

Follow the herring – A case study on the interplay between management and markets for marine resource utilization

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ABSTRACT

Seafood offers opportunities for more sustainable diets through having a generally high nutritional value at lower environmental pressures relative to other animal protein. Opportunities for, and challenges of, seafood production and consumption are however context dependent. Here, a case study of Swedish fisheries for Atlantic herring *Clupea harengus* in the Baltic Sea is added to the scientific discourse. Motivated from a heated public debate in Sweden, the purpose is to provide a first sustainability assessment of current value chains: direct consumption versus fish meal and oil production. The case study highlights the importance of taking a value chain perspective for seafood from capture fisheries – i.e., the prerequisites, constraints and opportunities for different actors – and pay attention to misaligned economic incentives that may conflict sustainable use. Although lower greenhouse gas emissions, higher nutritional value, more affordable seafood for consumers and higher economic value for fishermen may be achieved by direct consumption of herring, several challenges exist. These include above all an urgent need to safeguard sustainable and equitable fisheries exploitation; current management is increasingly eroding opportunities for value chains producing herring for food. It is also vital with realistic expectations; redirecting more herring to direct consumption also requires strategies for how potential health risks can be reduced and consumer interest could increase. Overall, the study illustrates net-effects on marine resource utilization from interplay between actors along the value chain in various ways – with implications and insights of importance for a long-term sustainable Blue Economy.

1. Introduction

Seafood offers many opportunities for future food and nutrition security, with favorable nutritional value and many environmental advantages over land-based animal production [19,4]. Growth in production and consumption is thus seen as integral in recent visions of a sustainable Blue Economy, where improved use of the oceans has the potential to solve many of present-day challenges (e.g., [41]). However, the notion of that opportunities exist from exploitation of the ocean is nothing new and may not necessarily promote sustainable use [9]; it is vital with realistic expectations and evidence-based strategies to enable a truly sustainable societal transformation (e.g., [18,61]).

It has however been found that seafood in general fails to be integrated in a fair and relevant manner in the scientific discourse on sustainable diets [17]. To unlock the potential of seafood in the Blue Economy, further investigations on the local prerequisites today and potential future role of seafood are therefore needed. As an example, it has often been suggested that increased utilization of fish directly as food instead of indirectly through feed is needed (e.g., [8]), but the

specific circumstances behind current practice in different fisheries need improved understanding (see e.g., [33]). Here, a case study of Swedish pelagic fisheries in the Baltic Sea is investigated.

1.1. Seafood production in Sweden

Sweden is a country with a long coastline and has in recent years developed strategies and ambitions both related to aquaculture and capture fisheries [56] and domestic food production [57]. Today, however, inertia prevails for the seafood sector; aquaculture production is marginal and not growing (~10 000 ton live-weight annually) and capture fisheries experience overall decrease in landings and number of vessels [49] – consequently, current seafood consumption at ~124,000 t edible is today by two-thirds dependent on imports [25]. The promises of a Blue Economy in Sweden – i.e., a growing and prosperous seafood sector in line with national strategies [56] and ambitions of strategic funds allocated (<https://www.bluefood.se/en/>) – are yet to be realized.

The most important Swedish seafood production volume today comes from pelagic fisheries (94% of volume, or around 130,000 tons in

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2022), a fleet mainly targeting Atlantic herring *Clupea harengus* and European sprat *Sprattus sprattus* in the Baltic Sea [48]. Individually transferable fishing rights (ITQ) was introduced in 2009 with the aim to enable a restructuring of the fleet to improve economic performance and decrease risks for overfishing [55]; there was a mismatch between fishing capacity and available quotas, a situation which is the most common motivation for introducing ITQs globally [26]. With this regulation, the pelagic fleet was reduced from 82 to 37 vessels between 2009 and 2013 when it stabilized. The overall, stated policy objective was arguably in line with realizing a sustainable Blue Economy in the form of enabling a prosperous seafood sector: establish a long-term sustainable fishery – economically, socially and ecologically – and enable improved opportunities for the processing industry on land to plan their businesses while allowing for the fishery to adjust their activities to meet the demands on land [55].

Today it can be concluded that unintended consequences occurred when ITQs were implemented in relation to the stated policy objectives, reinforcing earlier challenges identified and exacerbating a development into a societal trajectory less sought for. The main output of the fishery today – large and irregular landing volumes of small fish of lower quality by large vessels – is mainly suitable for fish meal and oil production. The share of landings directly destined for feed (a.k.a. reduction fisheries) has increased from around 50–77% of volume from the total pelagic sector between 2013 and 2022 [48]. Although the large-scale pelagic fishing sector is profitable today [49], the Swedish processing industry is struggling with lack of fish and needs to change sourcing strategy through e.g., import herring. Furthermore, there is a lack of large sizes of herring and declining coastal fisheries in the Baltic Sea (e.g., [51,45,46,52]). Disentangling effects on sustainable use from an ITQ introduction relative to other factors such as quota setting, uncertainties in stock assessments and markets is commonly a challenge [26]; the development may not be attributed to introduction of an ITQ in Sweden alone but represents a change in path that merit further investigation. Current situation is also related to that market opportunities are limited for herring from certain parts of the Baltic Sea due to presence of undesired substances such as dioxins. This problem is particularly related to fish of larger sizes caught in areas further north [25]. With growth of global aquaculture, also an ambition of realizing a Blue Economy, fish as a resource is a highly valuable raw material for an industry that is experiencing shortages relative to demand [16]. This provides economic incentives for fisheries to catch high volumes of fish that does not require premium food grade quality.

Meanwhile, there has been a change in the societal debate in Sweden. A few years back, consumer issues raised concerning Baltic Sea herring mainly concerned fear of associated health risks with consumption (e.g. [58]), a risk underpinned by the Swedish Food Agency in the dietary advice [42]. It may thus not be surprising that the pelagic fishing fleet has increasingly shifted effort towards fish meal and oil production, given low consumer interest and the opportunities to reduce harmful substances during processing to fish meal and oil. However, more recently, the societal debate has increasingly centered around concern of the low utilization for direct consumption and that a few large vessels make high profits, seen in Swedish media coverage (e.g., [10,54]) and governmental discussions [53]. From a scientific perspective, there is also evidence for risks to stocks and ecosystem from current exploitation pattern (e.g., [45,50]). Large volumes of mixed catches of herring and sprat also adds to uncertainties to stock assessments, with occurrence of species misreporting [27]. It seems like there is a surprise or even shock across various actors that the development of the fishery took this course. With this recent attention to how pelagic fisheries are performed today, Sweden is now seeing a development that can be described as ‘governance via persuasion’ – other societal actors than fishery management are pushing for change [35]. Swedish policy makers are now increasingly urged to act, but it is unclear on what and how and what is possible to change.

To this end, current management objectives for Swedish fisheries and

supply chains of herring from the Baltic Sea are not seen as fulfilling the desired trajectory for the future. It is however unclear what characterizes a realistic transformation towards meeting societal goals – “more food from the sea” – and the effect on sustainability of the food system from alternative utilization. As a starting point, there is a need for both a better understanding of the Swedish pelagic fisheries-based production system today, potential drivers and conflicting policy objectives and which alternative supply chains are realistic and desirable to pursue. The objective of this study is to provide a first sustainability assessment of value chains based on Swedish pelagic fisheries of herring in the Baltic Sea with the aim to identify and discuss hindrances and opportunities for allowing for a larger share of herring landings to be used directly as food.

2. Material and method

Data were collected and compiled from different sources to quantify a set of environmental, social and economic indicators for the current values chain, linked to societal goals related to sustainable food systems (Table 1). The two value chains considered were direct consumption of

Table 1
Indicators quantified and evaluated for current value chains for Swedish herring fisheries in the Baltic Sea.

Dimension	Indicator	Motivation and details
Environmental	Sustainable exploitation of target stocks	One of the objectives of the ITQ introduction in Sweden was to decrease risks for overfishing[55] and sustainable exploitation is a prerequisite for supply chains based on capture fisheries (e.g.,[59]). Analyzed in terms of trends in fishing mortality (F) and spawning stock biomass (SSB) over time as reported in the latest ICES advice.
	Greenhouse gas emissions	Societal goals to reduce emissions[28, 59]. Quantified in kg CO ₂ e/kg product for i) edible herring fillet and ii) fish meal and oil through Life Cycle Assessment.
Social	Contribution to Swedish seafood self-sufficiency	Dietary advice in Sweden recommends increased consumption of seafood[42] and the Swedish food strategy includes an ambition of improved self-sufficiency[57]. Quantified in terms of current supply chains percentage theoretical contribution to i) direct seafood consumption and ii) indirect seafood consumption through sustaining herring raw material requirements for aquaculture, exemplified here as farmed salmon (top consumed seafood in Sweden).
	Nutritional value	Nutritional quality of food intake forms the basis of dietary advice[42]. Analyzed in terms of nutrient density score (NDS ₂₁) of herring from the Baltic Sea and salmon farmed in Norway, representing the combined nutritional value of 21 nutrients based on Hallström et al.[21].
Economic	Economic value for producers	Profitability for fishermen, one of the objectives of Swedish fishery management[55]. Quantified in SEK per kilo landing based on sale slip data.
	Seafood affordability	Affordability of seafood for consumers, motivated from cost being an important determinant for seafood consumption[20]. Analyzed in terms of Consumer Price Index (CPI) development for herring and salmon based on Statistics Sweden.

herring versus indirect consumption through fish meal and oil production that may support consumption of farmed Atlantic salmon (*Salmo salar*); of important note, the fish meal and oil production enter a global market and not necessarily end up in salmon farming, but salmon is chosen here since it represents the top consumed seafood product in Sweden [25]. The selection of indicators was motivated from a combination of i) the possibility to quantify outcome (based on official data or limited collection effort) and ii) current societal debate and policy ambitions in Sweden. The intention was to allow for a simple and initial evaluation of aspects commonly discussed concerning these value chains. The list of potential indicators thus represents a sub-set of indicators and could be considerably longer (e.g. health risks, employment, equity, ecosystem effects, size structure of fish stocks) but is here attempting to narrow down to long-term sustainable food provisioning, including nutritional value and economy for producers and consumers.

Input data to the indicators was based on sales slip data (destination of landings to feed or food, price at first sale) and logbook data (landings, vessel sizes, fishing area, mesh sizes, gear types) for herring fisheries in the Baltic Sea (ICES subdivisions 22–32), provided by the Swedish Agency for Marine and Water Management (SwAM) for the years 2015–2021. Additional data and information related to challenges and potentials of current and future supply chains, including input needed for quantifying indicators, was collected through literature, societal agendas and views (such as newsletters from industry, political debates and scientific reports and policy briefs), and informal discussions with different value chain actors on different occasions (pelagic processing industry in Sweden, Danish fish meal and oil industry, Swedish pelagic fisheries' representatives). For specific indicators, data input and analysis are described below for each indicator.

2.1. Sustainable exploitation

Available time series for spawning stock biomass (SSB) and fishing mortality (F) for herring stocks caught in the Baltic Sea was extracted from the latest ICES advice [27]. There are three management units (stocks) of relevance to Swedish fisheries (out of four in total in the Baltic Sea), i.e., the western Baltic stock (subdivisions 20–24), the central Baltic stock (subdivisions 25–29 and parts of 32) and the Gulf of Bothnia stock (subdivisions 30–31); however, stock mixing occurs. Because Sweden is not the only country fishing for herring in the Baltic Sea, the Swedish share of quota for the different stocks was also gathered. The indicators were analyzed in terms of SSB and F development under the time period 2009–2021 (covering the development since the year of introduction of ITQ in Swedish fisheries) as provided in the latest advice by ICES.

2.2. Greenhouse gas (GHG) emissions

Greenhouse gas (GHG) emissions were modelled based on Life Cycle Assessment (LCA) methodology [29,30] with IPCC 2013 [28] impact factors. Allocation was based on mass, i.e. equal contribution to emissions from the production of fillet and side products generated, motivated by all volumes being utilized (either for direct consumption or for fish meal and oil production). Emissions (in kg CO₂e) from current Swedish value chains were quantified for two functional units, i) per kg herring fillet processed for direct consumption and ii) per kg fish oil or meal at factory gate.

Fuel use data was collected from Swedish fisheries for the year 2021 through a questionnaire jointly developed with the board of the Swedish Pelagic Federation (SPF). The questionnaire was distributed to the members of the SPF, who were asked to provide estimates on fuel use per landing for their fishing activities on a trip basis for the year 2021. The results were collected by a SPF board member and included 24 vessels categorized as small-scale (<12 m) and large scale (>12 m), which based on logbook data together landed 86% of the Swedish landings of herring in the Baltic Sea in 2020. Questions included average fuel use

per trip from different fishing areas (ICES subdivisions 25–29 or 30–31) and for different purposes (reduction for fish meal and oil or for direct consumption), total landings for the same trips and share of herring, share destined to direct consumption and a voluntary comment on what matters most for their fuel efficiency. When ranges in landing volume and fuel use was reported, fuel use intensity (in l/kg) was based on average values reported for both fuel use and landing volume. Data from one vessel was excluded since it was judged to be an outlier relative to the other vessels. For conversion of fuel use intensity (l/kg) to GHG emissions, diesel combustion was based on Drivkraft Sverige [12] and emissions from production was based on the database Ecoinvent version 3. Furthermore, non-fuel related emissions from fisheries were added following the approach initially developed by Parker et al. [37] but adjusting the conversion factor to pelagic fisheries based on Ziegler et al., [62], i.e. multiplied by 1.3.

Primary data from one fish meal and oil processing plant in Denmark was used for modeling GHG emissions from one kilo of fish meal and oil at factory gate. Contribution from processing to GHG emissions included energy use in the form of natural gas and electricity. Plants are located right by the sea and receive fish predominately via direct landing [39]. Remaining transport distances and transport mode (ferry or road) were estimated via Google maps to model contribution to GHG emissions from transports. Contribution of fisheries of pelagic fish to GHG emissions were modelled using the fuel use data provided by the SPF members.

Fillet yield was based on the Swedish Food Agency food database (42 g herring fillet or 41 g salmon fillet from 100 g; [43]). No specific data on the emissions from filleting Baltic Sea herring for direct consumption could be provided by the Swedish processing industry. This contribution was instead based on a Norwegian report in which it was estimated that on average ~225 kWh/ton is required for processing of pelagic fish [44]; the GHG emission of the energy requirement was based on Ecoinvent data (average European grid mix).

2.3. Contribution to self-sufficiency

Current Swedish seafood consumption volumes for the latest available year (2019) were retrieved from Hornborg et al. [25]. Sale slip data on landings from Swedish herring fisheries in the Baltic Sea during 2021 were used to separate production volumes into i) potential direct consumption of seafood and ii) theoretic contribution to indirect seafood consumption through delivery of herring raw material to sustain aquaculture, here based on requirements of farmed salmon (top consumed species in Sweden). Of note, the market for seafood and fish meal and oil is highly globalized, and herring from the Baltic Sea does not necessarily end up producing salmon farmed in Norway, nor does the herring for direct consumption necessarily end up with Swedish consumers; only theoretic contributions could be quantified since no data could be obtained on where exactly the different flows ends up. Indirect consumption was based on herring landings for fish meal and oil production (including unknown destination, on average ~17% between 2015 and 2021), the fish meal and oil yield of herring (based on Danish processing data; [39]) and the current herring inclusion rate (from all fishing grounds) in Norwegian salmon feed [31]. This indirect consumption through farmed salmon is to a large extent also supported by other ingredients, both marine and terrestrial; in 2016, over 1.63 million tons of feed (of which 25% was based on marine ingredients) was required to produce over 1.25 million tons of salmon in Norway [1]. Only considering herring contribution intends to illustrate the general relationship with the current demand of herring resources for salmon production, and between Swedish seafood production and consumption.

2.4. Nutritional value

Different seafood consumed in Sweden have a highly variable contribution of amounts of different nutrients [21]. To account for the

overall nutrition provisioning from consumption of farmed salmon relative to Baltic herring, the Nutrient Density Score (NDS) that was identified to be the most relevant in Hallström et al. [21] was used, i.e., NDS-C. This represents an index of the combined nutritional value of a certain amount of seafood based on 24 nutrients, with i) no weighting of individual nutrients to adjust the score to the Swedish nutritional status, and ii) no capping of individual nutrients to 100% of the recommended daily intake level. This data was retrieved for raw herring from the Baltic Sea and raw salmon farmed in Norway from Supplementary Material Table S9 in Hallström et al. [21].

2.5. Economic value for producers

Average annual first-sale prices for fishers at landing (based on sale slip data) was calculated and analyzed separately for landings destined for direct consumption in Sweden versus those directed towards fish meal and oil production in Denmark.

2.6. Seafood affordability

Consumer Price Index (CPI) measures the price development for products on a monthly basis relative to a certain base year (set as 1). This data was retrieved from Statistics Sweden for the herring and salmon products available in the database: pickled herring and fresh salmon [47]. No data was available on fresh herring, however, these are the products commonly bought by Swedish consumers in retail and are thus comparable for this indicator, although noting that the nutritional value may differ between fresh and pickled herring. The latest available base year for CPI was 2003 for both products.

3. Results

3.1. Swedish pelagic fisheries for herring in the Baltic Sea

During 2015–2021, overall landings of herring from Swedish fisheries in the Baltic Sea (ICES subdivisions 22–32) decreased from peaks at around 80 000 tons to less than 50 000 tons (Fig. 1). Roughly 8–15% of the landings was of food grade quality at the point of landing, while an additional 13–26% has a non-specified post-harvest destination. Uncertainties are based on that utilization is not mandatory information in landing declarations. From instead looking at logbook data on mesh sizes used in the fishery, it can be seen that 5–16% of reported landings come from fisheries with a mesh size of ≥ 32 mm (a targeting pattern for direct consumption), indicating that the non-specified landings in the sale slip data are also destined for feed.

In Swedish fisheries, Baltic herring is today mainly caught by vessels over 12 m in length (96–97% of landings during 2015–2019), but there is still a high number of small fishing vessels (<12 m) landing small volumes of herring from the Baltic Sea (up to 500 tons per vessel and year, most vessels considerably smaller volumes).

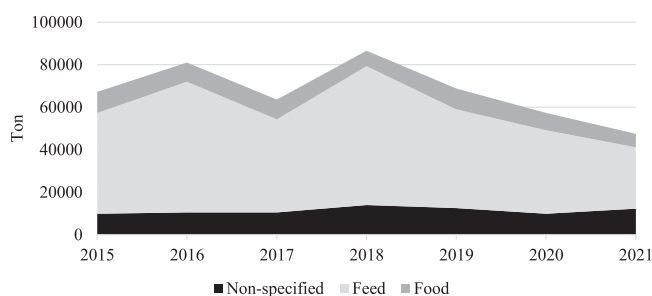


Fig. 1. Development of reported herring landings from Swedish fisheries in the Baltic Sea (ICES subdivisions 22–32) for different purposes. Non-specified implies that the destination of landings has not been reported. Source: sale slip data from Swedish Agency for Marine and Water Management.

The vessels associated to the Swedish Pelagic Federation (SPF) comprise of mainly larger vessels, but also includes a few smaller ones (four included in this analysis). Based on information from a representative of the SPF, maximizing volumes is more important than species for the largest vessels fishing for fish meal and oil production. Therefore, due to quota restraints for herring stocks in the Baltic Sea, this has led to European sprat becoming increasingly important for the Swedish large scale fishing industry; herring may to some extent be seen as an unwanted by-catch in these fisheries if limiting fishing opportunities. When landing herring, the Swedish fleet in the Baltic Sea can today be separated into six to nine different sub-fisheries (depending on if fisheries should be categorized as separate sub-fisheries when engaged seasonally or having full year fishing activities). Overall, more vessels are active in the southern part of the Baltic Sea, which is also where most vessels are fishing herring for direct consumption (Table 2). For the fishers participating in the study, different shares of the landing end up being used as food, even when targeting herring for direct consumption. According to the fishing industry, this has two main reasons. One is based on catch composition; the catch may be dominated of herring too small to be of interest to the filleting industry. The other is targeting behavior: vessels may fish with large meshes (38–40 mm) to selectively target large fish; use small meshes (16 mm) with catches including small fish that are directly frozen for consumption and exported; or fish with varying mesh sizes but instead sort catches at landing to allow for different percentages to be used for consumption. Pure reduction fisheries are more pre-determined activities to maximize for volume and may also include vessels more active in other fishing areas that seasonally enter the Baltic Sea to be able to fish all year round.

3.2. Sustainability assessment

3.2.1. Sustainable exploitation of target stocks

Based on time series available from ICES [27], stock status has deteriorated over time, with SSBs between 66% and 80% in 2020 compared to 2008 (Fig. 2). The stocks are managed under the Common Fisheries Policy of the EU and are to different extent shared between member states. The most alarming signal is seen for the western Baltic stock (ICES subdivisions 20–24), which is the stock Swedish fisheries has the largest share of (56%) – zero catch advice from ICES for the year 2023. Fishing mortality has been high or fluctuating since the start of the time series with no positive development seen after 2009 – it is higher today for two of the stocks (the Gulf of Bothnia and central stock; ICES subdivisions 25–27, 32 and 30–31), but lower for one of the stocks (the western stock; ICES subdivisions 20–24) (Fig. 2). The level of exploitation of the stocks has varied during the studied time period:

- For the Gulf of Bothnia stock (ICES subdivisions 30–31), reported landings increased until 2016 and have since declined. Fishing pressure relative to management objectives for sustainable exploitation (F_{MSY}) was low until around 2010, when it suddenly increased but has declined in recent years. Biomass (SSB) has shown a downward trend since the early 1990s
- For the central stock (ICES subdivisions 25–29 and 32 excl. Gulf of Riga), reported landings also increased in the mid-2010s but has declined in recent years, with a fluctuating fishing mortality. Fishing pressure has varied, but generally been above F_{MSY} . Biomass (SSB) has declined since the 1980s
- For the western stock (ICES subdivisions 20–24), reported landings have been declining continuously, with fishing mortality generally high relative to reference points. Biomass (SSB) has been below B_{lim} since around year 2006.

3.2.2. Greenhouse gas emissions

Landing volume and fuel consumption considerably varied in absolute values both between vessels and between trips for individual vessels, but the overall variation in mean value for fuel use intensity was

Table 2

The Swedish Pelagic Federation (SPF) associated pelagic fishing fleet operating in the Baltic Sea. Note that one vessel can be active in several sub-fisheries and the whole Swedish fleet is not represented (mainly lacking small vessels, in particular in the northern Baltic Sea).

Area (ICES subdivision)	Fleet segment	Sub-fishery	No. of vessels	Share of landings destined for food	Site for landing
Southern Baltic Sea (25–29)	Large scale (>12 m)	Reduction, seasonal Consumption	14 4 (seasonal); 6 (full year)	< 10% ~80–90%, but varies between vessels and seasons	Sweden or Denmark Sweden, Denmark, Latvia
	Small-scale (<12 m)	Reduction, mainly full year Consumption, seasonal and full year	3 2	- < 20%	Sweden Sweden
	Large scale (>12 m)	Reduction, seasonal Consumption, seasonal	6 1	- ~30%	Denmark or Sweden Latvia
Northern Baltic Sea (30–31)	Small-scale (<12 m)	Consumption	no data obtained		

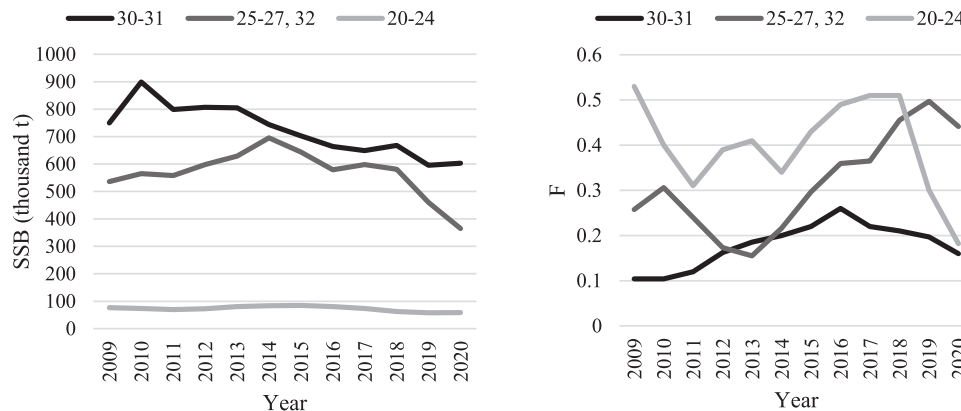


Fig. 2. Development for herring stocks in the Baltic Sea of relevance to Swedish fisheries, the Gulf of Bothnia (30–31), the central (25–27, 32), and the western stock (20–24) since 2009 in the form of spawning stock (SSB) development (left panel) and fishing mortality (F) for ages 3–6 (for 20–24 and 25–27, 32) and ages 3–7 for 30–31 respectively (right panel). Based on time series provided in latest ICES advice [27].

small (0.08 ± 0.04 l/kg LW for all fisheries). Precise estimates are complicated because some vessels reported ranges in both fuel consumption and landing volume. When analyzed separately, small differences may be seen, e.g., in the higher end for fisheries in the northern part of the Baltic Sea (ICES subdivisions 30–31) whereas lower in the southern part (ICES subdivisions 25–29) respectively. The data did not allow for separation between fishing gears. Otherwise, no overall differences in fuel efficiencies can be seen between vessel sizes nor targeting pattern other than minor differences for individual vessels between targeting pattern. Based on the average fuel use intensity, herring fillets from the Baltic Sea is associated with ~ 0.40 kg CO₂e per kg after processing (Table 3).

For landings destined for fish meal and oil production, they are either landed directly in Denmark at the processing plants or transported by trucks. Based on data from one Danish processing plant, production of one kg of fishmeal and oil is associated with ~ 1.86 kg CO₂e/kg fish meal and oil after processing (Table 3). After processing, the fish meal and oil production in Denmark have different markets: 95% of the fish oil is directed to aquaculture (the remaining 5% to the pet feed industry) whereas only 49% of the fish meal is directed to the aquaculture industry; fish meal is besides aquaculture to a larger extent directed to land-based animal production (37%) and pet feed (14%).

3.2.3. Self-sufficiency

The total Swedish seafood consumption in 2019 was $\sim 124,000$ tons in edible form of which $\sim 30,000$ tons comprised of salmon and $\sim 15,000$ tons herring respectively. Swedish herring fisheries in the Baltic Sea for direct consumption could sustain a theoretic contribution of 17% of the Swedish herring consumption the same year (or 2% of total seafood consumption). Based on current inclusion rate of herring in Norwegian salmon feed and fish meal and oil yields, approximately 0.24 kg

live weight herring (whole or trimmings), would be required to produce one kilo live weight farmed salmon (feed conversion ratio 1.3, the remaining feed requirements come from other marine species and terrestrial ingredients). Based on this relationship, herring landings from Swedish fisheries in the Baltic Sea (from reduction fisheries and side-streams generated from filleting combined, $\sim 45,000$ tons) can have a theoretical, indirect contribution of herring raw material that may support the herring requirements of a salmon production volume corresponding to 256% of current Swedish consumption of farmed salmon (or 62% of total Swedish seafood consumption); the herring share of total feed demand of salmon is however small and it is unclear to which extent Baltic Sea herring is directed towards Norwegian salmon farming.

3.2.4. Nutritional value

The nutrient density score for herring from the Baltic Sea is 8.7 whereas Atlantic salmon 6.8. Content of different nutrients varies between the two species, where the nutrient density score of herring is mainly driven from content of vitamin B12, vitamin D and Omega-3 whereas for farmed salmon, it is the content of vitamin D, vitamin B12 and niacin.

3.2.5. Economic value for producers

The economic value at first sale for fishermen in SEK/kg has been relatively stable, but with slight increase for herring for feed (average value 1.98 ± 0.19 SEK/kg). For herring destined directly as food, the economic value is higher but has fluctuated more (average value 5 ± 0.75 SEK/kg) and show no trend over time. Fisheries for feed is also generally associated with higher landing volumes per trip. Based on data collected from the SPF, fisheries for food catch between 7 and 500 tons per trip depending on vessel size (trips predominantly lasting one day) but could catch up to 700 tons on longer trips. For reduction fisheries,

Table 3
Sustainability indicators and policy perspectives for the current value chains based on Swedish Baltic Sea herring fisheries.

Dimension	Indicator	Outcome	Policy perspectives
Environmental	Sustainable exploitation of target stocks	In 2020 compared to 2008, biomass (SSB) has been reduced for all stocks. Fishing mortality has decreased for one stock (in ICES subdivisions 20–24) but is still high and has increased for the other two stocks.	Quotas are set for the stocks regardless of destination of landings, but current exploitation is conflicting obligations on ensuring sustainable use (e.g., [59]).
	Greenhouse gas emissions	Around 0.40 kg CO ₂ e/kg herring fillet and 1.86 kg CO ₂ e/kg fish meal and oil.	Emissions are lower for a value chain with herring for direct consumption, with current practice conflicting climate mitigation [28,59].
Social	Self-sufficiency	Theoretically, fisheries destined for fish meal and oil production has a larger indirect contribution to Swedish total seafood consumption (62%) in the form of provision of marine raw material to aquaculture compared to direct contribution (2%) in the form of herring for direct consumption.	Due to the uncertainties on where actual volumes end up, only allowing for theoretical estimates, the net effect is unclear.
	Nutritional value	Herring from the Baltic Sea has a higher nutrient density score (8.7) compared to farmed Atlantic salmon (6.8).	Direct consumption of herring has a favorable nutritional value compared to farmed salmon; however, undesired substances in Baltic herring from some areas require strategies to minimize risks [42].
Economic	Economic value for producers	Landings for direct consumption fluctuates more in value but offers higher revenue for fishermen per kilo (5 ± 0.75 SEK/kg) compared to fisheries for fishmeal and oil (1.98 ± 0.19 SEK/kg).	A fishery for direct consumption is associated with higher value of landings per kilo, but profits are maintained in the reduction fishery by higher catch efficiency and thus larger volumes, in line with the intention behind restructuring of the fleet [55].
	Seafood affordability	The consumer price of salmon relative to herring has more than doubled compared to 2003.	The price development of salmon compared to herring is unfavorable from a consumer affordability perspective, conflicting economic dimensions of sustainability [59].

trip length is more variable (lasting from 1 to 10 days), with catches between 1 and 1 300 tons per trip.

3.2.6. Seafood affordability

The Consumer Price Index indicates that salmon has become more than three times more expensive since 2003 whereas the herring price has only increased by 54%.

3.3. Summary of outcome for the two value chains

Outputs generated from 1 000 kg live-weight herring from Swedish Baltic Sea fisheries is today either around 420 kg fillets for direct consumption or 201 kg fish meal and 67 kg fish oil. Many indicators are in favor of a value chain producing herring fillet for direct consumption (Table 3). Regardless of value chain, ensuring sustainable exploitation levels is still required for fishery management agencies regulating the fishery. From a post-harvest perspective, fillets for direct consumption are associated to less than one fourth of greenhouse gas emissions of the production of fish meal and oil and herring has a higher nutritional value compared to salmon. From a consumer preference perspective, the current utilization however allows for a theoretical higher indirect contribution to Swedish seafood consumption through providing feed for aquaculture relative to sustaining demand of herring for direct consumption. Economic indicators also favor value chains based on fillets over fish meal and oil production, in the form of higher price per kilo for the fishing sector and seafood affordability for consumers.

3.4. Perspectives from actors

Based on informal discussions with value chain actors from fisheries and processing on different occasions, a combination of drivers can be identified to for the development into current value chains and thus requires different targeted actions if change in practice is sought for:

- **Locked-in effects.** The change in fleet structure towards fewer and larger vessels has changed fishing behavior. Fisheries for fishmeal and oil with the large vessels need to maximize catch volume per time unit, and by this obtain a high total value of the catch due to lower price per kilo at first sale. For fillet production, herring from the Baltic Sea is highly perishable and requires short fishing trips with smaller volumes, use of cooling and delivery to the processing industry within 24 h to keep the quality needed. Thus, although fishermen are given a better price per kg for herring for direct consumption, it is not enough to motivate the different handling required. Furthermore, harbors and processing capacity of facilities along the Swedish Baltic Sea coast today does not match the new fleet structure with larger vessels and a fishing pattern aiming at maximizing volumes, volumes that however can be landed at fish meal and oil plants in Denmark. Swedish processing industry for direct consumption also has contracts with different fishing vessels supplying raw material, limiting possibilities for new vessels to deliver. Lastly, the fishery could before more freely fish between different areas which allowed for a quality of landings better suited for filleting (based on fat content and size); fishing regulations imposed over time in the form of closures of fishing opportunities in the southern part is now hindering this targeting pattern.
- **Synergy effects.** The quota for the herring stock from the Baltic Sea that is of most interest for direct consumption (the western stock caught in ICES subdivisions 24–25) have decreased over time, and herring sizes between 10 and 14 cm are ideal for producing fillets while the landings comprise of a large volume of smaller herrings. Combined, there is now a mismatch between what the filleting industry calls for and what is available in terms of fish resources. Economy for the filleting industry is also compromised from high variability in yield; depending on size and season, fillet yield may vary between less than 20% and up to around 50%.

- **Cascading effects.** Although there is consumer demand for herring from the Baltic Sea, current Swedish processing industry for direct consumption is constrained from lack of raw material, costs and limited market opportunities. Product development such as utilizing smaller fish and identifying strategies to mitigate risks for dioxins may improve the current situation, but this requires investments. These investments are challenging in Sweden as the market for direct consumption is economically constrained from high price competition and the need to keep production cost low – herring is generally seen as cheap seafood by consumers. Consumer interest for herring from the Baltic Sea is in fact higher outside of Sweden – a large share of current herring for direct consumption from Swedish fisheries is or has been exported to markets in e.g. Estonia, Latvia, Denmark, Poland, Russia and Ukraine of which some markets have and are directly or indirectly affected by embargoes. As the herring quota restricts fishing opportunities for sprat, Swedish fisheries are also trading away their herring quotas to fisheries in other countries around the Baltic Sea or land in countries where investments have already been made on land to process for direct consumption (e.g., Latvia).

4. Discussion

4.1. On current value chains

This case study on Swedish Baltic Sea herring fisheries has illustrated the need for a full value chain perspective – from sea to table – and revisit current economic incentives to enable a long-term sustainable Blue Economy. Several drivers have combined trajected the development into current value chains: Swedish fishing policy restructuring the fishing fleet to favor efficiency [55], focus on maximizing volumes in stock management objectives [15] and presence of undesired substances leading to dietary restrictions of fatty fish from some areas of the Baltic Sea [42]. Overall, current situation can be boiled down to fishing economy. Different adaptations have over time been done to maintain fishing economy and mitigate the effects from a continuous but accelerated degradation of a natural resource – including abundance, size structure and presence of undesired substances – a resource that has been highly valued over the course of over a millennium [2]. As a

hindsight, with a fishery management strategy aiming at economic optimization, accompanied with market pulls from a growing aquaculture industry while consumer interest is not enough, current Swedish value chains was arguably a foreseen development. The total economic value of the herring resource as feed ingredient is today substantial (Fig. 3), especially if a few vessels share the profit. Less attention has been paid to ecosystem effects and long-term sustainable use of limited fish resources, including effects on conditions for value chains for direct consumption.

From a food systems perspective, the sustainability of the two current value chains can be addressed in different ways. A few vessels landing large volumes offer efficiencies (see e.g., [40]) – but as seen here, may also compromise quality of landings unless other incentives are present, and it is vital with effective management to ensure long-term sustainable exploitation. Use of fish meal and oil in aquaculture allows for these production systems to be more efficient than current alternatives; pelagic fish as a feed ingredient is associated with lower greenhouse gas emissions than the main alternatives used today, i.e., soymeal and rapeseed oil [60]. Swedish consumers also prefer farmed salmon over herring from the Baltic Sea; in fact, even the herring consumed in Sweden today is mainly imported from other fishing grounds [25]. This situation is driven from the quality of the raw material and consumer preferences on different markets, where a large share of the Baltic herring currently landed is too small or doesn't have the fat content suitable for pickling. There is also the perspective of undesired substances such as dioxins. Although the nutritional value is higher for herring compared to farmed salmon, salmon is not associated with the same potential health risks as are found for some of the Baltic Sea herring catches. Current consumption of herring is however far below tolerable limits for posing health risks, thus allowing increase [38], but caution is important since intake of fatty fish even from non-polluted areas is seen as a dietary hot spot in dioxin intake [36]. Opportunities to minimize risks may also exist in only targeting sizes most suitable for filleting (10–14 cm), which are also below sizes with potential dietary restrictions (21 cm for ICES subdivision 28.1 and 17 cm for other subdivisions with restriction); this is already applied in Estonia [38]. For consumers, affordability to buy seafood is negatively affected from producing farmed salmon instead of herring fillets. Greenhouse gas emissions are also higher for producing farmed salmon compared to herring for consumption – estimated at

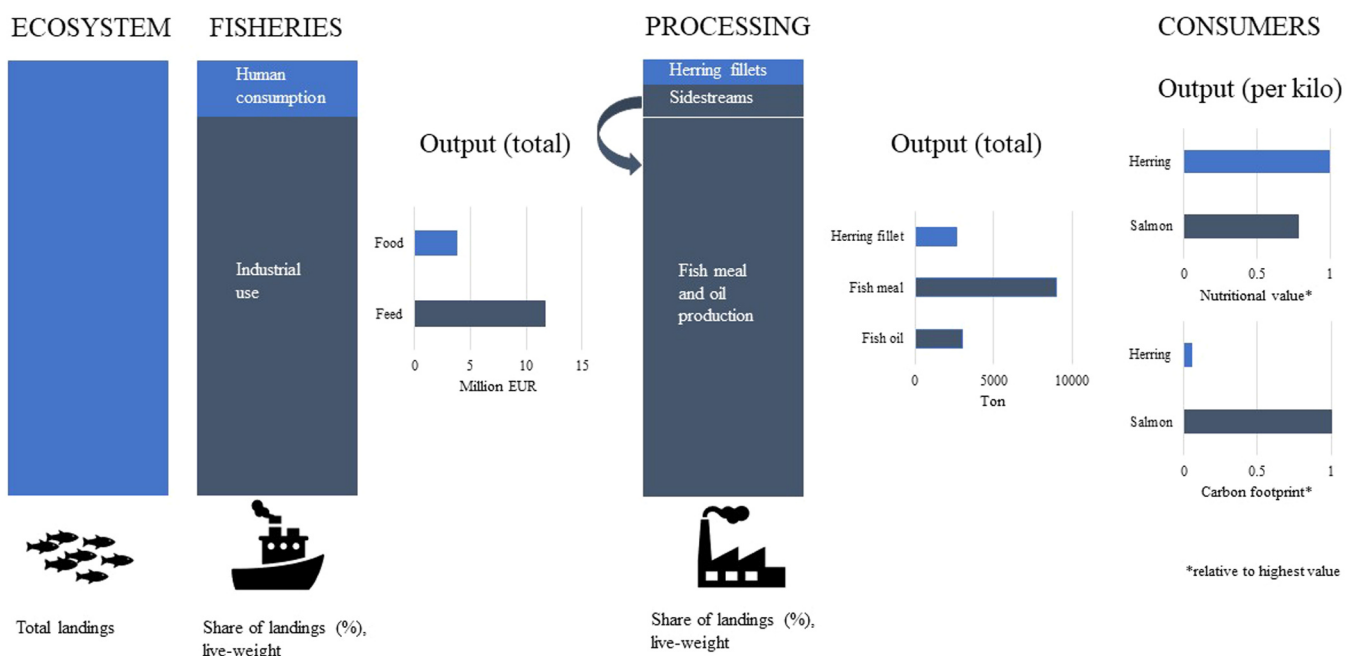


Fig. 3. Swedish fisheries for herring in the Baltic Sea, illustrating volumes, destination and outputs for different actors.

between 4.2 and 5.8 kg CO₂ e/kg live-weight salmon at farm-gate [60] whereas only around 0.3 CO₂e/kg live-weight herring at landing as estimated here.

From an ecological perspective, ensuring a governance structure of fisheries that allows for a healthy stock structure and avoid collapse of fish stocks is vital and increasingly urgent – the prerequisite for all value chains based on capture fisheries. The Common Fisheries Policy of the European Union [15] has a target stock management objective set relative to Maximum Sustainable Yield (MSY). This is a fishing strategy focused on maximizing volumes to be taken out of the stock, not considering preservation of a size structure allowing more large fish and neglecting sub-populations and distributional changes. There are many arguments for shifting focus away from MSY and allow for a size structure with more large fish, which is preferable from both the perspectives of ecosystem structure and functioning (also ambitions of the EU Marine Strategy Framework Directive; [13]), and fish processing for direct consumption. Lesson learnt from history of fisheries exploitation that are of value for present Blue Economy ambitions includes, amongst others, a responsive management that can properly address industry growth and potential loss of supporting systems [9]. A recent analysis of herring fisheries also stresses the importance of minimizing negative interactions between fishing sectors, where decline in small scale fisheries is projected, and to safe-guard size structure and ecosystem structure and function [7]. With these two studies in mind, the introduction of ITQ in pelagic fisheries in Sweden has been successful in improving efficiency and fishing economy but has failed to decrease risks for overfishing and avoid conflicts between sectors.

It should be emphasized that the high but theoretic indirect contribution from Baltic Sea herring to support Swedish seafood consumption of farmed salmon is not straightforward and should be seen as a theoretical thought-experiment. Although a large share of the landing volume of herring is destined for fishmeal and oil production, it enters a global market and does not necessarily end up supporting farming of salmon in Norway. Swedish herring landings from the Baltic Sea contribute with 5% of the total fish meal and 2% of the total fish oil in the Danish production, and a large share of the total volume produced in Denmark is exported to Norway – 41% of the fishmeal and 85% of the fish oil in 2020 [34]. However, the market is highly dynamic and where a certain volume of fish meal and oil ends up is based on customer specifications and demand related to quality and origin in combination with volumes available and prices. According to Johansen et al. [31], only 413 t (0.1%) of the fishmeal and 2 827 t (0.5%) of the fish oil used by farmed salmon in Norway is specified as originating from the Baltic Sea. It is also important to acknowledge that although, theoretically, current value chain with fish meal and oil production overall indirectly supports current Swedish seafood consumption to a higher extent than directly through provisioning of herring for direct consumption, larger seafood volumes would be available for consumption if a larger share of herring could instead be used for direct consumption.

Lastly, during the period of preparation, submission and peer-review of this manuscript, the situation for the herring stocks in the Baltic Sea has become increasingly alarming. On August 31st, 2023, the EU commission released that they are proposing a closure of targeted fisheries for both the northern and central herring stocks in the Baltic Sea while asking for further scientific support by ICES on e.g., by-catch quotas before a potential final adaptation later this fall [14]. In the end, final decisions on fishing opportunities will be made by politicians representing different EU countries.

4.2. Further investigations needed

The fuel use intensity (FUI; in l/kg) found here brings empirical insights to the relationship between FUI and stock status of different fisheries, where it has been suggested that fishing at higher fish stock abundance is associated with lower FUI (e.g., [62,24]). Even if the size of vessels and magnitude of landing volumes varied in the collected data,

the FUI was in the end rather similar across the different fishing operations and stocks based on the information at hand. Large vessels may however fish over large areas, and fisheries for feed optimize operations for large landing volumes per fishing trip. It is unclear if and how this type of fishing pattern may affect dynamics of pelagic fish stocks in the Baltic Sea. It has previously been found that in spatially heterogeneous fisheries, congestion and a race to fish in higher abundance areas may occur in an ITQ system aiming at maximizing efficiency, which may lead to serial depletion of sub-populations and affect productivity even if catch is maintained within the allowed quota [23]. In the Baltic Sea, a complex mixing of herring stocks is found, with an intricate intraspecific diversity of an unknown number of sub-populations adapted to local conditions with different migratory behavior (e.g., [22,32]). Thus, the changed fishing pattern may have allowed for effects on local populations. Nevertheless, by focusing on catch efficiency in pelagic fisheries, it is here shown that it may sustain overall fuel efficiency of a fishery even as stocks are showing signals of overfishing. In fact, for the pelagic fishery in the Baltic Sea, the FUI is remarkably aligned with other studies on herring fisheries, e.g. 0.08 l/kg live-weight in Iceland [6], 0.07 l/kg live-weight in the North Sea [3], 0.07–0.09 l/kg live-weight in Norway [60] and 0.06 l/kg live-weight in Scotland [40] – all can be rounded to 0.1 l/kg live-weight but with different stock abundance. Stock status is thus perhaps not a strong predictor for pelagic fisheries; it would however be interesting with more information on small-scale fisheries, development over time and the opportunity to separate between different gear types and fishing areas.

This study has focused on the relationship between seafoods in the form of farmed salmon and herring, but a share of the fish meal and oil production is also directed to other sectors such as chicken and pet food. The farmed salmon is also to a large extent dependent on agricultural commodities as feed ingredients [1], commodities that could be used as food. The overall implications on nutrition from the full food system based on fish meal and oil production relative to a situation where a higher degree of fish resources is utilized for direct consumption would be interesting to evaluate. Likewise, the affordability was also only evaluated as a comparison between farmed salmon and herring; considering the consumer price index development for the full range of food commodities associated with the fish meal and oil production would be interesting to explore.

Lastly, several data deficiencies have become apparent in this study, hence the need for some proxy analysis. The sustainability of current value chains can thus only be evaluated to a certain extent due to lack of robust and relevant data on e.g., actual flows and prices. This calls for improved data collection. Follow-up analysis would also benefit from including more aspects if robust methods and data could be identified, such as issues related to effects on stock structure from different fishing patterns and risks related to presences of dioxins. Lack of, or uncertain, data for analysis of value chains and effects from different policy also highlights that decision-support is incomplete in a policy-making context and societal discussions regarding these value chains.

4.3. Conclusions – lessons learnt and a future outlook

- Marine resource use follows the money. The market effect on utilization goes beyond Baltic Sea herring fisheries. While fish is a limited natural resource and may produce food with important nutritional values [4], perverse economic incentives allow a bait-to-landing ratio of 3:1 in American lobster fisheries [11] – i.e., nutritious herring is turned in to a luxury commodity with low edible yield with higher greenhouse gas emissions [5]. Thus, economic incentives in fisheries relative to contribution to food security need to be paid careful attention to in fishery management to allow for an equitable use and long-term sustainable Blue Economy.
- Long-term value chain perspectives in fishery management are prerequisites for realizing Blue Economy ambitions. Past and present practice of marine resource use has and is being scrutinized for how a

more sustainable use of the ocean could be achieved, with different scientific understanding, arguments and targeted actions over time. Farming of species such as salmon has as an example over time decreased dependency on marine resources [1]. Today, urgent actions are needed to both curb biodiversity loss and greenhouse gas emissions – the only way forward for long-term sustainable value chains based on capture fisheries is to move away from myopic perspectives and ensure that protection of ecosystem structure and function goes hand in hand with fishing activities.

CRedit authorship contribution statement

Sara Hornborg: Conceptualization, Formal analysis, Writing – original draft.

Data Availability

Data will be made available on request.

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