

An historic fishery collapse driven by socioeconomic and environmental factors

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In the Late Middle Ages, the western Baltic herring fishery played a central role in Europe. Salted herring was the basis for welfare and political power. We make use of a 450-year time series of Baltic herring catches (1200–1650), to identify which factors drove the herring catch dynamics during different phases of our time series. By the year 1570, the fishery suddenly collapsed, causing large-scale dislocations in trade, with major social and political consequences. Using a recently established bioeconomic stock assessment method based on catch and price data, in tandem with a loop analysis, we find that a combination of climate change, overfishing and socioeconomic factors can explain the drastic collapse of the fishery. The results underline the need for interdisciplinary approaches, including social sciences, to understand the dynamics of fishery systems. This has relevance for fisheries management today, in the Baltic and elsewhere.

For nearly 300 years (1280–1570), the western Baltic herring fishery, located in a small sound area between Denmark and Sweden (Sound fishery; Supplementary Fig. 1) was the main producer of salted herring in Europe¹. From the British Isles to Middle and Eastern Europe and all the way to Northern Italy, western Baltic herring was traded. During the autumn fishing season (15 August to 9 October), fairs held near small towns became important centres of commerce. A time series of herring catches in the western Baltic Sea has been reconstructed by ref. 1 from fragmentary historical evidence by combining direct records with indirect economic and environmental indicators. Where available, the authors relied on concrete data from customs records, toll books, royal pre-emption (kongekøb) accounts and other archival sources that reported trade volumes for specific years and locations (see Supplementary Information for a detailed description of the creation of the time series in English language; the original publication is in German). According to the authors, the Sound fishery can roughly be described by four phases, which show some peculiar similarities to the progression of events that led to collapses in modern fisheries (for example, the Atlantic northwest cod fishery): (1) expansion, (2) stagnation, (3) boom phase and (4) collapse (Fig. 1). Over the analysed time horizon,

the fishery had no meaningful harvest or entry restrictions, although limited gear restrictions and lump-sum taxation did exist in certain areas².

During the expansion phase (1200–1315) the Sound fishery for western Baltic herring emerged. At the end of the thirteenth century, catches from this relatively small area dominated the whole western Baltic herring production³. A first maximum of catches was reached around 1300, with 23,000 t. The expansion of the fishery is in line with an increase in demand⁴ and favourable economic conditions, as high-quality salt from saltworks in northern Germany became more easily available as a main production factor⁵.

In the stagnation phase (1315–1520), the economy was stagnant: agricultural output declined as temperatures had decreased and stayed low, leading to famines⁶ (1315–1322). Moreover, Europe was hit hard by the Bubonic plague around 1350, which killed 25–35% of the population⁷. This decimated the workforce of fisheries as well⁸. In the fifteenth century, climate conditions were variable but the economy remained stagnant, mainly because of deflation caused by a lack of bullion (gold and silver). Money ran short⁹. Additionally, a series of wars in the Baltic region hindered herring catch and trade. Total output amounted to 19,000–23,000 t during this period.

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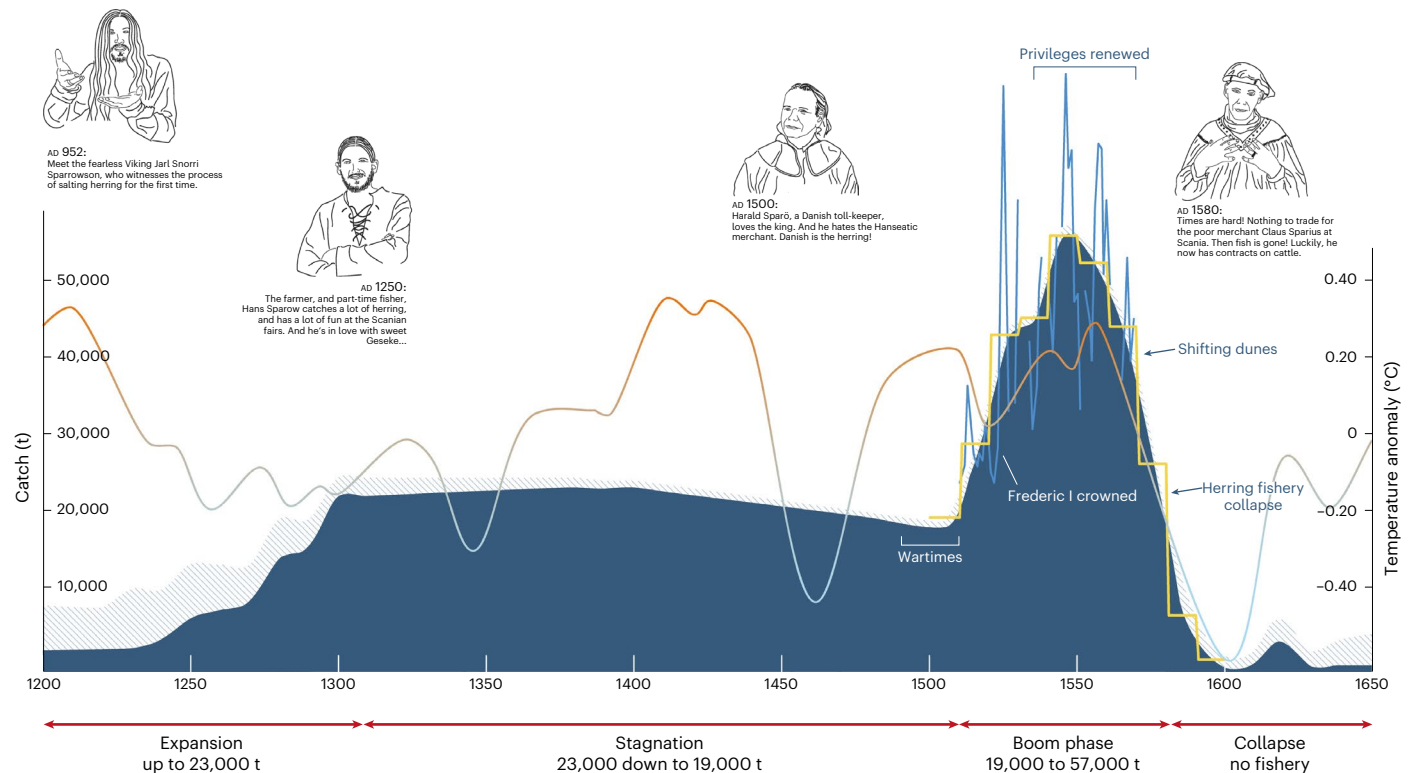


Fig. 1 | Estimated catches of western Baltic autumn-spawning herring as well as temperature anomalies in the period 1200–1650. Smoothed profile of catches taken in the Sound fishery are shown as a dark blue area; catches in the whole western Baltic are indicated by the striped blue area. Yellow and light-blue lines in the period 1500–1600 show decadal means and yearly catch values, respectively.

Specific historic events are indicated. The following URLs provide short YouTube videos of 'contemporary witnesses': The viking, <https://youtu.be/5xI24Oam-eM?si=wZel57etvztz5YY>; The fisher, https://youtu.be/ykzvjLmCw?si=M3d7IFi4PYD1_56W; The toll-keeper, https://youtu.be/FBqg_j9hSQ0?si=6_hPMafgTiD53s72; The merchant, <https://youtu.be/fcfTbklepv8?si=xZHmPhkA2E1t3E8>.

When the fishery reached its boom phase (1520–1570), the crisis of the Late Middle Ages was overcome: the population size recovered and an influx of gold and silver provided the economy with new momentum⁹. Acreage was enlarged⁶ and the herring market expanded. Still, in the first two decades of the sixteenth century the Sound fishery could not benefit from general economic growth. Danish wars hindered its expansion. Finally, under the reign of Frederic I (1523–1533), trade improved^{3,10}. Average outputs of the Scanian fishery amounted to about 55,000 t between 1524 and 1570, with catches reaching up to 75,000 t in some years.

The collapse of the Sound fishery began in the 1570s. Skanor and Falsterbo suffered from shifting dunes, destroying the economic infrastructure (a phenomenon linked to climatic changes at that time¹¹). In the 1580s, appearance of herring shoals increasingly fluctuated in the Sound^{13,12}. Temperatures were falling again¹³. Fishermen emigrated to Bohuslän, a Swedish province on the northernmost part of the west coast of the present country, where herring harvest was booming in the 1580s¹⁴. The situation worsened as nobility enforced serfdom (clod duty) in the early seventeenth century, barring peasants from leaving their landlord's grounds in autumn to fish, which massively limited the available workforce. Demand for herring shifted to imported, cheap and presumably larger North Sea herring, provided by an uprising fishery. Considering the number of fishers taxed in Kronborg Len (North Zealand) in the seventeenth and eighteenth centuries¹⁵, the yields of the Sound fishery (after a meantime rise in the 1620s) must have dropped to an average of 1,000 t per year.

It took until the 1950s for outputs to reach medieval levels again¹⁶. In this paper, we investigate the particular roles that overfishing, climate and socioeconomic factors played in this sudden collapse of the Baltic herring fishery in the sixteenth century, drivers that also have relevance for many fisheries today.

Shortly before the collapse of the fishery, catch quantities reached >70,000 t in certain years. To evaluate the potential harmfulness of historic catch quantities on the autumn-spawning herring stock, we need to estimate the corresponding stock size.

Herring stock productivity and hence catch potential is influenced by climatic conditions, for example temperature. Autumn-spawning herring is considered sensible against harsh winter conditions¹⁷. In the period under consideration, climate cooling had the potential to limit autumn-spawning herring stock growth, as a period of regional cooling, particularly pronounced in the North Atlantic region¹⁸ and known as Little Ice Age, started¹⁹. The herring fishery was (and still is) embedded in a complex socioecological network and was therefore also affected by socioeconomic factors, for example those influencing fish demand or larger-scale production conditions such as wars in the area. We collected a wealth of socioeconomic context data to evaluate the importance of these factors potentially acting in synergy or counteracting climate and stock dynamics.

Our approach builds on a long tradition of bioeconomic modelling of renewable resources, which has demonstrated how interactions between resource dynamics and human exploitation can generate nonlinear outcomes, including overexploitation, collapse and regime shifts in fisheries and socioecological systems (for example, refs. 20–22). Conceptually related models, sharing a common analytical structure that links ecological dynamics with economic drivers, have also been applied to broader historical cases of resource use and societal development (for example, Pleistocene megafauna extinction²³). However, empirical applications of such frameworks to long-term, data-constrained historical fisheries remain rare, particularly where quantitative reconstruction and system-level analysis are combined.

Here we first estimate historic sustainable fishing limits as well as stock depletion rates (biomass relative to carrying capacity), using

a bioeconomic stock assessment (BESA) method based on catch and price data time series. This allows us to test the hypothesis that a stock collapse caused the breakdown of the fishery. Then, we construct a qualitative model of the fishery system and evaluate its dynamic behaviour using loop analysis. Thereby, we identify which forcing factors were most important in determining fishery outputs during different phases and that finally caused the collapse of the fishery. Our analysis highlights that proper management of natural resources cannot be achieved without considering environmental conditions as well as the human components of the system.

Results

Sustainable fishing limits and stock depletion rates

Applying a BESA tool²⁴, we estimated sustainable fishing limits (estimates of maximum sustainable yield, MSY) for the different phases of the fishery (Fig. 2). BESA exploits information on the variation of catch and price data over time and assumes that rents are driven to zero, as is classic for an unregulated fishery. We further assume that this happens rapidly at each point in time, considering the fishery as one with a high speed of adjustment. Each of the four price data time series yielded an estimate of sustainable fishing limits, compared with realized catches across phases of the fishery. During the expansion and stagnation periods, realized catches were well below sustainable fishing limits (Fig. 2a,b). The boom period of the fishery (Fig. 2c), however, is characterized by overfishing of the resource. The catches during this phase would not have been sustainable over longer periods. After the collapse of the fishery, catches were well below estimates of MSY (Fig. 2d). The time series of estimated stock depletion rates (biomass relative to carrying capacity) (Fig. 2e) show an initial decrease of the stock during the expansion phase. We find that stock size substantially increased between 1400 and 1500 during the stagnation period. This holds true for all investigated models (Supplementary Fig. 2). Stock size decreased from around 1510 onwards (exact onset depending on the price data series used; Supplementary Fig. 2). During the boom phase of the fishery, this decrease is quite substantial (reduction to 41–51% of maximum observed biomass), but there is no indication of a collapse of the stock. As expected, BESA results indicate that stock productivity changed over time and was significantly associated with climatic conditions. During the investigated periods, the temperature anomaly had a positive and concave effect on the natural growth rate (Supplementary Fig. 3).

As a reference point, we also show mean depletion estimates from the catch-maximum sustainable yield (CMSY) method²⁵, which relies only on harvest data and thus does not include price and temperature impacts. We use CMSY to generate parameter priors for BESA (Supplementary Table 2). As visible, the price data used in BESA leads to more variability in stock depletion estimates (Fig. 2e) because it incorporates varying incentives to fish for fishers. This additional information also leads to narrower highest density intervals (HDI), that is, reduced uncertainty. However, uncertainty is probably under-represented, as confidence bands capture only the internal precision of the model, how well the bioeconomic equations fit the provided catch trajectory, given observation and process error and

the priors used, rather than the uncertainty of the catch reconstruction itself. The estimated observation error is relatively low, partly because interpolated data points increase internal consistency and reduce noise artificially. These estimates are therefore not intended to quantify depletion or its annual variability as precisely as a decision-based stock assessment would require; rather, they reflect smoothed, most-likely trajectories shaped by the interpolated/extrapolated input data and internal filtering.

In conclusion, the collapse of the fishery is not directly linked to a collapse of the herring stock. Still, overfishing played a crucial role, as it is likely that costs in the fishery were stock dependent, which is also assumed in BESA. Since the sixteenth century, markets were increasingly supplied by the highly productive North Sea fisheries, where the fishing season was three times longer and boats were seaworthy, outperforming western Baltic Sea vessels by a factor of 20 (refs. 1,26). It is therefore conceivable that the Baltic herring fishery was no longer competitive after the decrease in stock size led to a substantial cost increase.

Loop analysis to identify the key drivers of system dynamics

To investigate the particular roles overfishing, climate and socioeconomic factors had in the dynamics of the herring fishery, we applied the qualitative algorithm of loop analysis²⁷. This approach requires representing networks of interacting variables as signed, directed graphs (digraphs). Loop analysis is an ideal tool to integrate the modelling of variables that belong to different domains (ecological, economic and social). Besides predicting the consequences that several press perturbations (that is, changes in external forcing factors such as climate) have on the entire system, loop analysis allows clustering the variables based on similarities in either their response to disturbance or the impact they trigger when perturbed. The final socioecological network comprises nine variables and integrates knowledge about the system (Table 1).

We identified a unique representation of the system, which covers the full period under consideration (Fig. 3a). The network stands for a reasonable compromise between system complexity and the possibility to analyse and verify model predictions. The digraph provides the input for loop analysis, with all variables considered equally important for system dynamics. The basis for verification was the herring catch time-series data.

Press perturbations

The socioecological network (Fig. 3a) was analysed across four periods of major catch dynamics, as identified by BESA. For each period, we defined a set of press perturbations that acted on the system based on historic knowledge¹.

- (1) Expansion (1200–1315): The climate is cooling, although starting from a relatively high level. The economy is increasing as trade is flourishing and high-quality salt is available from the Lüneburg saline. Demand is increasing as herring becomes an everyday dish. Workforce is available as farmers are free to go fishing in autumn after the work on the fields is done.

Fig. 2 | Estimated MSY levels for different price data time series and realized mean catch during different phases of the fishery. a–d, MSY estimates are calculated for the four periods of the fishery: expansion (1200–1315) (a); stagnation (1315–1520) (b); boom (1520–1570) (c); and collapse (1570–1600) (d). Data time series are in light blue and realized mean catch in dark blue. Values from the different locations correspond to four separate estimates of the same indicator, derived by applying different price time series to the same catch data. They should not be summed. Data distribution is visualized using standard box-and-whisker plots. The central horizontal line within each box represents the median; the lower and upper boundaries of the box indicate the 25th and 75th percentiles, respectively. The whiskers (error bars) extend to the 10th and

90th percentiles to illustrate the distribution tails. Individual data points lying outside this range are plotted as outliers. Number of observations is reported in the figure. e, Depletion rates (biomass relative to carrying capacity) of western Baltic autumn-spawning herring during 1270–1600, based on the BESA model. The lines show the mean values of the estimated posterior distributions, surrounded by the areas representing the associated 95% HDI. The four location lines show separate estimates regarding the same stock for the four different price time series (BRAB, Brabant; ENG, England; HH, Hamburg; and UT, Utrecht). The fifth line shows mean depletion estimates (and HDI) from the CMSY method (Supplementary Table 4). Estimated from $n = 331$ (ENG), $n = 151$ (HH), $n = 211$ (BRAB) and $n = 181$ (UT) annual observations.

- (2) Stagnation (1315–1520): Climate is on average warming, however showing large variability. The economy is weak, among others things because of a series of Black Death pandemics and deflation (shortage of money). The western Baltic is hit by a series of wars.
- (3) Boom phase (1520–1570): Climate is warming. The economy is boosting, among others factors because of the influx of noble

metal. Finally, wars in the Baltic region end. Demand increases as the population gains wealth and the workforce is increasingly available as a result of population growth.

- (4) Collapse (1570–1600): Climate cools dramatically. Economic conditions for the fishery worsen, as shifting dunes destroy the infrastructure at central fairs. Demand is decreasing, as cheap

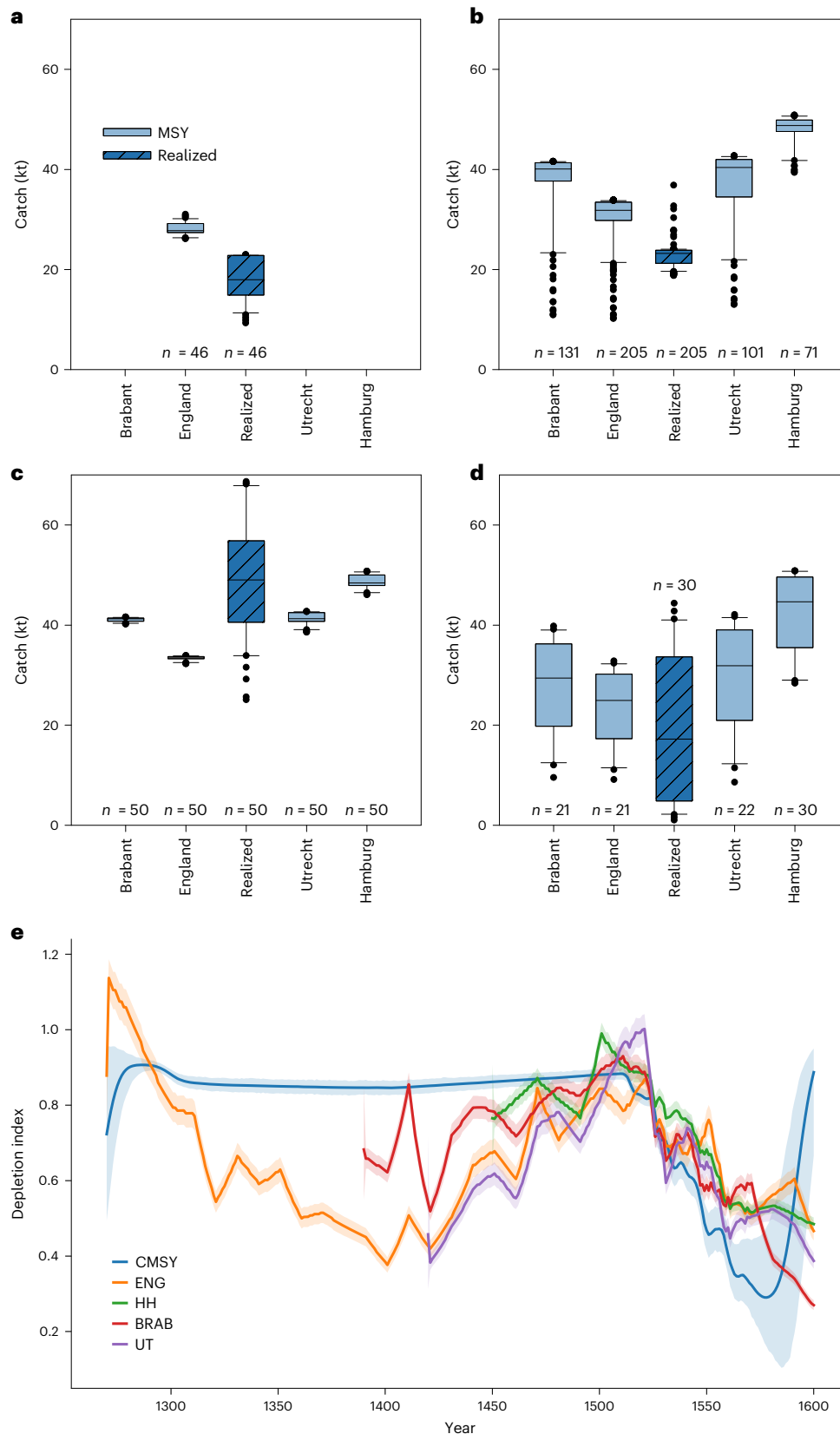


Table 1 | Variables used to represent the socioecological system of the medieval herring fishery in the western Baltic region

Symbols	Variables	Interactions
	Herring harvest (HA)	The amount caught in the Scanian herring fishery. Loop analysis predictions are compared with HA time series as constructed by historic sources, which represents the benchmark for model validation. It is influenced by different socioeconomic variables and depends on herring stock (HS).
	Climate cooling (CC)	The variable shows phases of climate cooling during the medieval temperature anomaly; CC exerts a direct negative impact on the size of the HS via reduced productivity ¹⁷ , while also contributing to a range of indirect effects mediated by AG.
	Herring stock (HS)	An increase in HS results in greater HA.
	Agriculture production (AG)	Agriculture positively influences human PO, as increased food security allows larger populations to be sustained. It negatively impacts DE, as food alternatives are more easily available.
	Population size (PO)	Increased population size positively affects workforce (WF) and promotes economic growth (EC).
	Workforce (WF)	This variable represents the workforce available for catching herring at the Scanian fairs. It positively influences HA.
	Demand for herring (DE)	Higher demand for herring leads to higher HA to fulfil market request.
	War (WA)	Wartimes in the western Baltic region have a negative impact on HA, as fishing operations are not safe. Moreover, war has negative impacts on EC and AG because of destroyed infrastructure.
	Economy (EC)	EC comprises all economic variables with respect to the herring fishery. It resembles the gross domestic production of today but on a multinational level and focused on herring production. Economic growth is beneficial for DE, as people can afford buying herring. It is as well beneficial for HA, as production factors such as salt are available via improved trade. A better economy decreases the probability of feuds (for example, by robber barons) and WA.

For each variable, icons used in the signed digraph (Fig. 3a), full name, two-letter code and interactions with other variables are summarized.

herring from the North Sea is available. Less workforce is available as feudal services are installed and as the temporarily up-rising Boshulän fishery (1570s–1580s), another historic herring fishery at the west coast of Sweden, absorbs part of it.

Our main interest was to identify the reasons for the sudden collapse of the fishery. As data availability was especially low after the collapse, we omitted the low catch period 1600–1650 from this part of the analysis. Loop analysis was used to assess how perturbations that alter the growth rate of individual variables affect system dynamics and their cumulative impacts. We applied this approach to test whether factors influencing the socioecological system could reproduce the herring stock and harvest responses estimated with BESA

across the four phases of the time series. Results are reported in the table of predictions (Fig. 3b), which shows how a positive perturbation of each variable in the rows influences the others in the columns. Clustering along rows identifies variables with comparable system-level impacts and grouping along columns reveals similarities in response patterns.

Herring stock (HS), herring harvest (HA), workforce (WF) and demand (DE) cluster together as factors that, if perturbed (that is, row direction), result in similar responses at the whole-system level. A second cluster groups population size (PO), state of the economy (EC) and agriculture (AG), which are socioeconomic factors with similar impacts on the system, usually under-represented in biocconomic models. The influence of AG on the system deviates slightly from the consistent pattern observed for EC and PO: an increase in AG growth rate in fact reduces the demand for herring (DE), whereas herring stock (HS) decreases only mildly and herring harvest (HA) increases slightly. Finally, climate cooling (CC) and war (WA) represent large-scale factors outside regional control. Climate cooling exerts a complex response. Although colder years directly reduce herring stock, indirect positive effects could partly offset this impact and even yield a slight net increase in stock size (Supplementary Table 3). Therefore, the network architecture can account for a net negative response of the herring stock to climate cooling, but only if the direct effect outweighs the longer chains transmitting positive signals.

The major dynamics of the catch time series are reproduced by our model when the assumed press perturbations are applied (Table 2). First, we observed a clear chance of increase in harvest during the expansion period (1200–1315). Second, a slight tendency towards decreased herring harvest during the stagnation period (1315–1520) was found, which is followed by a strong likelihood of increase during the boom phase (1520–1570). Finally, our predictions combine for an unambiguous signal in the fourth phase, which points towards a very likely, strong decrease in harvest, that is a fishery collapse (1570–1600).

Climate cooling by itself cannot explain the dynamics of the fishery, especially if we assume that the same magnitude of impacts is transmitted across chains of all lengths (Supplementary Table 3). For example, climate cooling also affected agriculture adversely and the associated decline in population reduced the workforce for fishing. Instead, the interplay of ecological, economic and social factors is needed to reconstruct and understand the system reaction. Furthermore, it is a combination of local- (workforce), regional- (economy and demand) and large-scale factors (climate cooling and war), which determined the fate of this fishery (Table 2).

Discussion

The reconstructed time series of western Baltic autumn-spawning herring catches from 1200 to 1650 showed distinct dynamics. Stock assessment results in combination with loop analysis suggested that the collapse of the fishery was caused by a combination of climate change, overfishing and socioeconomic factors. This closely resembles the situation today of western Baltic spring-spawning herring fisheries.

Direct data on the yields of Sound fishery (toll books and chronicles) are sparse, making the construction of a Baltic herring catch time series more challenging than for the better-documented North Sea herring fisheries (1600–1850)^{3,4}. Hence, the question as to whether the collapse of Sound fishery was caused by overfishing remained unanswered⁴. Although direct data are lacking, demographic, economic, climate and political history provide a wealth of contextual factors (prices, market-volumes and legal framework), which was harnessed only rudimentarily^{15,28}. We validated historic records and filled gaps by projections, considering the availability of salt as the main production factor for the 'herring industry'. Combining all available information yielded a catch-data time series, which mirrors the major dynamics of

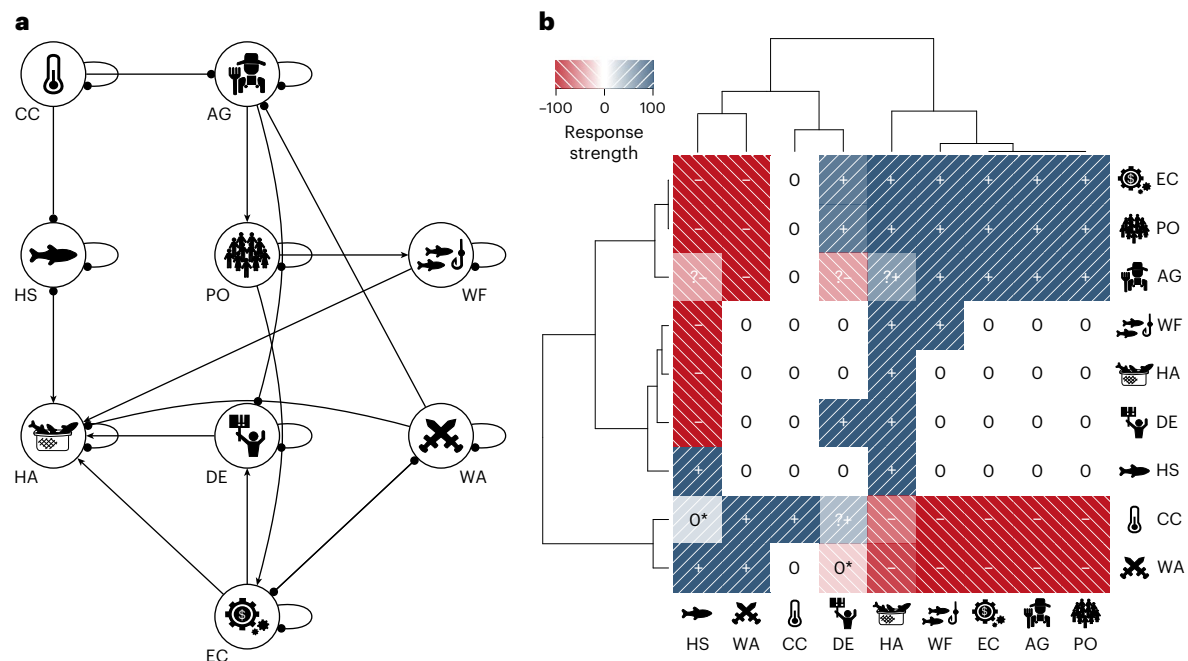


Fig. 3 | Signed digraph depicting the socioecological network of the western Baltic autumn-spawning herring fishery in the period 1200–1650. a. Direct, positive effects on a variable are portrayed by arrows pointing to it; direct, negative effects correspond to circle-headed links towards the variable affected. Meaning of icons and interactions and abbreviations for variables are given in Table 1. **b.** Table of predictions derived from the signed digraph. Colours indicate the probability of either negative (red) or positive (blue) responses of the variables along the columns following a positive press perturbation targeting row variables. Predictions for a negative press perturbation can be obtained by

inverting the signs of the responses. Signs in each cell provide a classification of strength, with question marks indicating weaker responses. The value 0 denotes the absence of directed pathways between pairs of variables in the network; the symbol 0* stands for a substantial balance between the probabilities of net positive and negative effects. Variables clustered along the rows are those that, when perturbed, produce similar effects on other system variables; clustering along the columns indicates variables that show similar responses to all system perturbations.

Table 2 | Overall loop analysis predictions for HA in the four phases of the time series, resulting from press perturbations on selected variables

Press perturbations					
Period	CC	EC	WA	DE	WF
1200–1315	–72.1	+92.9	–	+100	+100
1315–1520	+72.1	–92.9	–83.3	–	–
1520–1570	+72.1	+92.9	+83.3	+100	+100
1570–1600	–72.1	–92.9	–	–100	–100

Values represent net percentage differences within the interval –100 to +100; the more they deviate from zero, the greater the likelihood that net impacts will manifest in the direction indicated by the sign of the difference. Changes reported in historical sources always match the overall predictions derived from averaging the responses to specific perturbations.

the fishery. Data density is highest during the boom phase and the onset of the collapse, when yearly estimates can be provided¹.

For most periods, continuous direct records did not exist (see Supplementary Information for a detailed description of time-series construction), so the series was built through extrapolation and interpolation linked primarily to production-related proxies, most notably salt availability and salt prices and to environmental indicators; broader socioeconomic variables (for example, demographic trends and general economic conditions) served only as contextual consistency checks, not as quantitative inputs. This distinction matters for avoiding circularity: the reconstruction is constrained by direct trade

records and material production factors, whereas the socioeconomic variables analysed in the loop analysis (population, demand, economy and workforce) are treated as external drivers not quantitatively embedded in the reconstruction, allowing the subsequent analyses to evaluate their influence on temporal variation independently. Plausibility was checked against constraints on production (salt and labour availability, legal frameworks, fishing technology and market demand) and ecological conditions (spawning season, fish size and age structure); estimates were deliberately conservative, with adjustments for unregistered catches, subsistence consumption and double counting of kongekøb quantities. Certainty varies considerably over time: relatively robust figures exist for some years in the late fourteenth and early sixteenth centuries, whereas thirteenth- and early-fourteenth-century yields are inferred indirectly from salt production and demographic proxies and the post-1570s decline relies on sparse tax records and comparisons with other fisheries. The final output is therefore not a precise year-by-year dataset but a smoothed trend curve for 1200–1650 synthesizing fragmentary evidence at varying confidence levels; still, the major dynamics underlying our analysis are well documented and beyond doubt.

Initially, there had been some indications of overfishing and a subsequent stock collapse as the cause of the fishery breakdown. The average size of herring caught declined. On the basis of processing information, the average weight of an individual herring was 82 g (in around 1400). In 1485, it temporarily dropped to 67 g. In the Viking Ages (around 900), average herring caught reached a length of 26 cm, making a weight of 154 g (ref. 1). Because of an expanding ‘fish industry’, its weight halved; that is, herring was caught about 3–4 years younger (assuming there was not a change in growth rate). Contemporaries seem to have been aware of the problem early on: pelagic trawl nets were prohibited in 1371³ and there are indications that net mesh-size

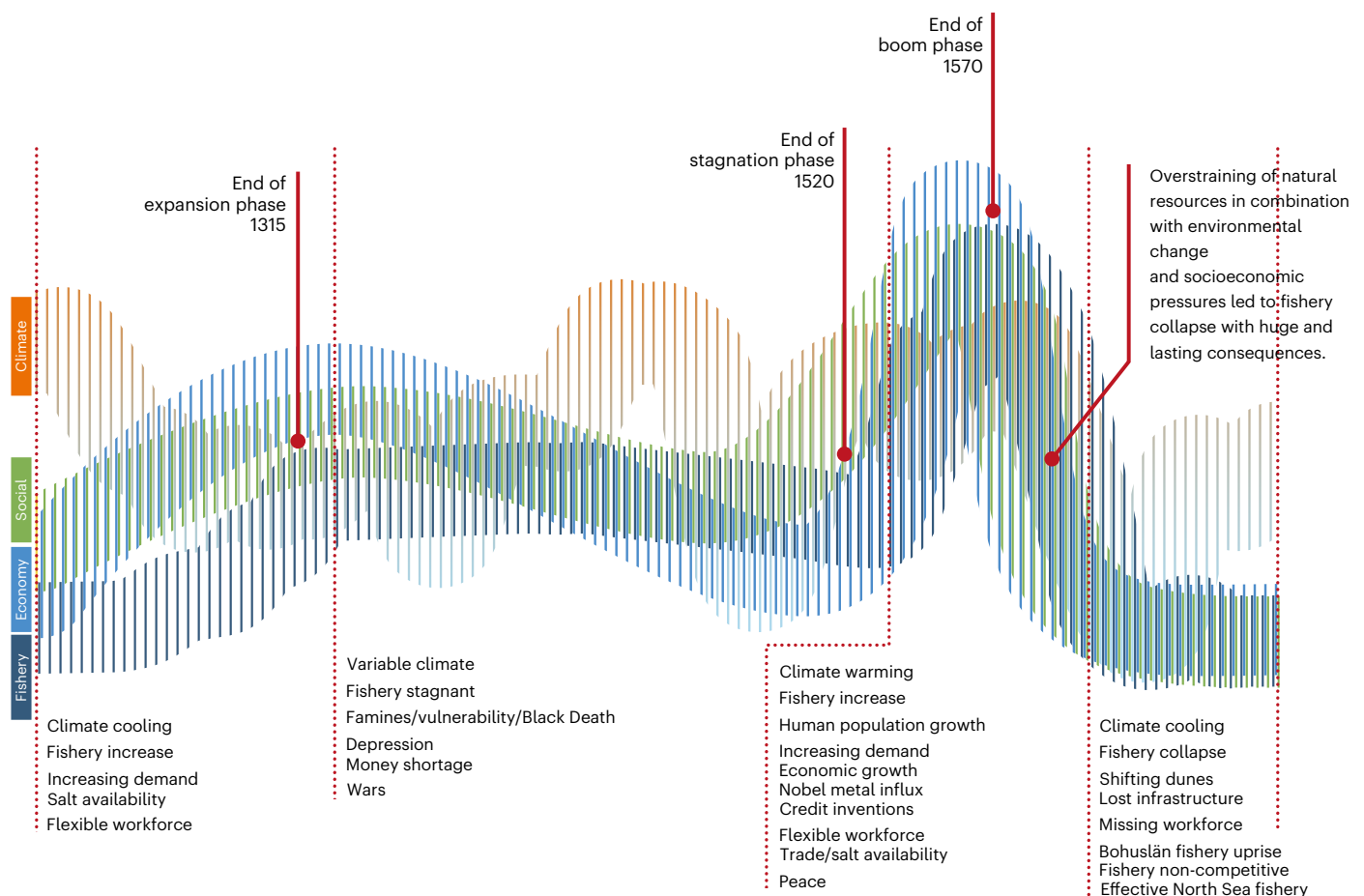


Fig. 4 | Conceptual representation of major press perturbations influencing the western Baltic autumn-spawning herring fishery. Trends of such perturbations have been grouped to climate, social and economic. Change points in fishery dynamics (tipping points) are indicated together with important context data.

was regulated (1386). Our analysis confirms findings from ref. 29 that catches of autumn-spawning herring amounted to between 10,000 and 50,000 t during the period considered in our analysis. However, they also show that the western Baltic autumn-spawning herring stock did not collapse in the second half of the sixteenth century²⁹. Using ancient DNA and genomics, they conclude that the fishery had a negative impact, but that population dynamics were consistent with environmental change. The herring stock declined, but this was not the only reason for the collapse of the fishery. Excessive fish extraction caused the stock to shrink. Smaller stock size most probably exacerbated the exposure of these autumn spawners to the unfavourably cooler climate^{30,31}, which lowered the herring stock productivity.

During several phases of our time series, environmental change (that is, climate cooling) negatively affected the herring stock productivity. Temperature is known to strongly affect many fish populations^{32,33}, including herring^{34,35} and low temperatures negatively affect herring stock productivity in autumn spawners, including in the Baltic Sea^{6,36}. In contrast to historic times, in recent years the role of climate warming for stock dynamics has been the focus of many studies, including western Baltic spring-spawning herring³⁷. The drastic, complete breakdown of this important fishery dependent on autumn spawners can, however, only be understood as an interplay of overfishing, climate, social factors and economy (Fig. 4). The overall negative effect of cooling phases on the western Baltic autumn-spawning herring stock is justified only if the magnitudes of their direct impacts outweigh those transmitted through long, indirect pathways (Supplementary Table 3).

Climate effects refer to the direct impact on herring stock dynamics, but the loop model explicitly captures how cooling/warming events can be mediated by socioeconomic variables, an outcome that may challenge intuitive cause–effect interpretations. Over centuries, the major pressures partly offset each other, leading to relatively moderate changes in catch quantity (Table 2, upper two rows). At the beginning of the sixteenth century, all pressures suddenly became reinforcing, promoting a boost of the fishery (Table 2, second last row). In the middle of the sixteenth century, the situation reversed and climate, social, economic and fishery pressures influenced the fishery negatively, resulting in its collapse (Table 2, last row). Loop model predictions allow clustering system variables based on the way they respond to disturbance (columns in Fig. 3b). Herring harvest is close to local (workforce) and regional (economy, agriculture and population size) socioeconomic factors whereas the biological component (herring stock) clusters together with a large-scale factor such as war. This outcome highlights that proper management of natural resources cannot be achieved without considering the human components of the system.

Our results are consistent with core insights from bioeconomic theory, which predict that renewable resource systems can exhibit nonlinear dynamics arising from feedbacks between ecological processes and human behaviour. In particular, the combination of increasing exploitation pressure, changing environmental conditions and evolving socioeconomic drivers observed here aligns with theoretical expectations of overexploitation and regime shifts in coupled human–natural systems, for example refs. 20,21. The absence of a complete

biological stock collapse, despite the breakdown of the fishery, further supports the idea that economic viability and ecological sustainability may diverge over time, as highlighted in previous bioeconomic studies. More broadly, our findings resonate with theoretical and empirical work on long-term resource use in human societies, where models of coupled population-resource dynamics show that even simple feedback structures can produce collapse or transition dynamics when external pressures or internal thresholds are crossed^{23,38}. The western Baltic herring fishery provides a rare empirical example over several centuries that supports these general insights, while also demonstrating how several drivers such as climate variability, economic incentives or institutional constraints, interact to shape outcomes in real-world systems.

Our analysis gains practical relevance for management today by lending support to an ecosystem-based fisheries management approach. We show that the collapse of a fishery can significantly be triggered by socioeconomic pressures. Any effort to guide fisheries towards a sustainable future amid global change will therefore need to include socioeconomic considerations. An illustrative example is the present western Baltic spring-spawning herring fishery, which is now outside safe biological limits³⁹ and on the brink of collapse. This fishery targets spring-spawning herring, unlike the autumn spawners of medieval times. The stock size has decreased drastically and, accordingly, there has been a 'zero catch' advice³⁹. Stock decline has been driven by overfishing^{40,41}. The population is now so depleted that recovery is constrained by unfavourable environmental conditions (for example, climate-driven negative effects on recruitment³⁷) and food web interactions that, together with residual fishing, prevent any surplus production. In the absence of fishing mortality, however, the stock would probably still cope with these other stressors and recover. Herring fisheries have long been an important part of coastal economies, societies and cultural heritage. Preventing this looming collapse is therefore of high societal interest and a severe challenge for fisheries management. While recovery of the resource stock remains the prime target, (national) management measures increasingly also address socioeconomic pressures on the stock and the fishery, as now discussed in high-level political groups in Denmark and Germany. Consequently, the recently published report of the German Commission on the Future of Baltic Sea Fisheries⁴² suggests measures to improve socioeconomic framework conditions, for example infrastructure and diversification. Management will need to include socioeconomic considerations, if truly sustainable fisheries and optimal outcomes, are to be achieved. This is the lesson learnt from history as described here.

Methods

Climate forcing

Information on medieval climate anomaly is based on a climate field reconstruction approach by ref. 13. To impute a yearly temperature anomaly time series, we used the data provided for specific years and imposed a linear interpolation function (`na_interpolation`) from the R package `imputeTS`⁴³. The linear interpolation resulted in a time series with 'hard corners' based on the original data. Therefore, we used the `smooth.spline` function from R⁴⁴ to fit a cubic smoothing spline to the imputed data with a smoothing parameter of 0.3. As we assumed that climate conditions impacted herring productivity, we further included temperature anomalies as a factor in the BESA analysis.

Estimation of sustainable fishing limits

We used a newly developed BESA²⁴ to evaluate sustainable fishing limits of the herring stock over time, based on catch data and available price time series. BESA assumes that the herring stock was fished under open access conditions, where fishers could freely enter and exit the fishery and each year will do so until profits are driven to zero. It then exploits variation in prices, which stems for example from

demand shocks, varying market conditions and changes in the supply of elsewhere-sourced herring, and which would have induced the Baltic Sea herring fishers to adapt their fishing effort as a result of the open access nature of the fishery. Normally, price data time series need to be corrected for potential deflation before being used in BESA. In this special historic case, it was not possible to achieve a meaningful correction. Therefore, results have to be treated with caution. Moreover, BESA accounts for stock-dependent harvesting costs, meaning that, all else being equal, the cost of harvesting a unit of fish increases as stock size declines. Given these assumptions, BESA then relies on a state-space model combined with an extended Kalman filter and can identify through Bayesian estimation the time series of MSY levels, stock biomass, the natural growth rate, carrying capacity as well as the cost parameter on the economic side.

We combined annual herring harvest data with four decadal price time series from major herring markets that contained sufficient observations of salted herring prices overlapping with the harvest records, namely in England (1270–1600), Hamburg (Germany, 1450–1600), Brabant (1390–1600) and Utrecht (1420–1600) (the last two, located in present-day Netherlands), as compiled by ref. 1. We estimated the climate impact as a quadratic effect of the climate anomaly on the natural growth rate of the stock (Supplementary Fig. 3). Supplementary Information, section 2 gives details on model, estimation, results, diagnostics and robustness checks.

Loop analysis to identify the key drivers of system dynamics

Loop analysis makes predictions for the dynamic behaviour of complex systems starting from simple information such as presence/absence of interactions and their signs. Hence, it does not require knowing the form of the equations that describe the relationships between variables, it is not constrained by the need for using the same units and the user does not have to quantify interaction strengths⁴⁵. The catch time series used in BESA is independent of the socioeconomic variables included in the loop analysis, as these variables were not used as quantitative predictors during the reconstruction procedure. The signed digraph used in loop analysis depicts interactions between pairs of variables (nodes) and informs on the sign of each relationship (link), distinguishing between positive (+) and negative (−). To execute the loop analysis, the signed digraph has to be converted into a square Jacobian matrix where each link is represented by a non-zero element of absolute value equal to 1, indicating either a positive or a negative direct effect of the row variable on the column variable. Loop analysis predicts the direction of change of variables (for example, 'herring harvest') in response to press perturbations, that is sustained external inputs acting on the rate of change of other variables⁴⁶. Here one such press perturbation is climate cooling. The output is the table of predictions, which summarizes the net, cumulative impact that an increase in the growth rate of the row variable has on the column variables. Such a net impact is obtained by combining the effects that travel through the direct connection and all indirect pathways linking each pair of variables⁴⁵. Prediction values range between −100% and +100% and represent the relative frequency of negative or positive responses across simulation runs, rather than quantitative changes in variable magnitude. They therefore indicate the certainty of the direction of change, but not its intensity. To generate these predictions, interaction strengths were randomly varied across simulations while preserving the sign structure of the network and only stable matrices were retained. Determining the timing of shifts in conditions and system responses is inherently challenging. The asynchronous occurrence of perturbations, together with lags in the propagation of indirect effects, complicates the evaluation of net impacts on response variables. To address this, we focus on four extended intervals, the shortest spanning 50 years (the boom phase, 1520–1570), and integrate the effects of perturbations over each interval, rather than resolving fine-scale dynamics. Besides predicting the consequences that press perturbations have on the entire

system, loop analysis allows clustering the variables; here we grouped variables according to the scores reported in the table of predictions, using the Manhattan distance (R function `dist`). Clustering along the rows groups variables whose perturbation leads to comparable overall responses patterns across all other system variables, considering both the sequence of signs and their relative intensity along the entire row. Because each variable also responds to perturbations affecting itself through self-loops and indirect feedback pathways, self-responses are included in the table of predictions. Clustering along the columns, in turn, groups variables that show similar response patterns when compared across all possible perturbations applied to the system. In the dendrograms, branch lengths reflect the degree of dissimilarity between clusters, with longer branches indicating greater differences; the ordering of variables along the axes is determined by the hierarchical clustering so that more similar variables are placed closer together. Further details about the algorithm and the R script for its execution are found in ref. 47. Supplementary Information, section 4 gives details for the pathways through which climate cooling may influence herring stock and harvest.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Data supporting the findings of this study are available in the paper, Supplementary Information and referenced publications. Source data are provided with this paper.

Code availability

Freely accessible example code for BESA is available on GitHub (<https://github.com/klancker/BESA.git>). The specific Stan code for the BESA model used here is provided in Supplementary Information, section 3. R code for loop analysis is available as supplemental information to ref. 47 and can be accessed at <https://aslopubs.onlinelibrary.wiley.com/action/downloadSupplement?doi=10.1002%2Fino.10713&file=ino10713-sup-0001-supinfo1.pdf>.

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Author contributions

Conceptualization: R.V., J.O.S. Data curation: R.V., O.L., D.O., K.L., A.G., M.S. Formal analysis: R.V., D.O., K.L., M.S. Investigation: R.V., O.L., P.P., K.L., M.S. Methodology: R.V., J.O.S., P.P., K.L., M.S. Software: R.V., K.L., M.S. Visualization: R.V., A.G., M.S. Writing—original draft: R.V. Writing—review & editing: R.V., J.O.S., O.L., D.O., P.P., K.L., A.G., M.S. Other: O.L., historic context specialist; K.L., BESA assessment specialist; A.G., information design specialist; M.S., loop analysis specialist.

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Competing interests

The authors declare no competing interests.

Additional information

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Data collection	n.a.
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Study description	Using a time series of Baltic herring catches spanning 450 years, this study examined the socio-economic and environmental drivers of the collapse, offering lessons for today's fisheries management. We use a combination of quantitative and qualitative data and modelling tools.
Research sample	Historic documentations of herring catches.
Sampling strategy	no sampling
Data collection	Basic data were extracted from historic sources.
Timing and spatial scale	n.a.
Data exclusions	no data exclusions
Reproducibility	No experiments; replicability of model results via provided source data and code.
Randomization	n.a.
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