FISHERIES & AQUATIC LIFE (2024) 32: 137 - 154
Archives of Polish Fisheries
DOI 10.2478/aopf-2024-0013

sciendo

RESEARCH ARTICLE

Fishery stock dynamics in the Baltic Sea: The dichotomy between total allowable catch limits and spawning stock biomass

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Received – 27 October 2023/Accepted – 27 October 2024. Published online: 30 September 2024; ©National Inland Fisheries Research Institute in Olsztyn, Poland

Citation: Rosciszewski-Dodgson, M. J., Cirella, G. T. (2024). Fishery stock dynamics in the Baltic Sea: The dichotomy between total allowable catch limits and spawning stock biomass. Fisheries & Aquatic Life 32, 137-154

Abstract. When managing heavily exploited fisheries, the primary objective is ensuring the long-term sustainability of stocks. Policy makers employ various measures to achieve this, with one important approach being the establishment of total allowable catch (TAC) limits for commercial fish stocks. These limits are set to maintain a target level that can sustain or rebuild the spawning stock biomass (SSB), which is an indicator of a stock's reproductive capacity. Ideally, a strong correlation between TAC quotas and SSB exists, indicating that reductions in TAC are positively impacting SSB. However, in practice, the influence of TAC quotas on fish populations is diminished by other factors affecting reproductive capabilities. This study conducted on the eight most commercially valuable stocks in the Baltic Sea examined this relationship using statistical analysis. The findings revealed that five stocks exhibited a strong-to-moderate positive association between variables, while data for the remaining three stocks were insufficient. The results indicated that stocks with a strong correlation between TAC limits and SSB can be managed more effectively, offering greater potential for sustainability. In contrast, those without this correlation need a more holistic approach that incorporates external ecological factors, as management alone may not suffice to prevent declines. Future strategies should balance TAC and SSB while considering broader environmental factors to ensure sustainable stock dynamics.

Keywords: fisheries resources, ICES, population size, stock assessment, statistical strength

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Introduction

In the fisheries industry, populations are categorized as stocks for the purpose of management and monitoring (Cardin and Dickey-Collas 2014). Stock assessments in fisheries involve estimating the present population size and predicting its future size under various pressures and scenarios. This process aims to establish quotas that align with the maximum sustainable yield (MSY) equilibrium, balancing the environmental and economic requirements between the exploited stock and fishing activity (Farcas and Rossberg 2016). Fishery catch data is collected annually for each stock directly from the fishing industry, providing insights into historical changes in fish stocks. These observations are also utilized in computer models to make predictions about future trends in fish populations (Skalski et al. 2007).

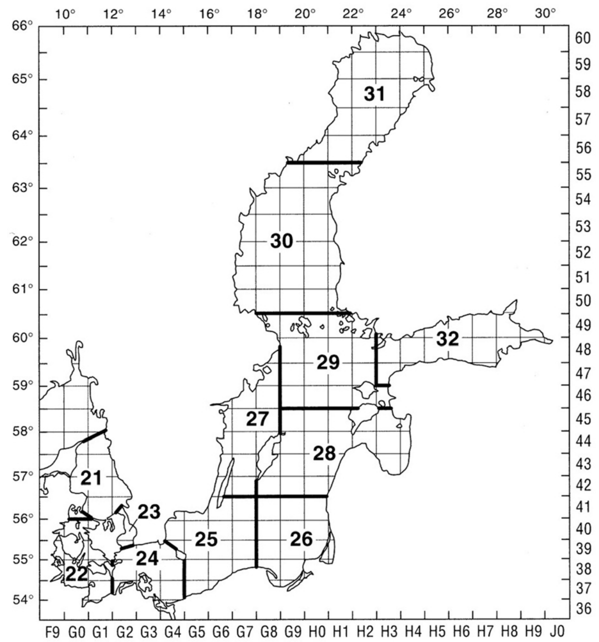

Figure 1. Statistical subdivision map of the Baltic Sea.

However, due to the inherent uncertainty in scientific predictions, there is always some degree of error involved when scientists claim 80 or 90% confidence in their projections. Fisheries models are employed to establish the relationships among different variables, enabling researchers to address "what if" scenarios. For instance, they can assess the potential impact on the future abundance of mature spawning fish in the sea if catches increase or decrease by a specific amount (Skalski et al. 2005). Based on these findings, scientists can provide recommendations on quotas and other management measures to ensure the long-term sustainability of fish stocks for future generations. This note elucidates the analytical methods employed by the International Council for the Exploration of the Sea (ICES) and the European Commission to assess fish stocks, along with the reference points used to evaluate their status in comparison to previous years.

Currently, sprat (*Sprattus sprattus*) and herring (*Clupea harengus*) stocks are of significant economic importance in the Baltic Sea (Guedes Soares et al. 2015, HELCOM 2018a, Dippner et al. 2019, ICES 2024c, 2024d, 2024e, 2024f, 2024i). Additionally, several flatfish species, particularly plaice (*Pleuronectes platessa*), hold regional value in the South Baltic Sea (Ulrich et al. 2013, Guedes Soares et al. 2015, HELCOM 2018a). These species dominate the commercial stocks to such an extent that they accounted for 90% of the total fish catch in 2018 (HELCOM 2018a). Furthermore, cod (*Gadus morhua*) stocks are closely monitored, with the hope that they will eventually recover and become economically viable in the Baltic Sea once again (Voss et al. 2019, Möllmann 2021, ICES 2024a, 2024b, 2024c, 2024d, 2024e, 2024f, 2024g, 2024h, 2024i). These stocks are divided using the ICES subdivision map (Figure 1).

Since the 1960s, fisheries data and stock dynamics for these species have been recorded systematically (HELCOM 2018b). The management of fishing fleets and fish stocks is governed by the Common Fisheries Policy (CFP) mechanism, which was initiated in 1970 and was reformed significantly in 2014. The revised CFP aimed to achieve sustainable fishing levels by implementing stricter total allowable catch (TAC) limits for a greater number of stocks (European Commission 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022). The Baltic Sea presents unique environmental conditions characterized by its semi-enclosed, brackish, shallow nature, limited biodiversity, and the growing impacts of climate change. These factors pose challenges for commercially exploited species to thrive (Meier et al. 2011, HELCOM 2018b, Voss et al. 2019, Cederqvist et al. 2020). Consequently, effective management measures are necessary to preserve or rebuild the stocks. The management of stocks involves the implementation of TAC limits, which establish maximum fishing limits for specific stocks within a designated timeframe (Kane et al. 2024). Moreover, TAC advice is fundamentally connected to the status of a stock, with annual updates to the TAC limits reflecting the stock's present size. Stocks with a high spawning stock biomass (SSB) are granted greater catch allowances compared to species that have experienced significant population declines. Consequently, if a stock was determined to be overfished in the previous year, a reduction in TAC should be implemented in the

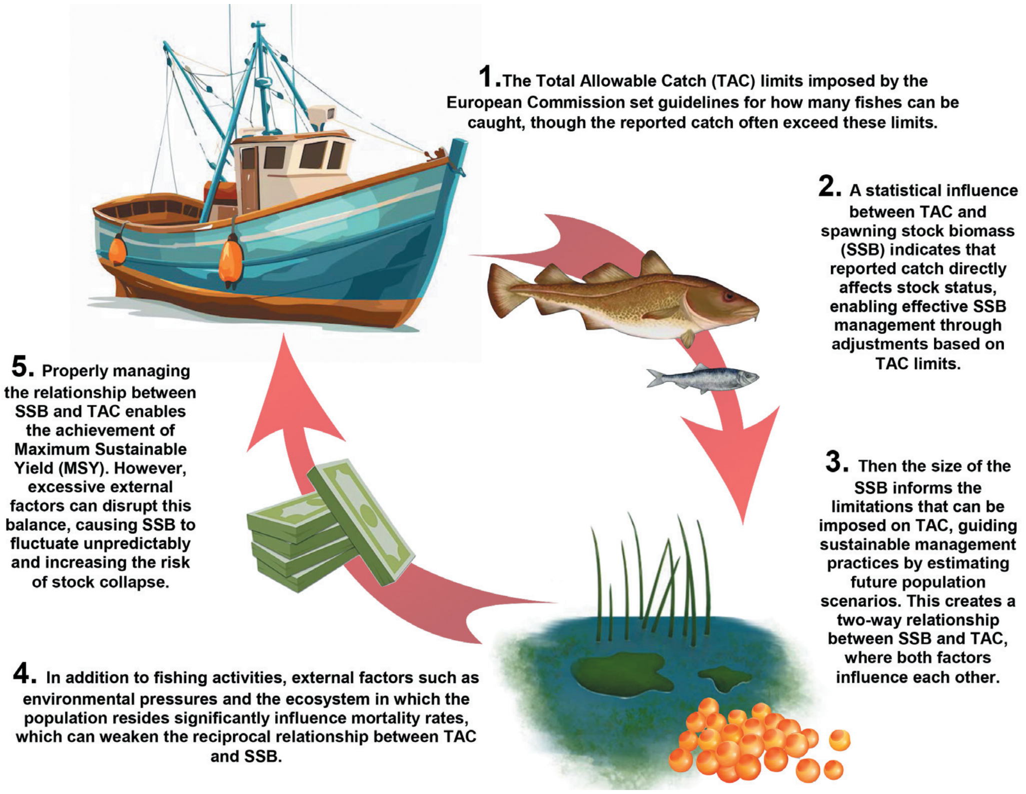

Figure 2. Dynamic relationship imposed by the European Commission between TAC and SSB (European Commission 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022).

following year. On the other hand, managers strive to maintain MSY targets, which ensure adequate catch allowances for a given fish stock, enabling the highest possible annual catch that can be sustained over time.

Maintaining a strong relationship between TAC quotas and SSB is central to the effective management of heavily exploited fish stocks. Ideally, this connection ensures that reductions in TAC directly and positively influence SBB recovery, thus promoting stock sustainability. However, achieving this state of equilibrium is challenging due to the inherent complexities of accurately monitoring stocks and the dynamic environmental conditions in regions like the Baltic Sea. These conditions-including variations in salinity, temperature, and oxygen levels—directly affect fish recruitment and growth, often leading to unpredictable stock responses to TAC adjustments (Rosciszewski-Dodgson and Cirella 2024). Compounding these environmental factors on top of changes in reproductive rates, age structure, and natural mortality make it challenging to establish a fixed link between TAC reductions and SSB improvements. This variability means that TAC limits are often set higher than what is considered biologically sustainable (Carpenter et al. 2016), resulting in TAC quotas that are insufficient in improving a stock's status. Consequently, frequent adjustments to catch limits are necessary to adapt to a stock's fluctuating condition (Figure 2).

Since the 2014 reform, TAC limits for key Baltic Sea stocks have undergone significant changes to determine appropriate TAC limits (European Commission 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022). The difficulty lies not only in identifying correct TAC limits but also in addressing the underlying environmental and biological factors that influence stock recovery. These challenges underscore the need for more adaptive and responsive fisheries management approaches, as traditional methods may be insufficient in dealing with the complexities of both stock variability and ecosystem dynamics. Understanding these factors is crucial to improving the management strategies that govern TAC-SSB relationships, which is the focus of this study.

Material and methods

The primary research question (*PRQ*) of the study focused on examining the degree of influence between TAC quotas and SSB estimates. TAC and SSB were chosen as the main variables due to their critical roles in fisheries management. This selection aligns with the frameworks used by organizations such as ICES and the European Commission, which utilize regularly updated data to accommodate fluctuations in TAC and SSB. Understanding the relationship between these two variables is essential for assessing the effectiveness of management strategies. To investigate the relationship between TAC limits and SSB for each stock, a null hypothesis (H_0) was tested using a sample of the eight most commercially valuable stocks in the Baltic Sea.

PRQ: Does a significant association exist between TAC limits and SSB estimates for commercial fish stocks in the Baltic Sea during the period of 2015–2023?

H_0: TAC limits and SSB estimates between 2015 and 2023 did not exhibit a significant influence on each other.

H_a: TAC limits and SSB estimates between 2015 and 2023 did exhibit a significant influence on each other.

The null hypothesis was employed in this study to statistically test the *PRQ*, with the possibility of either rejecting or not rejecting H_0 (Stunt et al. 2021). This approach facilitated the examination of the association between TAC limits and SSB estimates. Data collection for this study focused on fishery stock assessment variables obtained from historical time-series data. These variables commonly include metrics such as abundance, mortality, age, size, and sex ratios (Skalski et al. 2007, Martell 2008). While it is not necessary to have all these data types to estimate historical impacts, at least one of them is essential (Skalski et al. 2005). In the context of this study, three specific variables were utilized: TAC, reported catch, and SSB. TAC represents the annual catch limits expressed in tonnes that are established by the European Commission (2014) for the key fish stocks in the Baltic Sea. These TACs are allocated among European Union (EU) member states in the form of national quotas (Psuty et al. 2021). Reported catch, also referred to as fisheries mortality rates or landings data, provides an indication of the level of exploitation of a stock. It entails recording the annual volume in tonnes of harvested and sold stock by commercial fishers, serving as a census for each stock (ICES 2024a, 2024b, 2024c, 2024d, 2024e, 2024f, 2024g, 2024h, 2024i). SSB is a key indicator used to assess the status of a stock and its reproductive capacity. It is quantified as the total weight in tonnes of sexually mature individuals within a fish stock that are capable of reproduction (ICES 2024a, 2024b, 2024c, 2024d, 2024e, 2024f, 2024g, 2024h, 2024i).

It is important to note that in 2015, TAC limits were assigned for the first time under the newly reformed and improved CFP (European Commission, 2014). In contrast, the latest available information on SSB estimates and fishery landings data are for 2023 (ICES 2024a, 2024b, 2024c, 2024d, 2024e, 2024f, 2024g, 2024h, 2024i). The data for this study was collected from various sources, including CFP press releases that provide agreements on catch limits in the Baltic Sea for a given year and ICES scientific reports that offer advice on fishing opportunities and detail catch and spawning stock estimates in the Baltic Sea.

Statistical test

R Version 4.3.0 software was utilized to perform correlation analysis, aiming to examine the relationship between reported catch and SSB. The strength of this association was assessed using the correlation coefficient *r*, which measures the linear association between the variables and ranges from +1 to -1 (Ratner 2009). This analysis permitted assessing the extent to which reported catch and SSB influence each other, as well as whether the variables exhibited a positive or negative correlation. Moreover, reported catch data was utilized instead of TAC limits to compare with the SSB variables, providing an assessment of the actual number of fish extracted from the water by fisheries. This comparison is crucial for testing H_0, as annual reported catch statistics, whether higher or lower, reflect the extent to which TAC quotas influence fisheries in practice. As a result, this approach allows examining the relationship between TAC limits and SSB of Baltic stocks.

To assess the statistical significance of the results, the P-value was employed. A P-value of ≤ 0.05 was considered indicative of a small probability (≤ 5%) of a sampling error (Andrade 2019). While it does not guarantee absolute certainty, a P-value less than or equal to 0.05 would lead to the rejection of H_0 and acceptance of the alternative hypothesis, *Ha*. Conversely, a P-value greater than 0.05 indicated insufficient evidence to reject H_0. These statistical tests were performed eight times for each stock to identify stocks with a strong positive association, moderate positive association, or data deficiency.

Secondary analysis

While visualization and external sources can provide insights, it is crucial to confirm relationships between variables through statistical analysis. Merely relying on visualizations or external information is insufficient to establish the existence of a relationship (Andrade 2019). Consequently, this study incorporated additional research questions (*RQs*) to facilitate a comprehensive discussion on the status of each stock. The combination of line graphs and clustered bar columns was employed to visually depict the relationship between the three datasets for each stock (Slutsky 2014). Furthermore, extensive analysis of academic and ICES literature was conducted to gain deeper insights into the challenges faced by each stock. This approach allowed for a thorough investigation of the meaning behind the statistical results, even in cases where there was insufficient evidence to reject H_0. The following *RQs* were considered in this study:

RQ1: Which variable serves as the influencer, and which one is influenced for each stock?

RQ2: How and why did TAC limits and SSB estimates influence each other, or why was there no influence observed?

RQ3: To what extent do external factors hinder the improvement of SSB through TAC limits for each stock?

Results and discussion

Table 1 provides a comprehensive overview of the reported catch and SSB estimates, as well as the ICES-approved agreements on TAC limits for each stock from 2015 to 2023 expressed in tonnes. The summary reflects the recorded catch volumes and the estimated SSB for respective stocks. Table 2 presents the correlation matrix for each stock, showcasing the correlation coefficient denoted by *r* and the statistical significance indicated by the P-value. It provides a comprehensive summary of the strength and significance of the correlations between variables.

Gadus morhua

Cod populations in the Baltic Sea have traditionally been evaluated as two distinct units, namely the East and West stocks, due to their biologically divergent characteristics (Nielsen et al. 2001). These stocks were managed as a single entity until 2003. However, to facilitate region-specific regulatory measures, ICES introduced separate assessments for the Eastern and Western stocks (Guedes Soares et al. 2015).

Eastern cod, subdivisions 25–32

Based on the statistical analysis, the Eastern cod stock demonstrated a significant relationship between TAC limits and SSB, as indicated by a P-value of 0.03. The correlation coefficient, represented by *r*

Table 1
History of reported catch, SSB estimates, and EC council agreement on TAC limits for each stock in tonnes, 2015-2023

Stock	Variable	2015	2016	2017	2018	2019	2020	2021	2022	2023
Eastern cod	TAC	65,934	41,143	30,857	28,388	24,112	2	595	595	595
	R catch	50,008	37,438	30,965	21,605	11,938	2,899	1,764	1,181	—
	SSB	132,347	113,74	85,337	73,682	68,094	64,835	69,026	76,713	76,713
Western cod	TAC	8,793	12,72	5,597	5,597	9,515	3,806	4	489	489
	R catch	14,78	11,112	6,286	6,326	8,993	3,534	1,409	403	—
	SSB	17,42	12,742	9,029	10,456	12,896	9,133	5,303	5,661	—
Bothnian herring	TAC	186,534	120,872	140,998	84,599	88,703	65,018	65,018	111,345	80,047
	R catch	114,942	130,029	104,358	97,366	88,907	72,956	71,924	78,614	66,827
		704,477	659,804	643,673	651,895	580,202	591,753	564,985	548,671	526,061
Western herring	TAC	22,22	26,274	28,401	17,309	9,001	3,15	1,575	788	788
	R catch	49,978	54,972	53,309	42,25	21,745	21,918	14,918	1,365	3,338
	SSB	87,504	83,61	70,608	53,449	42,554	41,929	45,107	54,162	66,152
Central herring	TAC	170,185	177,505	191,129	229,355	170,36	153,384	97,551	53,653	70,822
	R catch	174,433	192,056	202,517	244,365	204,438	177,079	128,961	83,821	98,696
	SSB	625,069	560,793	582,76	571,495	464,975	384,556	387,052	340,407	—
Riga herring	TAC	38,78	34,915	31,074	28,999	31,044	34,445	34,446	47,697	45,643
	R catch	32,851	30,865	28,058	25,747	28,922	33,215	35,758	41,117	42,8
	SSB	109,811	98,553	97,99	106,943	108,283	12,694	117,333	127,561	136,638
Sprat	TAC	199,622	202,32	260,993	262,31	270,772	210,147	222,958	251,947	224,114
	catch	247,3	247,2	288,5	312,188	317,65	274,06	284,89	300,788	265,9
	SSB	796,356	119,3575	1,194,111	1,016,795	916,438	892,276	1,083,527	1126,771	890,326
Plaice	TAC	3,249	4,034	7,862	7076	10,122	6,894	7,24	9,05	11,313
	R catch	4,126	5,044	4,661	6497	7,129	5,495	3,82	2,732	3,037
	SSB	8,82	9,123	9,114	9707	10,259	9,142	9,548	13,12	20,477

Note: SSB estimate figures include subdivisions 21-32, due to there being no data available that excludes the Kattegat Sea area; — data for these years is unavailable; Source: ICES 2024a, 2024b, 2024c, 2024d, 2024e, 2024f, 2024g, 2024h, 2024i and European Commission 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022.

Table 2
Correlation matrix of each stock with the *r* value representing the correlation coefficient and the P-value representing statistical significance

Stock	Variable	Reported catch	SSB estimate
Eastern cod	Reported catch	1.0000	r = 0.85, P = 0.03
	SSB estimate	—	1.0000
Western cod	Reported catch	1.0000	r = 0.97, P = <0.001
	SSB estimate	—	1.0000
Bothnian herring	Reported catch	1.0000	r = 0.87, P = 0.002
	SSB estimate	—	1.0000
Western herring	Reported catch	1.0000	r = 0.61, P = 0.8
	SSB estimate	—	1.0000
Central herring	Reported catch	1.0000	r = 0.71, P = 0.049
	SSB estimate	—	1.0000
Riga herring	Reported catch	1.0000	r = 0.88, P = 0.002
	SSB estimate	—	1.0000
Sprat	Reported catch	1.0000	r = 0.15, P = 0.709
	SSB estimate	—	1.0000
Plaice	Reported catch	1.0000	r = 0.69, P = 0.39
	SSB estimate	—	1.0000

= 0.85, signified a strong positive association between the variables, implying that they are moving in the same direction. Notably, SSB and reported catch had concurrent declines, with the SSB for Eastern cod decreasing substantially over the past eight years, from 132,347 tonnes in 2015 to 76,713 tonnes in 2023 (ICES 2024a). This suggests that despite the implementation of reduced TAC limits under the CFP, SSB for Eastern cod decreased by 42%. Initially, in 2015, the TAC limit for the Eastern cod stock was set at a high level of 65,935 tonnes, which accounted for approximately half of the estimated SSB. This indicated that the stock was being harvested beyond its sustainable biological limits. As SSB numbers continued to decline, a more precautionary approach was adopted under the CFP, resulting in a reduced TAC limit of 24,112 tonnes in 2019, representing just over a third of the total SSB. However, TAC limits did not accurately reflect the actual situation of the stock. This is evident from the recorded catch data, which consistently remained significantly lower than the TAC limit (Figure 3). Over the last five years, the reported catch never approached the TAC, with the largest disparities observed in later years: 77% in 2019 and 73% in 2020. In 2021, TAC limits were substantially reduced to a mere 595 tonnes as bycatch, reflecting the reported catch from the previous year (European Commission 2020). While it is too early to determine the impact of the new lowered TAC limits on the SSB of the Eastern Baltic stock, it is noteworthy that the latest recruitment statistics indicate the lowest values on record.

In addition to overfishing, the deteriorating condition of the Eastern cod stock is attributed predominantly to biological and environmental factors. These include reduced salinity and increased algal blooms, which hinder growth and diminish habitat availability (Schaber et al. 2012, Neuenfeldt et al. 2020). Natural mortality has also risen, surpassing fishing mortality over the past decade (Frommel et al. 2012, ICES 2024a). Furthermore, the size of the largest individuals has declined in the last two decades (Mion et al. 2018). Consequently, SSB now comprises smaller cod that produce fewer eggs, thereby limiting their reproductive success. It is important to acknowledge that the primary drivers contributing to the collapse of the Eastern cod stock in the past eight years are anthropogenic in origin. In this context, it was the SSB variable that exerted influence, leading to the decline and eventual closure of targeted cod fishing through TAC limits.

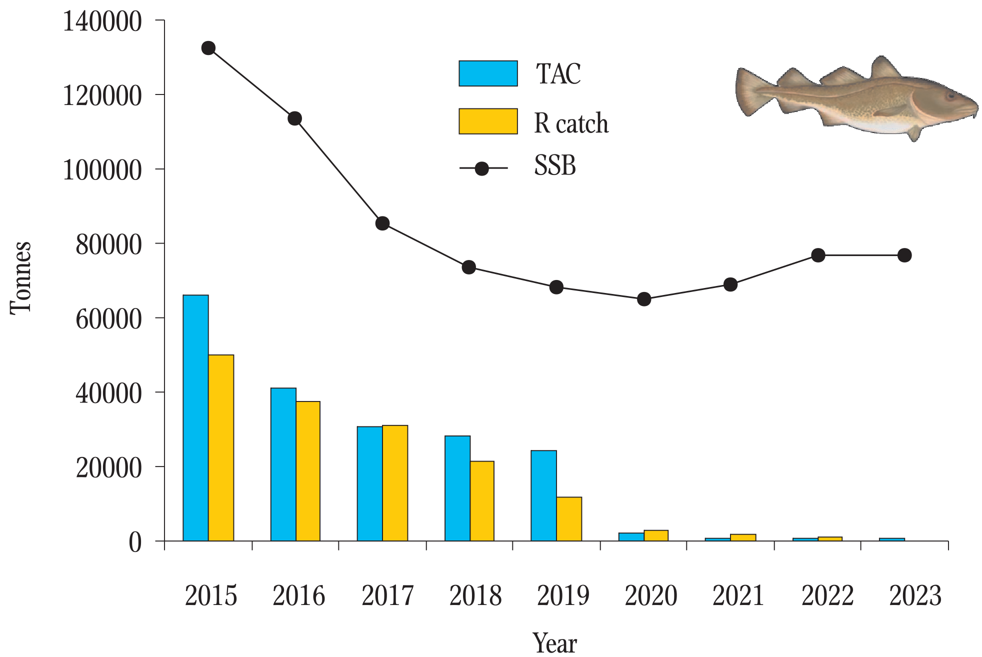

Figure 3. Eastern cod TAC limit, reported catch, and SSB estimate in tonnes, 2015-2023.

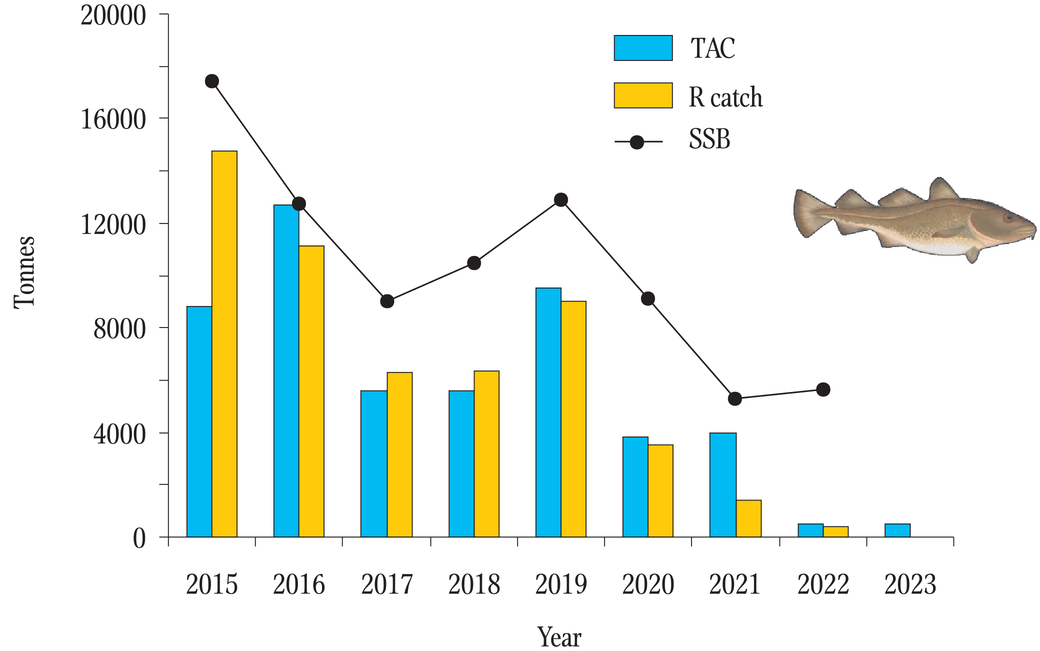

Figure 4. Western cod TAC limit, reported catch, and SSB estimate in tonnes, 2015-2023.

Western cod, subdivisions 22–24

The statistical analysis conducted on the Western cod stock revealed the strongest correlation with a correlation coefficient of r = 0.97. The corresponding P-value of 0.001 was below the significance threshold of 0.05, providing sufficient evidence to reject the null hypothesis (H_0). This indicated a strong statistical relationship between TAC and SSB variables, as reflected in the trends shown in Figure 4. For instance, the SSB of the Western cod stock declined substantially by 67% during the study period from 17,420 to 5,303 tonnes (ICES 2024b). Interestingly, the years characterized by high catch rates were followed by sharp declines in SSB in subsequent years. This pattern is exemplified in the period between 2016 and 2017 when a high TAC led to a sudden 29% decline in SSB from 12,742 to 9,029 tonnes within just one year. Notably, this decline occurred despite the reported catch (6,286 tonnes) never reaching the TAC quota. A similar phenomenon was observed in 2019 when, under the CFP, the TAC limit was raised to 9,515 tonnes and a substantial increase in reported catch from the previous cycle from 6,326 to 8,993 tonnes. Consequently, SSB plummeted to a historically low level of 5,303 tonnes in 2021. Conversely, in 2017 and 2018, when TAC limits and reported catch were significantly smaller, SSB exhibited an upward trend. These observations suggest that TAC limits implemented in these years potentially contributed to the improvement of SSB in the Western cod stock. Similarly, this trend is already evident between 2021 and 2022, when the SSB stabilized slightly following the ban on targeted cod catches. Since there are no SSB figures from 2023, it is too early to draw definitive conclusions. The small P-value suggests that limiting TAC to a 595-tonne bycatch could eventually aid in the recovery of the stock.

Western cod stocks are facing similar challenges to those of Eastern cod. Despite the closure of targeted cod fishing activities in 2019, the last two years have seen a slow increase of just 7% in SSB, which is far below expectations following the fishing ban. This pattern indicates that other factors are influencing the stock SSB. Increased natural mortality, likely caused by predation, hypoxia, elevated water temperatures, and reduced salinity, is contributing to this trend (Hüssy 2011, Petereit et al. 2014, Stiasny et al. 2016). Moreover, cod are frequently caught as bycatch in

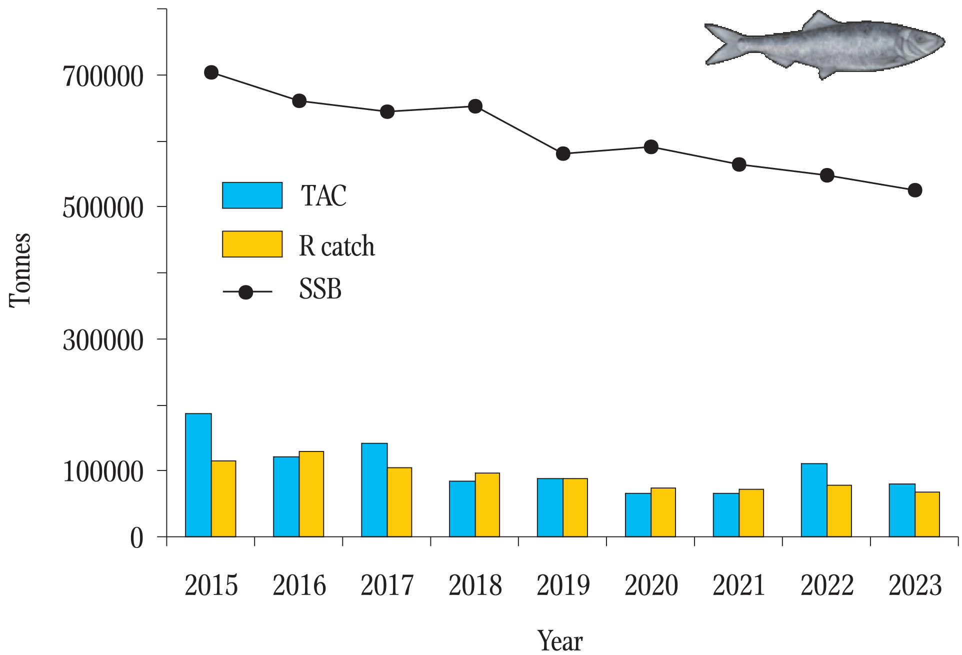

Figure 5. Bothnian herring TAC limit, reported catch, and SSB estimate in tonnes, 2015-2023.

flatfish fisheries and are extensively exploited by marine recreational fishing (MRF) activities. In fact, non-commercial catches accounted for 71% of reported catches in 2022 (ICES 2024b). Consequently, MRF poses significant risks to certain stocks as it directly competes with commercial fishing efforts. This competition is particularly evident through high, selective fishing mortality, the use of live bait from external sources, and the loss of lead-containing tackle, which can negatively affect fish populations and coastal environments (Lewin et al. 2019).

Clupea harengus

Herring has long been a primary target for commercial fisheries in the Baltic Sea, and ICES has been involved in managing herring stocks in this region since the 1970s. Herring populations in the Baltic Sea are assessed as four separate stocks: Bothnian, Western, Central, and Riga herring.

Bothnian herring, subdivisions 30–31

The statistical analysis of the Bothnian herring stock yielded a significant result with a P-value of 0.002, leading to the rejection of H_0, indicating that TAC limits and SSB have influenced each other. The strength of this association was substantial, as indicated by a correlation coefficient of $r = 0.87$, suggesting that the variables moved in the same direction (Figure 5). The SBB of Bothnian herring, which is caught primarily by Finnish and Swedish fisheries, declined by 25% over the study period, from 704,477 tonnes in 2015 to 526,061 tonnes in 2023. The revised assessment by ICES (2024c) reflected a downward adjustment in response to the reduced weight-at-age of adult herring. This decrease in size is partly attributed to environmental changes and competition with sprat for the same food resources (Eero 2012). This was reinforced by their feeding patterns, whereby the share of empty stomachs was higher in herring, indicating how sprat are more successful than herring at finding and consuming zooplankton (Ojaveer et al. 2010). Consequently, a significant reduction in TAC limit was implemented under the CFP and was decreased 57% from 186,534 to 80,047 tonnes (European Commission 2015, 2022).

The decline in recruitment and reduced size of adult Bothnian herring is also reflected in the reported catch statistics, which decreased by 41% over the eight-year period from 114,942 to 71,924 tonnes (ICES 2024c). Notably, from 2018 to 2021, there was a consistent trend where the reported catch slightly exceeded the imposed TAC limit. This suggested that in those four years, the annual catch limit for the stock surpassed the recommended acceptable biological catch that was precautionary in nature. As a response to maximize MSY, TAC slightly increased in the following years to accommodate increased fish landings. This has had a significant impact on SSB, resulting in a sharper decline starting from 2020. In comparison to other herring stocks, the Bothnian herring stock still maintains a healthy range between SSB and reported catch, indicating that current fishing activities have been managed to maintain a large reproductive population. Thus, the Bothnian herring stock is not currently overfished, but it is likely approaching its MSY limits. The ongoing decline in the stock has created a negative reciprocal influence between SSB estimates and TAC quotas.

Western herring, subdivisions 22–24

The western Baltic spring-spawning herring (WBSSH), the most westerly herring stock, is primarily distributed in the Skagerrak and Kattegat areas and ICES subdivisions 22–24. However, enforced TAC limits only apply to subdivisions 22–24. During the period between February and March, known as spring-spawning, herring aggregate from the North Sea to the Western coast of the Baltic Sea to spawn (Polte et al. 2021). These aggregations are harvested by Danish, German, Polish, and Swedish fishers using purse-seiners and trawlers (ICES 2024d). In recent years, the catch has mainly consisted of individuals caught as bycatch in targeted sprat fishery (ICES 2024d). The correlation coefficient for WBSSH shows a moderate strength with r = 0.61, but the P-value exceeds the 0.05 limit. Therefore, there is not sufficient evidence to reject H_0. Based on the data in Table 1, TAC limits declined by 96% from 22,220 to 788 tonnes, and the reported catch rates also experienced a drastic reduction from 49,978 to 3,338 tonnes, a decrease of 93%. This decline had a positive effect on SSB, which increased by 58% between 2020–2023 (Figure 6). ICES (2024d) recommend implementing a zero-catch policy in the Baltic Sea to sustain the small gains achieved in SSB over the last two years. This approach may facilitate stock recovery within the next five to 10 years.

The lack of sufficient evidence to reject H_0 can also be attributed to the substantial influence of external factors on Western herring SBB. These factors

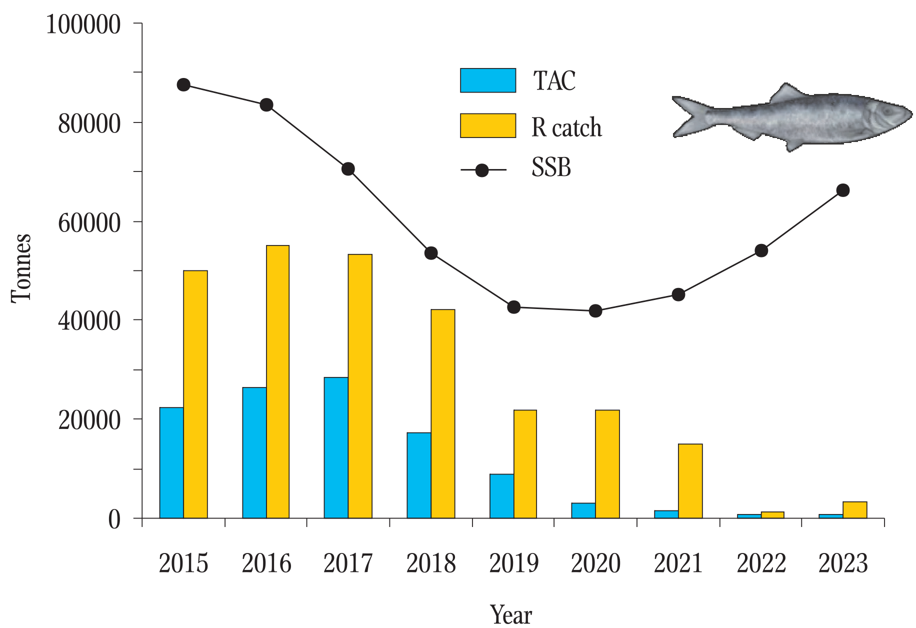

Figure 6. Western herring TAC limit, reported catch, and SSB estimate in tonnes, 2015-2023.

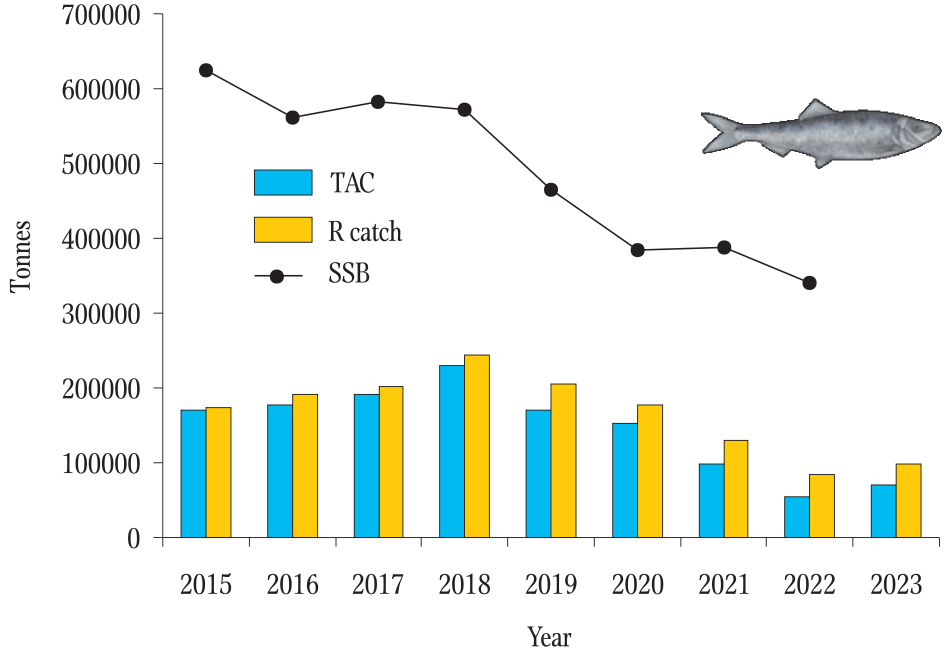

Figure 7. Central herring TAC limit, reported catch, and SSB estimate in tonnes, 2015-2023.

include bycatch from sprat and other herring fisheries that accounts for 73% of total bycatch, and catches by fishers operating in the North Sea, to which the WBSSH migrate from the Baltic Sea (Polte et al. 2021, ICES 2024d). The reported catch of Western herring in the North Sea averaged 5,688 tonnes between 2019 and 2021, while the mean reported catch in subregions 22–24 during the same period was 4,756 tonnes (ICES 2024d). Consequently, fishing mortality of Western herring was higher in the North Sea during this three-year period.

Central herring, subdivisions 25–27, 28.2, 29, 32

Central herring has been the dominant herring stock in the Baltic Sea for the past three decades, with the majority of Baltic herring landings attributed to it (Raid et al. 2015). The statistical analysis examining the relationship between reported catch and SSB resulted in a P-value of 0.049, which permitted rejecting H_0 and accepting the influence between TAC limits and SSB. However, the correlation coefficient, with an average value of $r = 0.71$, indicated a moderate association rather than a strong one. Figure 7 depicts the notable downward trend observed in the central herring stock in recent years. The SSB line reveals a significant decrease of 45% between 2015 and 2022 from 625,069 to 340,407 tonnes. In response to declining SSB, TAC limits were reduced by 58% over this eight-year period (ICES 2024e). These precautionary measures implemented under the CFP contributed to the stabilization of the stock in 2020 and 2022 despite reported catches remaining slightly higher. However, there are no SSB figures from 2023; therefore, it is too early to draw definitive conclusions. Notably, the period of maximum fishing mortality rate (FMSY) in 2018 was followed by sharp declines in SSB over the subsequent two years that indicated the influence of TAC limits on SSB. However, the moderate degree of association suggests that external factors also impacted central herring SBB. For instance, this stock is shared with Russian fishers who do not adhere to the management plan (ICES 2024e), while misreporting occurs in EU fisheries between sprat and central herring and Riga herring that coexist in these subregions (ICES 2024e).

In addition to fishing pressures, the central herring stock is influenced by various other factors, including climate change, eutrophication, habitat

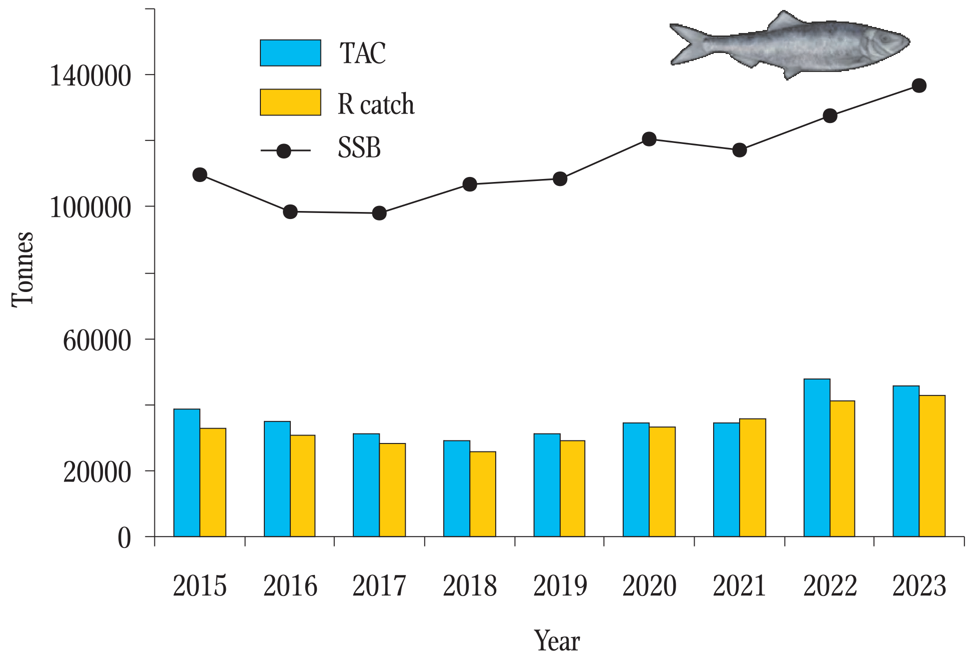

Figure 8. Riga herring TAC limit, reported catch, and SSB estimate in tonnes, 2015-2023.

degradation, shifts in zooplankton composition, and increased competition with other herring and sprat species (Dziaduch 2011, Frommel et al. 2014). In certain areas, up to 90% of all herring were found to have empty stomachs (Dziaduch 2011). The decline in SSB estimates can also be attributed to a significant decrease in the average weight at each age class, indicating a prevalence of smaller herring individuals within the stock (Dipner et al. 2019). Moreover, there has been a lack of strong recruitment since 2015, leading to a reliance on a single year class for the production of the next generation (ICES 2024e). These factors contribute to increased uncertainty in the relationship between variables, making effective TAC management of the central herring stock more challenging.

Riga herring, subdivision 28.1

Exclusively caught by Estonian and Latvian fisheries using trawls and trap-nets, Riga herring constitutes a distinct population in the Baltic Sea characterized by smaller length and weight at each age class (Raid et al. 2010). The statistical analysis of reported catch and SSB revealed a significant relationship indicated by the P-value of 0.002 and the rejection of H_0 and the acceptance of the influence between TAC limits and SSB. The strength of this influence is positive, with a correlation coefficient of r = 0.88, suggesting a strong degree of association. Figure 8 illustrates the substantial gap between SSB numbers and reported catch compared to other stocks. Over the eight-year period, SSB estimates for Riga herring generally showed an upward revision, increasing by 24% from 109,811 in 2015 to 136,638 in 2023 (ICES 2024f). Reported catch numbers also rose slightly from 32,851 to 42,800, representing a 30% increase. Fishing pressure on the stock remained below FMSY, and TAC limits were considered precautionary based on ICES advice. In fact, ICES (2024f) suggests that the stock's TAC limits could be increased by another 5% to 45,235 tonnes to achieve MSY. This finding explains the relatively weaker dynamics between TAC quotas and SSB. Interestingly, despite the strong relationship between the variables, the recruitment of Riga herring is robust enough to withstand current fishing activities, allowing both variables to coexist without significant adverse effects.

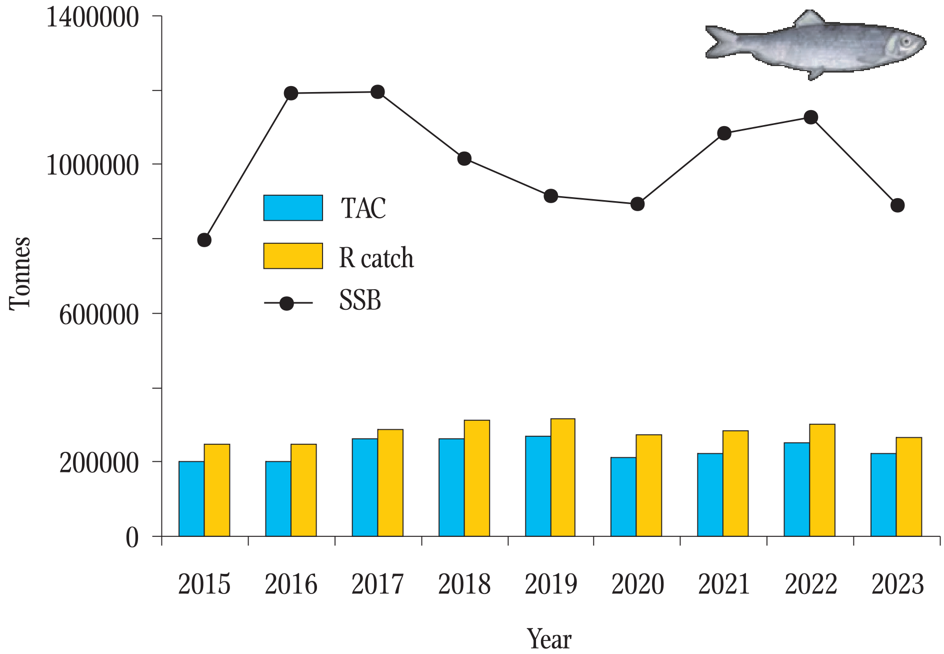

Figure 9. Sprat TAC limit, reported catch, and SSB estimate in tonnes, 2015-2023.

Sprattus sprattus

Sprat, subdivisions 22–32

Baltic Sea sprat are assessed as a single stock covering subdivisions 22–32 (ICES 2024g). Currently, they constitute the largest stock in the Baltic Sea, and reported catch figures have consistently exceeded TAC limits over the eight-year period. Despite this, the spawning capacity of the species has shown resilience, with a 13% increase in SSB from 2015 to 2023. However, the statistical test on sprat indicated no significant correlation, with correlation coefficient $r = 0.15$, and a P-value exceeding the 0.05 threshold, which was insufficient evidence to reject H_0. Figure 9 further confirms the limited degree of influence between TAC and SSB. Nonetheless, the sprat SBB fluctuated during the study period. Rapid SSB growth occurred when fishing mortality was 247,300 tonnes in 2015 and 2016, whereas a decline in SSB followed when catches exceeded 312,188 tonnes in 2018 and 2019. This pattern was repeated in 2022 when reported catches exceeded 300,788 tonnes, causing the SSB to fall to its lowest level in six years, suggesting that TAC limits can influence sprat SSB when the reported catch is too high. Conversely, adjustments to TAC limits and a reduction in catches to 274,060 tonnes led to a 12% increase in SSB in 2021. The ICES (2024g) report recognizes that sprat are being slightly overfished and recommends that sprat catches should not exceed 169,131 tonnes to stay within the MSY limit.

The lack of correlation between the variables can be attributed to various factors, given the size and geographical range of the sprat stock. The catch distribution per ICES subdivision has varied over time, with over 75% of the total sprat stock located in the Northern Baltic and the Gulf of Finland (subdivisions 27–32) (Casini et al. 2011). The specific reasons for this geographical change are not clear, but climate change, eutrophication, and changes in food-web composition have been suggested as potential contributing factors (Ojaveer et al. 2010, MacKenzie et al. 2012, Kulke et al. 2018). Sprat has demonstrated remarkable adaptability to the changing conditions of the Baltic Sea, benefiting from increasing temperatures that enhance larval survival, population distribution, and feeding patterns (Ojaveer et al. 2010, Voss et al. 2011, Eero 2012). Additionally, the reduced presence of cod, grey seals, and harbor porpoises,

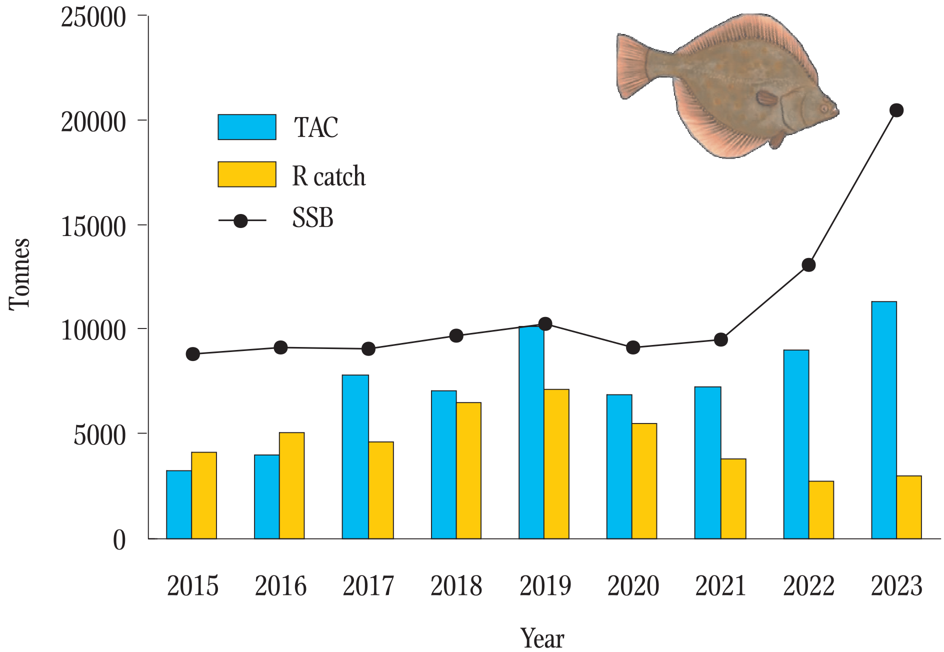

Figure 10. Plaice TAC limit, reported catch, and SSB estimate in tonnes, 2015-2023.

which have historically been their primary predators, has further contributed to their success (MacKenzie et al. 2011). Consequently, despite fluctuations in SSB resulting from fishing activities, the sprat population remains well above critical mortality rates, demonstrating a strong capacity to rebound. The resilience of this stock has led to a statistical test that lacks sufficient strength to reject H_0.

Pleuronectes platessa

Plaice, subdivisions 22–32

European plaice is the sole flatfish species subject to TAC limits. ICES (2024h, 2024i) oversees plaice fisheries as two distinct stocks: (1) subdivisions 21–23 (Kattegat, Belt Seas, and the Sound regions) and (2) subdivisions 24–32 (Baltic Sea, excluding the Sound and Belt Seas). However, the CFP combines subdivisions 22–32 into a single stock for monitoring purposes. Consequently, the reported catch and SSB data presented in Figure 10 encompasses ICES (2024h, 2024i) figures from both stocks to cover subdivisions where TAC limits are applicable. Moreover, the statistical analysis conducted on plaice revealed no correlation, with a correlation coefficient of $r = 0.69$, and a P-value exceeding the 0.05 threshold. Therefore, there was insufficient evidence to reject H_0. These results in Figure 10 further illustrate how the variables governing the status of plaice stocks move in different directions.

Plaice exhibited a robust increase in SSB, increasing from 8,820 to 20,477 (i.e., 132%) over the span of the eight-year period. This upward trend was likely driven by exceptionally high recruitment from the 2019 and 2020 year classes, rather than the effectiveness of TAC quotas (ICE, 2024f, 2024g). In response to strong recruitment, TAC limits for the stock increased significantly by 248% between 2015 and 2023. This increase can be attributed not only to the positive trajectory of SSB but also to the closure of cod stocks in 2019, which led to a shift in focus toward targeted flatfish catches (ICES 2024f, 2024g). These limits were subsequently revised downward in 2020 and 2021 due to concerns about high cod bycatch hindering their recovery (European Commission 2019, 2020).

In 2022 and 2023, SSB continued to rise, showcasing the species' resilience and rapid population growth. Despite these favorable developments, reported catch landings in the study period have consistently fallen short of the allocated TAC. Moreover, in the last two years, when TACs were at their highest, plaice landings decreased by almost 50% compared to 2020 and 2021. This is likely a consequence of the limited fishing opportunities for cod in the eastern Baltic, where plaice is caught as bycatch (ICES 2024h, 2024i). This suggests that the current fishing fleet lacks the capacity and motivation to fully utilize these quotas, rendering the generous TAC quotas ineffective. Furthermore, the number of active vessels under 12 meters in length, which make up the majority of plaice landings, continues to decline (Mickiewicz and Brocki 2018). This indicates that job opportunities exist within this stock, but there are no takers. Ultimately, the reason why the null hypothesis H_0 could not be rejected is that, rather than a direct influence, TAC quotas have no real-world impact on the reported catch or SSB dynamics.

Conclusions

The analysis revealed critical insights into the interplay between TAC limits and SSB across various fish stocks in the Baltic Sea, identifying two distinct groups (Table 3). Five stocks demonstrated a rejection of null hypothesis H_0 (i.e., group A), indicating a mutual influence between TAC limits and SSB between 2015 and 2023. This group included stocks that exhibited varying responses to TAC adjustments: two stocks experienced a collapse, two stabilized, and one showed growth.

Western cod had the strongest correlation (r = 0.97, P < 0.001), indicating a very strong relationship between TAC reductions and SSB. Eastern cod also showed a strong positive correlation (r = 0.85, P = 0.03), highlighting some degree of influence between the variables. Besides targeted extraction, the Eastern and Western cod stocks suffered from various external environmental conditions, resulting in significant declines in SSB. This decline necessitated drastic reductions in TAC quotas, ultimately making these stocks economically unviable. Bothnian herring and Riga herring exhibited strong correlations with TAC management, showing r = 0.87 (P = 0.002) and r = 0.88 (P = 0.002), respectively. Both stocks stabilized during the study period, indicating effective management through reduced TAC quotas that supported recovery and sustainability. Central herring, demonstrated a more moderate positive association (r = 0.71, P = 0.049), suggesting that while TAC reductions helped stabilize SSB, broader environmental factors also had an influence due to its larger geographic range, highlighting the need for a more nuanced understanding of its reproductive dynamics.

Table 3
Current status of each Baltic Sea stock: group A rejected H_0 and group B is not statically significant

Group A	Stock status	Group B	Stock status
Eastern cod	Collapsed	Western herring	Collapsed
Western cod	Collapsed	Sprat	Stable
Bothnian herring	Stable	Plaice	Healthy
Central herring	Stable		
Riga herring	Healthy		

In group B, the statistical tests resulted in P-values exceeding the 0.05 threshold, indicating insufficient evidence to reject the null hypothesis H_0. Despite this, trends observed in Table 1 and Figures 3–10 provide insight into the potential influence, or lack thereof, between the variables. For instance, Western herring (r = 0.61, P = 0.8) showed a weak correlation between TAC and SSB, indicating that attempts to adjust TAC quotas did not yield positive outcomes, primarily due to high natural mortality rates driven by anthropogenic changes and bycatch, rendering these management measures ineffective. Conversely, sprat (r = 0.15, P = 0.709) and plaice (r = 0.69, P = 0.39) demonstrated little to no correlation between TAC and SSB, suggesting that these stocks are influenced by favorable environmental conditions, reduced predation, and high recruitment rates rather than direct management interventions.

These findings emphasize the complexity of fisheries management in the Baltic Sea, revealing that the degree of influence between TAC and SSB varies significantly among stocks. When a strong positive correlation exists as seen in group A, effective management is crucial for enhancing SSB. In these cases, successful stock recovery is significantly influenced by management interventions. Conversely, the lack of correlation observed in group B reveals a more unpredictable scenario, where external ecological pressures dominate and management efforts alone may not be sufficient to curb SSB declines. This situation underscores the necessity for a more comprehensive management strategy that incorporates environmental and ecological factors, acknowledging that without a clear relationship, stock dynamics can resemble a "Wild West" environment, making outcomes far less predictable. In the future, fishery management should identify the optimal balance between TAC and SSB as well as external environmental factors to enable sustainable stock management.

Acknowledgments. The authors are grateful to the Faculty of Economics, University of Gdansk, for supporting this work. We are also thankful to several faculty members who have given us advice in piecing together the manuscript and its conceptual development. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Authors contributions. MR-D: formal analysis, investigation, writing and editing; GC: writing and editing, formal analysis, investigation, visualization.

Data Statement. The data that support the findings of this study are openly available in the repository "figshare" at: https://doi.org/10.6084/m9.figshare.22817750.v2.

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References

Andrade, C. (2019). The P Value and Statistical Significance: Misunderstandings, Explanations, Challenges, and Alternatives. Indian Journal of Psychological Medicine, 41, 210-215.

Cadrin, S.X., Dickey-Collas, M. (2014). Stock assessment methods for sustainable fisheries. ICES Journal of Marine Science, 72, 1-6.

Carpenter, G., Kleinjans, R., Villasante, S., O'Leary, B.C. (2016). Landing the blame: The influence of EU Member States on quota setting. Marine Policy, 64, 9-15.

Casini, M., Kornilovs, G., Cardinale, M., Möllmann, C., Grygiel, W., Jonsson, P., Raid, T., Flinkman, J., Feldman, V. (2011). Spatial and temporal density dependence regulates the condition of central Baltic Sea clupeids: compelling evidence using an extensive international acoustic survey. Population Ecology, 53, 511-523.

Cederqvist, J., Lidström, S., Sörlin, S., Svedäng, H. (2020). Swedish environmental history of the Baltic Sea: A review of Current Knowledge and Perspectives for the Future. Scandinavian Journal of History, 45, 663-688.

Dippner, J.W., Fründt, B., Hammer, C. (2019). Lake or Sea? The Unknown Future of Central Baltic Sea Herring. Frontiers in Ecology and Evolution, 7, 143, https://doi.org/10.3389/fevo.2019.00143.

Dziaduch, D. (2011). Diet composition of herring (*Clupea harengus* L.) and cod (*Gadus morhua* L.) in the southern Baltic Sea in 2007 and 2008. Oceanological and Hydrobiological Studies, 40, 96-109.

Eero, M. (2012). Reconstructing the population dynamics of sprat (*Sprattus sprattus balticus*) in the Baltic Sea in the 20th century. ICES Journal of Marine Science, 69, 1010-1018.

European Commission (2014). Baltic Sea: Commission confirms sustainability of herring stocks and proposes increased fishing opportunities for 2015. European Commission Press Release https://ec.europa.eu/commission/presscorner/detail/en/IP_14_959 (Accessed: April 5, 2024).

European Commission (2015). Commission proposes Baltic Sea fishing opportunities for 2016: more stocks than ever to be fished at sustainable levels. European Commission Press Releasehttps://ec.europa.eu/commission /presscorner/detail/en/IP_15_5563 (Accessed: April 5, 2024).

European Commission (2016). 2017 EU total allowable catches (TAC's) in the Baltic Sea. European Commission Press Release https://www.consilium.europa.eu/media /24265/eu-total-allowable-catches-tacs-in-the-baltic-sea-for-2017.pdf (Accessed: April 5, 2024).

European Commission (2017). 2018 EU total allowable catches (TAC's) in the Baltic Sea. European Commission Press Release https://www.consilium.europa.eu/media /23926/2018-eu-total-allowable-catches-tacs-in-the-baltic-sea.pdf (Accessed: April 5, 2024).

European Commission (2018). Baltic Sea: Council decides on how much can be fished in 2019. European Commission Press Release https://www.consilium.europa.eu /en/press/press-releases/2018/10/15/baltic-sea-counci l-decides-on-how-much-can-be-fished-in-2019/pdf (Accessed: April 5, 2024).

European Commission (2019). Council agreement on 2020 catch limits in the Baltic Sea. Press European Commission Press Release https://www.consilium.europa.eu/media/41053/191014-15-baltic-tacs_table.pdf (Accessed: April 5, 2024).

European Commission (2020). Council agreement on 2021 catch limits in the Baltic Sea. Press European Commission Press Release https://www.consilium.europa.eu/media/46485/20201019-baltic-tacs_table-ii_updated.pdf (Accessed: April 5, 2024).

European Commission (2021). Council agreement on 2022 catch limits in the Baltic Sea. Press European Commission Press Release https://www.consilium.europa.eu/media/52388/baltic-fish-table-2022_final.pdf (Accessed: April 5, 2024).

European Commission (2022). Council agreement on 2023 catch limits in the Baltic Sea. Press European Commission Press Release https://www.consilium.europa.eu/media/59663/baltic-fish-table-2023-final_revised.pdf (Accessed: April 5, 2024).

Farcas, A., Rossberg, A.G. (2016). Maximum sustainable yield from interacting fish stocks in an uncertain world: two policy choices and underlying trade-offs. ICES Journal of Marine Science, 73, 2499-2508.

Frommel, A.Y., Maneja, R., Lowe, D., Malzahn, A.M., Geffen, A.J., Folkvord, A., Piatkowski, U., Reusch, T.B.H., Clemmesen, C. (2012). Severe tissue damage in Atlantic cod larvae under increasing ocean acidification. Nature Climate Change 2, 42-46.

Frommel, A.Y., Maneja, R., Lowe, D., Pascoe, C.K., Geffen, A.J., Folkvord, A., Piatkowski, U., Clemmesen, C. (2014). Organ damage in Atlantic herring larvae as a result of ocean acidification. Ecological Applications, 24, 1131-1143.

Guedes Soares, C., Dejhalla, R., Pavletic, D. (2015). Fisheries Dynamics of the commercial fishery in the Baltic Sea: What are the driving forces? In: Towards Green Marine Technology and Transport (Ed.) C. Guedes Soares, R. Dejhalla, D. Pavletic, CRC Press: 917-926.

HELCOM, (2018a). Fisheries today, Available at: https://helcom.fi/action-areas/fisheries/commercial-fisheries/fisheries-today/ (Accessed: April 5, 2024).

HELCOM, (2018b). Commercial Fisheries, Available at: https://helcom.fi/action-areas/fisheries/commercial-fisheries/ (Accessed: April 5, 2024).

Hüssy, K., (2011). Review of western Baltic cod (*Gadus morhua*) recruitment dynamics. ICES Journal of Marine Science, 68, 1459-1471.

ICES, (2024a). Cod (*Gadus morhua*) in subdivisions 24-32, eastern Baltic stock (eastern Baltic Sea). ICES Advice: Recurrent Advice. https://doi.org/10.17895/ICES.ADVICE.21820497.

ICES, (2024b). Cod (*Gadus morhua*) in subdivisions 22-24, western Baltic stock (western Baltic Sea). ICES Advice: Recurrent Advice. https://doi.org/10.17895/ICES.ADVICE.21820494.

ICES (2024c). Herring (*Clupea harengus*) in subdivisions 30 and 31 (Gulf of Bothnia). ICES Advice: Recurrent Advice. https://doi.org/10.17895/ICES.ADVICE.21820521.

ICES 2024d. Herring (*Clupea harengus*) in subdivisions 20-24, spring spawners (Skagerrak, Kattegat, and western Baltic). ICES Advice: Recurrent Advice. https://doi.org/10.17895/ICES.ADVICE.25019273.

ICES 2024e. Herring (*Clupea harengus*) in subdivisions 25-29 and 32, excluding the Gulf of Riga (central Baltic Sea). ICES Advice: Recurrent Advice. https://doi.org/10.17895/ICES.ADVICE.25019276.

ICES 2024f. Herring (*Clupea harengus*) in Subdivision 28.1 (Gulf of Riga). ICES Advice: Recurrent Advice. https://doi.org/10.17895/ICES.ADVICE.25019279.

ICES 2024g. Sprat (*Sprattus sprattus*) in subdivisions 22-32 (Baltic Sea). ICES Advice: Recurrent Advice. https://doi.org/10.17895/ICES.ADVICE.25019687.

ICES 2024h. Plaice (*Pleuronectes platessa*) in subdivisions 21-23 (Kattegat, Belt Seas, and the Sound). ICES Advice: Recurrent Advice. https://doi.org/10.17895/ICES.ADVICE.25019435.

ICES 2024i. Plaice (*Pleuronectes platessa*) in subdivisions 24-32 (Baltic Sea, excluding the Sound and Belt Seas). ICES Advice: Recurrent Advice. https://doi.org/10.17895/ICES.ADVICE.25019438.

Kane, E.A., Ball, A.C., Brehmer, P. (2024). Dilemma of total allowable catch (TACs) allocated as shareable quotas: Applying a bio-economic game-theoretical approach to euro-mauritanian fisheries agreements. Aquaculture and Fisheries, 9, 674-681,

Kulke, R., Bödewadt, V., Hänselmann, K., Herrmann, J.-P., Temming, A., (2018). Ignoring the vertical dimension: biased view on feeding dynamics of vertically migrating sprat (*Sprattus sprattus*). ICES Journal of Marine Science, 75, 2450-2462.

Lewin, W.-C., Weltersbach, M.S., Ferter, K., Hyder, K., Mugerza, E., Prellezo, R., Radford, Z., Zarauz, L., Strehlow, H.V. (2019). Potential Environmental Impacts of Recreational Fishing on Marine Fish Stocks and Ecosystems. Reviews in Fisheries Science & Aquaculture, 27, 287-330.

MacKenzie, B.R., Eero, M., Ojaveer, H. (2011). Could seals prevent cod recovery in the Baltic Sea? PLoS ONE 6, e18998. https://doi.org/10.1371/journal.pone.0018998.

MacKenzie, B.R., Meier, H.E.M., Lindegren, M., Neuenfeldt, S., Eero, M., Blenckner, T., Tomczak, M.T., Niiranen, S., 2012. Impact of climate change on fish population dynamics in the Baltic Sea: A dynamical downscaling investigation. AMBIO 41, 626-636,

Martell, S.J.D. (2008). Fisheries Management. In: Encyclopedia of Ecology, Elsevier: 1572-1582.

Meier, H., Eilola, K., Almroth, E. (2011). Climate-related changes in marine ecosystems simulated with a 3-dimensional coupled physical-biogeochemical model of the Baltic Sea. Climate Research, 48, 31-55.

Mickiewicz, B., Brocki, W. (2018). Employment and wages in fisheries of the Baltic Rim countries. In: 19th International Scientific Conference "Economic Science for Rural Development 2018," 186-194, https://doi.org/10.22616/ESRD.2018.084.

Mion, M., Thorsen, A., Vitale, F., Dierking, J., Herrmann, J.P., Huwer, B., Von Dewitz, B., Casini, M. (2018). Effect of fish length and nutritional condition on the fecundity of distressed Atlantic cod *Gadus morhua* from the Baltic Sea. Journal of Fish Biology, 92, 1016-1034.

Möllmann, C., Cormon, X., Funk, S., Otto, S.A., Schmidt, J.O., Schwermer, H., Sguotti, C., Voss, R., Quaas, M. (2021). Tipping point realized in cod fishery. Scientific Reports, 11, 14259, https://doi.org/10.1038/s41598-021-93843-z.

Neuenfeldt, S., Bartolino, V., Orio, A., Andersen, K.H., Andersen, N.G., Niiranen, S., Bergström, U., Ustups, D., Kulatska, N., Casini, M. (2020). Feeding and growth of Atlantic cod (*Gadus morhua* L.) in the eastern Baltic Sea under environmental change. ICES Journal of Marine Science, 77, 624-632.

Nielsen, E.E., Hansen, M.M., Schmidt, C., Meldrup, D., Grønkjaer, P. (2001). Population of origin of Atlantic cod. Nature, 413, 272-272.

Ojaveer, E., Kalejs, M. (2010). Ecology and long-term forecasting of sprat (*Sprattus sprattus balticus*) stock in the Baltic Sea: a review. Reviews in Fish Biology and Fisheries, 20, 203-217.

Petereit, C., Hinrichsen, H.-H., Franke, A., Köster, F.W. (2014). Floating along buoyancy levels: Dispersal and survival of western Baltic fish eggs. Progress in Oceanography, 122, 131-152.

Polte, P., Gröhsler, T., Kotterba, P., Von Nordheim, L., Moll, D., Santos, J., Rodriguez-Tress, P., Zablotski, Y., Zimmermann, C. (2021). Reduced Reproductive Success of Western Baltic Herring (*Clupea harengus*) as a Response to Warming Winters. Frontiers in Marine Science, 8, 589242, https://doi.org/10.3389/fmars.2021.589242.

Psuty, I., Zaucha, J., Mytlewski, A., Saska, M., Szymanek, L. (2021). The use of the contribution margin on the valorisation of polish fisheries for maritime spatial planning. Ocean & Coastal Management, 211, 105751, https://doi.org/10.1016/j.ocecoaman.2021.105751.

Raid, T., Kornilovs, G., Lankov, A., Nisumaa, A.-M., Shpilev, H., Järvik, A. (2010). Recruitment dynamics of the Gulf of Riga herring stock: density-dependent and environmental effects. ICES Journal of Marine Science, 67, 1914-1920.

Raid,T.,Arula,T., Kaljuste, O., Sepp, E., Järv, L., Hallang,A., Shpilev, H., et al. (2015). Dynamics of the commercial fishery in the Baltic Sea: What are the driving forces? Towards Green Marine Technology and Transport, Proceeding of 620 the 16th International Congress of the International Maritime Assotiation of the Mediterranean (IMAM 2015), Pula, Croatia, 21-24 September: 897–906

Ratner, B. (2009). The correlation coefficient: Its values range between +1/-1, or do they? Journal of Targeting, Measurement and Analysis for Marketing, 17, 139-142.

Rosciszewski-Dodgson, M.J., Cirella, G.T. (2024). Environmental drivers affecting the status of top commercial fish stocks in the Baltic Sea: review. Frontiers of Marine Science, 11, 1399707, https://doi.org/10.3389/fmars.2024.1399707.

Schaber, M., Hinrichsen, H., Gröger, J. (2012). Seasonal changes in vertical distribution patterns of cod (*Gadus morhua*) in the Bornholm Basin, central Baltic Sea. Fisheries Oceanography, 21, 33-43.

Skalski, J.R., Ryding, K.E., Millspaugh, J.J. (2005). Analysis of Population Indices. In: Wildlife Demography. Elsevier: 359-433.

Skalski, J.R., Townsend, R.L., Gilbert, B.A. (2007). Calibrating Statistical Population Reconstruction Models Using Catch-Effort and Index Data. Journal of Wildlife Management, 71, 1309-1316.

Slutsky, D. (2014). The effective use of graphs. Journal Wrist Surgery, 03, 067-068.

Stiasny, M.H., Mittermayer, F.H., Sswat, M., Voss, R., Jutfelt, F., Chierici, M., Puvanendran, V., Mortensen, A., Reusch, T.B.H., Clemmesen, C. (2016). Ocean acidification effects on Atlantic cod larval survival and recruitment to the fished population. PLOS ONE, 11, e0155448, https://doi.org/10.1371/journal.pone.0155448.

Stunt, J., Van Grootel, L., Bouter, L., Trafimow, D., Hoekstra, T., De Boer, M., (2021). Why we habitually engage in null-hypothesis significance testing: A qualitative study. PLOS ONE, 16, e0258330, https://doi.org/10.1371/journal.pone.0258330.

Ulrich, C., Boje, J., Cardinale, M., Gatti, P., LeBras, Q., Andersen, M., Hemmer-Hansen, J., Hintzen, N.T., Jacobsen, J.B., Jonsson, P., Miller, D.C.M., Nielsen, E.E., Rijnsdorp, A.D., Sköld, M., Svedäng, H., Wennhage, H. (2013). Variability and connectivity of plaice populations from the Eastern North Sea to the Western Baltic Sea, and implications for assessment and management. Journal of Sea Research, 84, 40-48.

Voss, R., Hinrichsen, H.-H., Quaas, M.F., Schmidt, J.O., Tahvonen, O. (2011). Temperature change and Baltic sprat: from observations to ecological-economic modelling. ICES Journal of Marine Science, 68, 1244-1256.

Voss, R., Quaas, M.F., Stiasny, M.H., Hänsel, M., Stecher Justiniano Pinto, G.A., Lehmann, A., Reusch, T.B.H., Schmidt, J.O. (2019). Ecological-economic sustainability of the Baltic cod fisheries under ocean warming and acidification. Journal of Environmental Management, 238, 110-118.