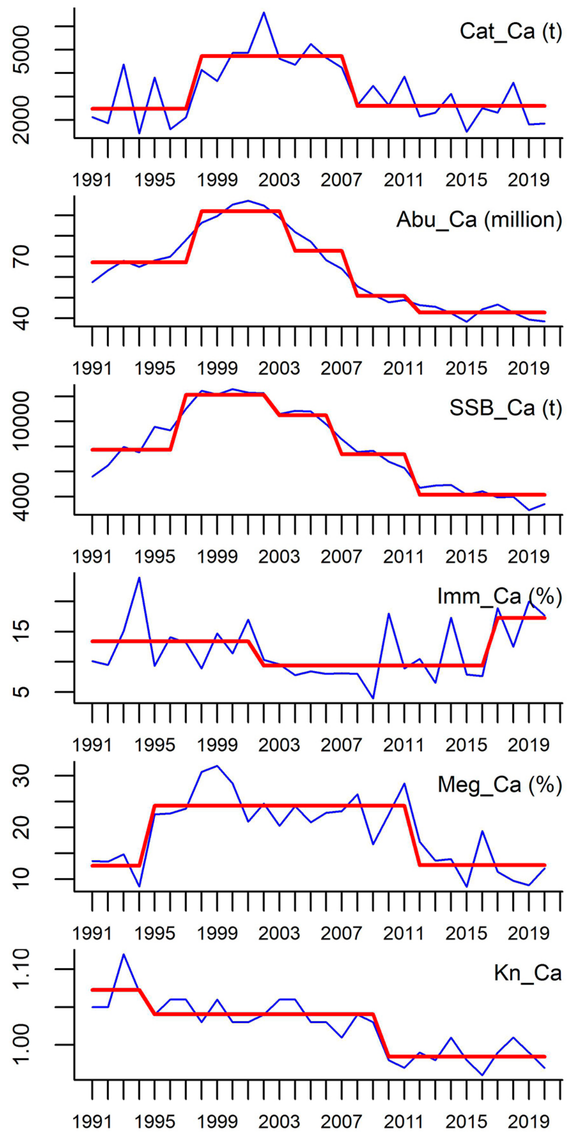

Fig. 3. – Time series annual catch (Cat), abundance (Abu), spawning stock biomass (SSB), percentages of immature (Imm) and mega spawners (Meg) and relative condition factor (Kn) of *Chelon aurata* (Ca) of the Caspian Sea. The red lines represent the mean values between breakpoints.

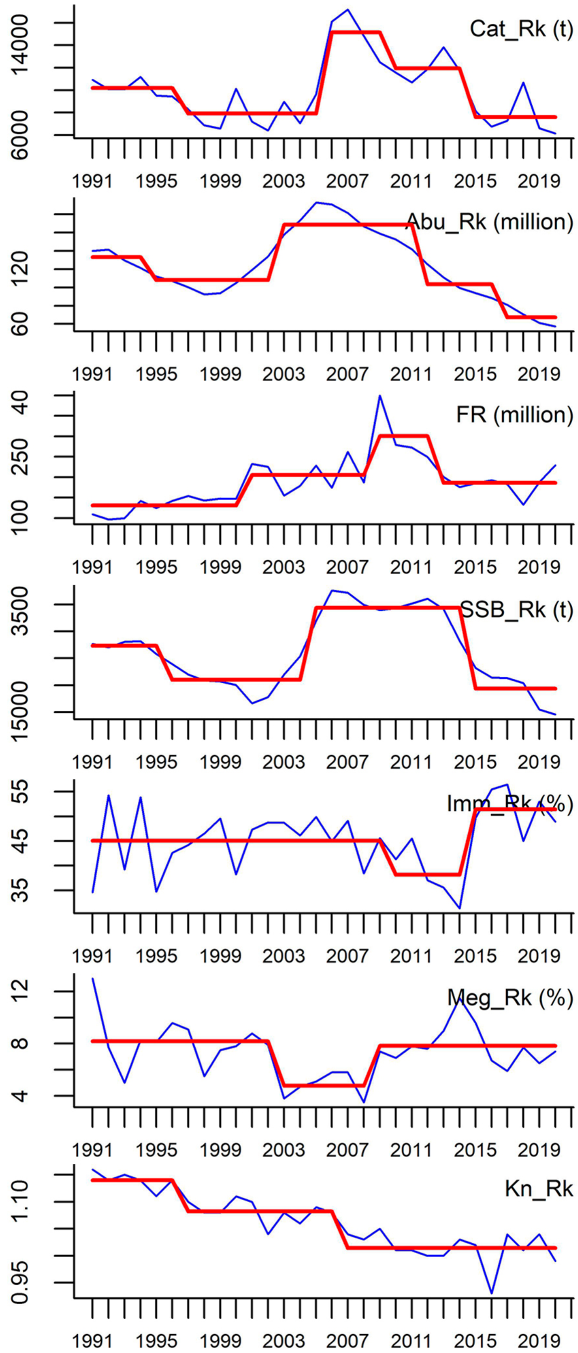

Fig. 4. – Time series annual catch (Cat), abundance (Abu), fingerlings released (FR), spawning stock biomass (SSB), percentages of immature (Imm) and mega spawners (Meg) and relative condition factor (Kn) of *Rutilus kutum* (Rk) of the Caspian Sea. The red lines represent the mean values between breakpoints.

Table 4. – The top 15 DFA models ranked in order of decreasing data support Akaike information criterion corrected for small sample size (AICc)]. The “M” values are different numbers (1–3) of common trends, and “R” represents the different combinations of measurement error covariance matrix structures. Covariate abbreviations are defined in Figure 2, and the best model is indicated in boldface.

Species	M	Environmental covariates	R	AICc	Δ AICc
Chelon aurata	**1**	**SST, SSL, E**	**diagonal and unequal**	**284.2**	**0.0**
	1	E	diagonal and unequal	289.9	5.6
	2	E	diagonal and unequal	290.4	6.1
	1	SST, SSL, RD	diagonal and unequal	292.5	8.2
	2	SSL	diagonal and unequal	293.1	8.8
	1	SSL, E	diagonal and unequal	293.1	8.9
	2	SST, E	diagonal and unequal	293.2	8.9
	2	SSL, E	diagonal and unequal	293.9	9.6
	2	Nocov	diagonal and unequal	296.0	11.8
	2	SST, SSL, E	diagonal and unequal	296.6	12.4
	2	SST	diagonal and unequal	296.9	12.6
	1	SST, SSL, E, RD	diagonal and unequal	296.9	12.7
	1	SST, SSL	diagonal and unequal	298.5	14.2
	1	SST, SSL, E, EAWR	diagonal and unequal	298.9	14.7
	3	Nocov	diagonal and unequal	299.0	14.7
Rutilus kutum	**2**	**SST, SSL**	**diagonal and unequal**	**442.8**	**0.0**
	3	Nocov	diagonal and unequal	443.1	0.2
	3	RD	diagonal and unequal	445.4	2.6
	2	SST, SSL, RD	diagonal and unequal	449.3	6.5
	2	E	diagonal and unequal	450.3	7.4
	2	SST, SSL, E	diagonal and unequal	451.2	8.4
	2	SSL	diagonal and unequal	453.2	10.4
	2	SSL, RD	diagonal and unequal	453.4	10.6
	3	SSL	diagonal and unequal	453.8	11.0
	3	E	diagonal and unequal	454.5	11.6
	3	SSL, RD	diagonal and unequal	455.5	12.6
	3	SST	diagonal and unequal	456.6	13.7
	3	EAWR	diagonal and unequal	459.4	16.6
	2	SST, SSL, EAWR	diagonal and unequal	459.6	16.8
	2	SST	diagonal and unequal	460.2	17.4

Dynamic factor analysis

Different DFA models were constructed, incorporating five environmental variables to establish a “multispecies-covariate” relationship with biological time series data. Of the 324 different models examined, the best model for *C. aurata* was identified as having a “diagonal and unequal” R matrix, one common trend and exploratory covariates of SST, SSL and E (Table 4). In contrast, for *R. kutum*, the best model was found to have a “diagonal and unequal” R matrix, two common trends and exploratory variables of SST and SSL (Table 4).

Figure 7 shows the patterns of common trends for *C. aurata* and *R. kutum*. For *C. aurata*, trend 1 exhibited a rapid increase from 1991 to 2001, followed by a sharp decline until 2015. Notably, this trend is positively related to all indices, and only Abu and SSB showed a strong positive correlation (factor loadings above ±0.2) with trend 1 (Fig. 7). For *R. kutum*, trend 1 exhibited a consistent decreasing trend from 1991 to 2001, increasing in 2011, followed by a decline until 2020 (Fig. 7). This common trend showed a strong positive relation with Cat, Abu, and SSB and a negative one with Imm. Trend 2 showed a pattern with a shorter decrease period from 1991 to 1999, followed by a rap-

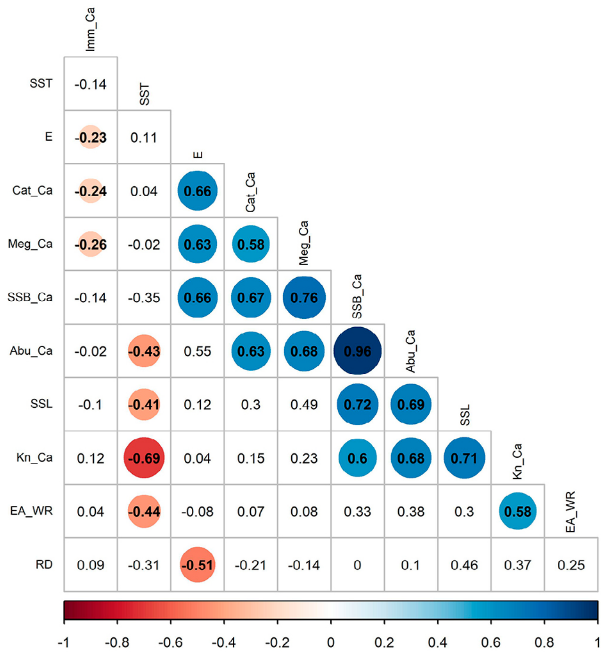

Fig. 5. – Correlations between the time series data for *Chelon aurata*. The significant correlations (p<0.05) are indicated in bold and coloured. See Figures 2 and 4 for a key to biological parameters and species name abbreviations.

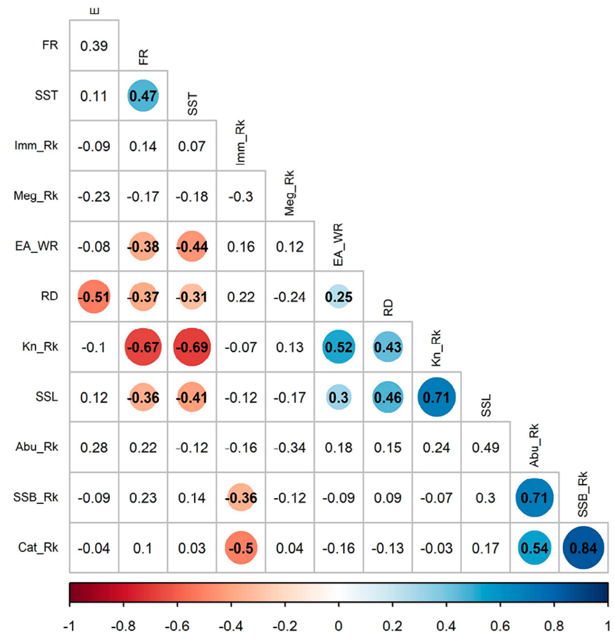

Fig. 6. – Correlations between the time series data for *Rutilus kutum*. The significant correlations (p<0.05) are indicated in bold and coloured. See Figures 2 and 4 for a key to biological parameters and species name abbreviations.

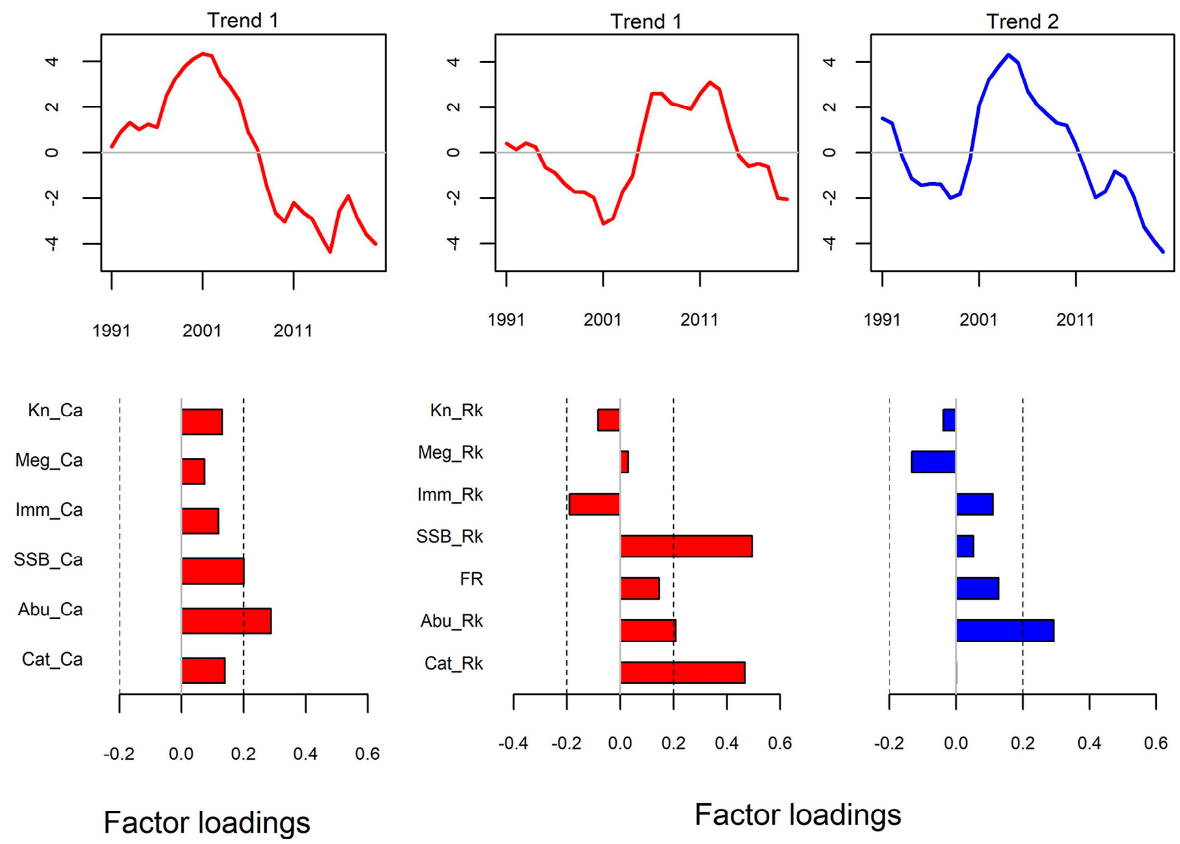

Fig. 7. Estimated trends (top row) and factor loadings per trend (bottom row) for the best-fitting model. Factor loadings greater than ±0.2 (indicated by the vertical dashed line) highlight species that significantly influenced the common trend. See Figures 2 and 4 for a key to biological parameters and species name abbreviations.

id increase peaking in 2005, and then a rapid decrease with the lowest level in 2020. This trend was positively related with Abu (Fig. 7). This observation suggests that these trends were relatively favourable for the time series of both species for most stock conditions. Figure 8 displays the standardized observed values and the model fitted to the stock condition index time series. The observed and predicted values demonstrate a high level of agreement for *C. aurata* and *R. kutum*.

DISCUSSION

The benthopelagic species (*C. aurata* and *R. kutum*) feed mainly on detritus and macrobenthos, and they could be impacted by the changes in the quality and quantity of the CS benthic community. Because benthic time series are rare in the study area, we used different environmental variables that affect the production and structure of both benthic and benthopelagic fish.

Many factors influence the condition of ecosystems in the CS. In the last century, the deterioration in the environmental conditions in the sea can be attributed primarily to changes in SSL and the volume of water entering local rivers, as well as pollution from a wide range of sources such as petroleum hydrocarbons and phenols (Kosarev 2005). Based on our experience and previous studies, since the 1990s three significant challenges have emerged as major threats to this ecosystem: illegal fishing and overfishing, exotic species invasion and global warming. These notable anomalies pose a direct threat because they lead to spatiotemporal gradients in the abundance of target species and habitat destruction. Additionally, they pose an indirect threat by affecting community structure and producing differential effects on functional groups. As a result, these challenges pose significant risks to the structure and function of the Caspian ecosystem (Pourang et al. 2016, Shiganova et al. 2023).

Given these challenges and their impact on the ecosystem, it is critical to examine the population dynamics of key species alongside environmental variables to gain insights into ecosystem health. In this study, we estimated six population indices, including Cat, Abu, SSB, Imm, Meg and Kn of two valuable benthopelagic species (and one more index of FR for *R. kutum*) from 1991 to 2020, which are useful for defining changes in their populations. Through DFA analysis, we examined common trends in the biological indices of each species. This approach allowed us to identify common trends and investigate their correlations with environmental indices. The results strongly supported the hypothesis that most biological indices of both species exhibit interannual patterns influenced by environmental variables. Notably, the patterns observed in the stock condition indices of the two benthopelagic fish displayed distinct trends over the past 30 years, which could potentially be linked to regional and local climate indices. The selected models identified one common trend with the exploratory covariates of SST, SSL and E for *C. aurata* and two common trends with the exploratory covariates of SST and SSL for *R. kutum* in the datasets spanning 30 years from 1991 (Fig. 7). Also, according to Zuur et al. (2003), if the covariates were not selected in the best models, it does not mean that these covariates did not affect the time series. The current study showed a strong negative correlation between Kn and SST and a strong positive correlation between Kn and SSL of both species.

The increasing trend of SST has been reported in several global studies conducted over the past decades (Barber et al. 2019, Bitetto et al. 2019, Feuilloley et al. 2020), which could be attributed to climate change (Xu et al. 2021). The increases in SST contribute to other environmental changes: noteworthy examples include the recruitment of *R. kutum* and *C. aurata* in response to the changes in SST in the late 1990s (Beyraghdar Kashkooli et al. 2017). Additionally, the declining recruitment and SSB of two small pelagic fish species, *Clupeonella engrauliformis* and *C. grimmi*, in the 2000s were influenced by SST and SSL (Fazli et al. 2021).

Kn serves as an indicator of environmental suitability, providing insight into the overall well-being and feeding activity of fish within a water body. A decrease in Kn below 1 signifies a decline in condition and feeding activity (Bagenal and Tesch 1978, Anderson and Neumann 1996, Sutton et al. 2000). According to the present study, the Kn of both species has shown a decreasing trend over the past three decades. However, only the Kn of *C. aurata* has declined, falling below 1 since the 2010s (Fig. 3), which coincides with a reduction in SSL. On the other hand, about 60% of the surface area of the CS is covered by its shelf zone. Therefore, the decrease in SSL has affected a wide area of the shelf zone, especially the North Caspian (covered by shallow waters), and can have a strong impact on the nutrition of the *C. aurata* that migrate to the North Caspian for feeding.

According to Ghasemi et al. (2014), following the invasion of *Mnemiopsis leidyi* into the Caspian ecosystem in the late 1990s, the composition of Caspian macrobenthos has undergone significant changes. Under the new conditions, numerous endemic macrobenthic species were displaced by the non-native species *Streblospio gynobranchiata* in the 2000s. As a result, the benthopelagic fish species, including *C. aurata* and *R. kutum*, have experienced substantial alterations in their diets over the past two decades, leading to a reduction in their Kn.

Meg is an indicator of population structure where there is no upper size limit for captures (in the case of both species in this study), with 30% to 40% of Meg representing a healthy population structure (Froese 2004). In the present study, the Meg of *C. aurata* was more than about 20% in 1994–2010, dropping to around 15% in the 2010s, and the Meg of *R. kutum* was less than 13%. Consequently, based on the Meg indicator, both species show an unhealthy population structure. Froese (2004) suggested that all of the harvested fish should be from mature fishes (Imm should be 0%) as a target. Based on this study, approximately 12% of *C. aurata* and 45% of *R. kutum* were immature

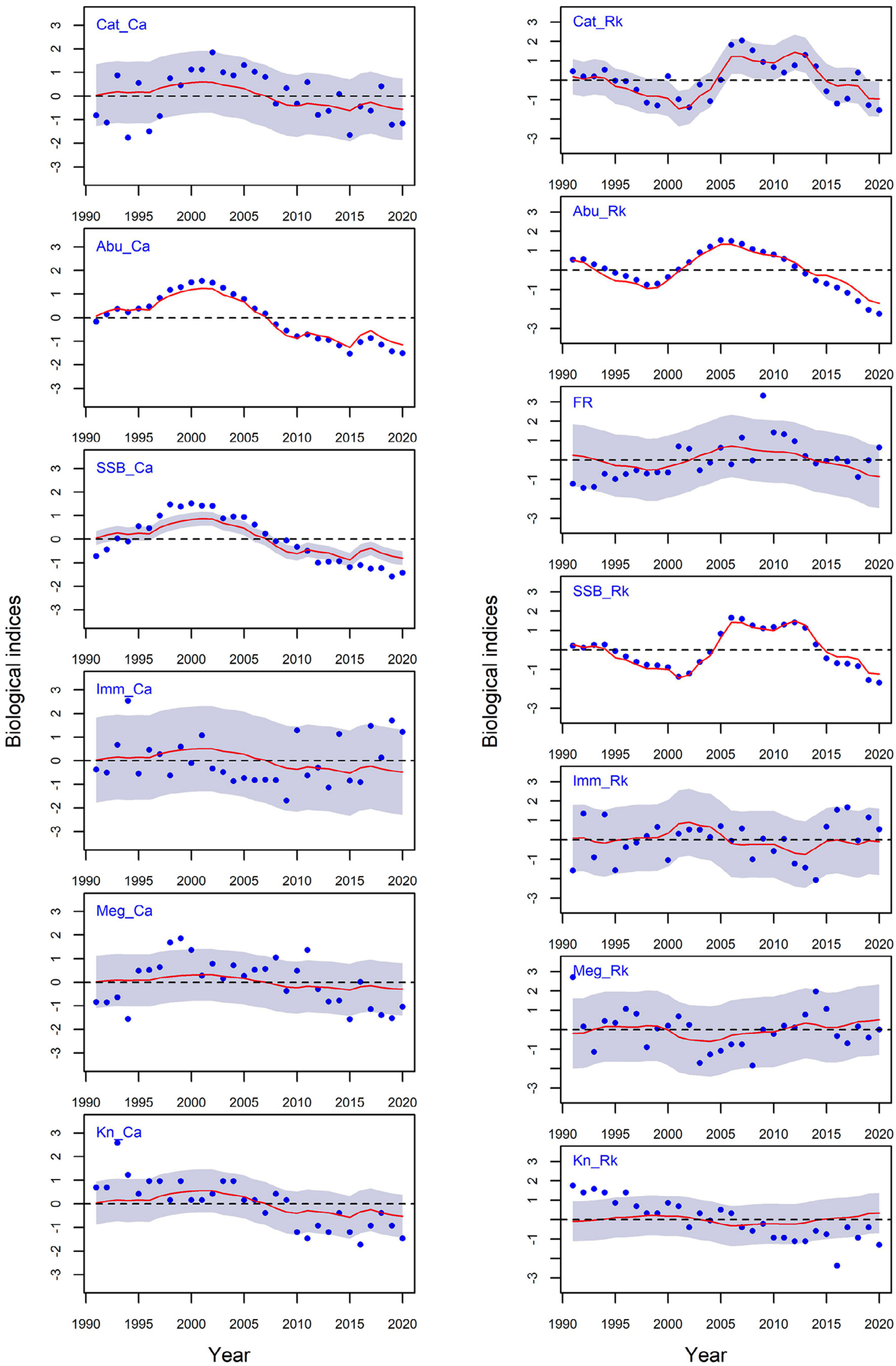

Fig. 8. – Dynamic factor analysis results for the best-fitting model: model-fitted values (red lines) and standardized biological observed data (filled blue circles) of *Chelon aurata* (Ca) and *Rutilus kutum* (Rk). Shading indicates the 95% confidence intervals of the model-fitted values. See Figures 2 and 4 for a key to biological parameter abbreviations.

fish, indicating that they were caught before they could fully realize their growth potential. This suggests that growth overfishing may have occurred in both species, especially *R. kutum*, over the last three decades.

E can have various effects on the Cat and Abu of fish species. The relationship between Cat and E and measures of Abu can be influenced by factors such as target fish species, fishing methods and management strategies (Mulazzani et al. 2015). In the CS, the increase in E until 2001 led to an increase in Cat of *C. aurata* until 2002, which caused overfishing, and despite the decrease in E in the following years, the Cat and Abu continued to decrease. In the case of *R. kutum*, the decrease in catch and abundance occurred three years later (in 2005).

Among the environmental (SST and SSL) and anthropogenic (E) variables affecting the biological indicators of *C. aurata* and *R. kutum*, only E can be controlled. The process of reducing E can prevent overfishing and increase the population. The effects of environmental variables on fish in the CS appear to be profound. Therefore, despite the decreasing trend of E, the Abu, Cat and Kn of the two species are still decreasing. Due to the increasing trend of global temperature and the decreasing SSL of the CS, it is likely that the decreasing trend of the biological indicators, especially the Cat, Abu, SSB and Kn of the two mentioned species, will continue in the years to come.

CONCLUSION

This study has provided a comprehensive analysis of the biological indicators of two commercially valuable benthopelagic species, *C. aurata* and *R. kutum*, within the CS over 30 years. By employing DFA, we discerned patterns in biological indices and their correlations with environmental and anthropogenic variables. We observed that SST, SSL and E have played a notable role in shaping the life history traits of *C. aurata* and *R. kutum*, as evidenced by the common trends identified. Also, the strong negative correlation between Kn and SST and the positive correlation between Kn and SSL suggest that rising temperatures may continue to adversely affect the health and vitality of these species. Furthermore, our study has highlighted the detrimental impact of overfishing, which is evident in the significant proportion of immature fish in catches and the downward trend in population metrics such as Cat, Abu and Kn.

SUPPLEMENTARY MATERIAL

Supplementary material contains figures on model innovations and quantile-quantile plots for the best-fitting DFA model.

ACKNOWLEDGEMENTS

We thank the staff of the Department of Stock Assessment at The Caspian Sea Ecology Research Centre, Inland Water Aquaculture Research Centre, and Inland Water Stocks Research Centre of the IFSRI for providing samples used in this study.

DECLARATION OF COMPETING INTEREST

All authors declare that they have no conflict of interest.

FUNDING SOURCES

This research was funded by the Iranian Fisheries Science Research Institute (IFSRI), which supported project number 2-76-12-033-020360.

AUTHORSHIP CONTRIBUTION STATEMENT

Hasan Fazli: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Visualization, Writing – original draft, Writing – review & editing. Golam Reza Daryanabard: Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing – review & editing. Akbar Pourgholami: Formal analysis, Investigation, Methodology, Project administration, Writing – review & editing. Seyed Abbas Hoseini: Formal analysis, Investigation, Methodology, Project administration, Writing – review & editing. Mohammad Reza Mirzaei: Formal analysis, Methodology, Visualization, Writing – review & editing. Parto Bahreini: Formal analysis, Software, Visualization, Writing – review & editing.

REFERENCES

Afraei Bandpei M.A. 2009. Age, growth, feeding regime, and reproduction of kutum (*Rutilus frisii kutum*) in the south of the Caspian Sea in survey, 2006-2007. Final report. IFRO. 97 pp. (In Persian).

Anderson R.O., Neumann R.M. 1996. Length, weight, and associated structural indices. In: Fisheries techniques, 2nd edition. American Fisheries Society, Bethesda, Maryland, USA. pp. 447-482.

Bagenal T.B., Tesch F.W. 1978. Methods of Assessment of Fish Production in Fresh Waters. IBP Handbook No. 3, third edition. Oxford Blackwell Scientific Publications, London. 365 pp.

Barber J.S., Ruff C.P., McArdle J.T. et al. 2019. Intertidal clams exhibit population synchrony across spatial and temporal scales. Limnol. Oceanogr. 64(S1): S284-S300. https://doi.org/10.1002/lno.11085

Beyraghdar Kashkooli O., Gröger J., Núñez-Riboni I. 2017. Qualitative assessment of climate-driven ecological shifts in the Caspian Sea. PLoS ONE 12(5): e0176892. https://doi.org/10.1371/journal.pone.0176892

Bitetto I., Romagnoni G., Adamidou A., et al. 2019. Modeling spatio-temporal patterns of fish community size structure across the northern Mediterranean Sea: an analysis combining MEDITS survey data with environmental and anthropogenic drivers. Sci. Mar. 83S1: 141-151. https://doi.org/10.3989/scimar.05015.06A

Burnham K.P., Anderson D.R. 2002. Model Selection and Multi-model Inference. A Practical Information-Theoretic Approach. 2nd edition. Springer, New York. 488 pp. https://doi.org/10.1007/b97636

Daryanabard G. et al. 2020. Reproduction and maturity of kutum (Rutilus kutum) in Iranian waters of the Caspian Sea. Iran. Sci. Fish. J. 29(5): 111-121. https://doi.org/10.22092/isfj.2021.123334

Esmaeili H.R., Sayyadzadeh G., Eagderi S. et al. 2018. Checklist of freshwater fishes of Iran. FishTaxa 3(3): 1-95.

Fazli H., Daryanabard G.R., Abdolmaleki S. et al. 2013. Stock assessment and management implications of golden grey mullet (*Liza aurata* Risso, 1810) in Iranian waters of the Caspian Sea. J. Appl. Ichtyol. 29: 431-436. https://doi.org/10.1111/jai.12003
Fazli H., Janbaz A., Taleshian H. et al. 2008. Maturity and fecundity of golden grey mullet (*Liza aurata* Risso, 1810) in Iranian waters of the Caspian Sea. J. Appl. Ichtyol. 24: 610-613. https://doi.org/10.1111/j.1439-0426.2008.01098.x
Fazli H., Janbaz A.A., Rabbaniha M. et al. 2021. Study of environmental and three kilka species regime shifts in the Caspian Sea. Iran. J. Fish. Sci. 20(5): 1247-1261. https://doi.org/10.22092/ijfs.2021.124701
Fazli H., Kaymaram F., Daryanabard G.R. 2022a. Effects of fishing and environmental parameters on the commercial bony fish assemblage in the southern Caspian Sea. Oceanol. Hydrobiol. Stud. 51(1): 90-99. https://doi.org/10.26881/oahs-2022.1.08
Fazli H., Khoshghalb M.R.B., Abdolmaleki S. 2022b. A Multi-species modeling approach to consider the effects of environmental parameters on Caspian sturgeon fishes stock status. Reg. Stud. Mar. Sci. 56: 102666. https://doi.org/10.1016/j.rsma.2022.102666
Feuilloley G., Fromentin J.M., Stemmann L. et al. 2020. Concomitant changes in the environment and small pelagic fish community of the Gulf of Lions. Prog. Oceanogr. 186: 102375. https://doi.org/10.1016/j.pocean.2020.102375
Froese R. 2004. Keep it simple: three indicators to deal with overfishing. Fish. Fish. 5: 86-91. https://doi.org/10.1111/j.1467-2979.2004.00144.x
Ghasemi A.F., Clements J.C., Taheri M. et al. 2014. Changes in the quantitative distribution of Caspian Sea polychaetes: Prolific fauna formed by non-indigenous species. J. Great Lakes Res. 40(3): 692-698. https://doi.org/10.1016/j.jglr.2014.05.004
Ghiasi M., Binaii M., Ghasem M. et al. 2016. Haemato-biochemical disorders associated with nodavirus like-agent in adult leaping mullet *Liza saliens* (Risso, 1810) in the Caspian Sea. VirusDis. 27(1): 12-18. https://doi.org/10.1007/s13337-015-0289-1
Holmes E.E., Scheuerell M.D., Ward E.J. 2021. Analysis of multivariate time-series using the MARSS package. Version 3.11.4. NOAA Fisheries, USGS WA Cooperative Fish and Wildlife Research Unit. 331 pp. https://doi.org/10.5281/zenodo.5781847
Jorgensen J.C., Ward E.J., Scheuerell M.D. et al. 2016. Assessing spatial covariance among time series of abundance. Ecol. Evol. 6(8): 2472-2485. https://doi.org/10.1002/ece3.2031
Karpinsky M.G., Shiganova T.A., Katunin D.N. 2005. Introduced species. In: The Caspian Sea Environment. pp.175-190. https://doi.org/10.1007/698_5_009
Kosarev A.N. 2005. Physico-Geographical Conditions of the Caspian Sea. In: The Caspian Sea Environment. The Handbook of Environmental Chemistry. Springer, Berlin. pp 5-31. https://doi.org/10.1007/698_5_002
Mackinson S., Daskalov G. 2007. An ecosystem model of the North Sea to support an ecosystem approach to fisheries management: description and parameterization. Cefas Science Series Technical Report 142. 196 pp.
Mulazzani L., Manrique R., Trevisan G. et al. 2015. The relationship among catch, fishing effort, and measures of fish stock abundance: implications in the Adriatic Sea. Can. J. Fish. Aquat. Sci. 72(3): 410-421. https://doi.org/10.1139/cjfas-2014-0337
Naseka A.M., Bogutskaya N.G. (2009). Fishes of the Caspian Sea: zoogeography and updated check-list. Zoosyst. Ross. 18(2): 295-317. https://doi.org/10.31610/zsr/2009.18.2.295
Pope J.G. 1972. An investigation of the accuracy of virtual population analysis using cohort analysis. Res. Bull. - Int. Comm. Northwest Atl. Fish. 9: 65-74.
Pourang N., Eslami F., Nasrollahzadeh Saravi H. et al. 2016. Strong biopollution in the southern Caspian Sea: the comb jelly *Mnemiopsis leidyi* case study. Biol. Invasions 18: 2403-2414. https://doi.org/10.1007/s10530-016-1171-9
Probatov S.N., Tereshchenko K.K. 1951. The Caspian Sea mullets and its fisheries. Pishchepromizdat, Moscow. 115 pp.
R Core Team. 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.
Shiganova T.A., Kamakin A.M., Pautova L.A. et al. 2023. An impact of non-native species invasions on the Caspian Sea biota. Adv. mar. biol. 94: 69-157. https://doi.org/10.1016/bs.amb.2023.01.002
Soltani M., Ghasemi M., Sharifrohani M. et al. 2010. Isolation and identification of Betanodavirus causing mass mortalities in golden grey mullet (*Liza auratus*) in the Caspian Sea. Iran. J. Vet. Res. 4(3): 201-208. https://doi.org/10.22059/ijvm.2010.21354
Sutton S.G., Bult T.P., Haedrich R.L. 2000. Relationships among fat weight, body weight, water weight and condition factors in wild Atlantic salmon parr. Trans. Am. Fish. Soc. 129: 527-538. https://doi.org/10.1577/1548-8659(2000)129<0527:RAFWBW>2.0.CO;2
Valipour A., Khanipour A. 2006. Kutum, Jewel of the Caspian Sea. In: www.Caspian environment.org
Wei T., Simko V. 2021. R package 'corrplot': Visualization of a Correlation Matrix. Version 0.92. In: https://github.com/taiyun/corrplot
Wickham H. 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag, New York. 260 pp. https://doi.org/10.1007/978-3-319-24277-4
Xu Z., Ji F., Liu B. et al. 2021. Long-term evolution of global sea surface temperature trend. Int. J. Climatol. 41(9): 4494-4508. https://doi.org/10.1002/joc.7082
Zeileis A., Leisch F., Hornik K. et al. 2002. strucchange: An R package for testing for structural change in linear regression models. J. Stat. Softw. 7: 1-38. https://doi.org/10.18637/jss.v007.i02
Zorriehzahra M.J., Nakai T., Sharifpour I. et al. 2005. Mortality of wild golden grey mullet (*Liza auratus*) in Iranian waters of the Caspian Sea, associated with viral nervous necrosis-like agent. Iran. J. Fish. Sci. 4: 43-58.
Zuur A.F., Fryer R.J., Jolliffe I.T. et al. 2003. Estimating common trends in multivariate time series using dynamic factor analysis. Environmetrics 14: 665-685. https://doi.org/10.1002/env.611