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Original Article

Economic development in times of population decline—a century of European eel fishing on the Swedish west coast

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The European eel stock is in a multi-decadal decline. When fishing yield diminished throughout Europe, the small-scaled fyke-net fishery for eel on the west coast of Sweden gradually increased. This contrary trend lasted from the early-1900s, until the 1990s when fishing restrictions eventually limited the catch. We identified the processes driving this aberrant historical development. Using data on the fisheries from 1914 to 2006, we analysed the relation of total landed quantities to stock abundance indices, weather conditions, technical development, and market indicators. No relation between landed volumes and abundance indices was found, but market price (inflation-adjusted) was clearly correlated. Weather and technical development had a minor influence on landed volumes. This indicates that the commercial eel fishery on the west coast developed due to increasing demand and increasing eel prices. We found no evidence that the local stock has been fully exploited, though the increasing catch must have gradually reduced the contribution to the international spawning stock. These results stress the importance of considering economic processes when interpreting historical catch data as a source of information on population size in stock assessments, and ultimately, understanding the collapse of the eel stock.

Keywords: *Anguilla*, economic development, European eel, fishery, stock decline

Introduction

The stock of European eel *Anguilla anguilla* (L.) is at a historical minimum. For over half a century, stock abundance and fishing yield have declined by ∼5% per year, to <10% of the historical level (Dekker, 2003a, 2004; ICES, 2019). In addition, from 1980 to 2010, recruitment of young eel (glass eel) from the ocean towards the continent dropped consistently by ∼15% per year, to 1–10% of its former levels (Moriarty, 1990; Dekker, 2000; ICES, 2019). The poor status of the stock is likely caused by a combination of factors, including habitat degradation and loss, and overfishing of all life stages in continental waters (EIFAC, 1993; Castonguay *et al.*, 1994; Dekker, 2004; Drouineau *et al.*, 2018).

While the landings of the eel fisheries generally started to decline as early as the 1960s, across Europe (Dekker, 2003b), as well as in the Baltic fisheries in Sweden (Dekker and Sjöberg, 2013), those at the Swedish west coast showed no decline up to the mid-1990s, even gradually increased throughout most of the 20th century. This was considered to indicate that the west-coast stock had not declined, due to its favourable location near the ocean. Density-dependent settlement, from the (diminishing) flow of recruits migrating into the Baltic, would have kept the abundance of recruits on the west coast stable (Svedäng, 1999). The deviating time trend on the west coast was thus explained by two biological processes (density-dependent settlement on the west coast, respectively, migration into the Baltic) that are in fact both unobserved and unquantified. While this could explain the stock being stable, it did not address the gradual increase in landings. Here, we consider alternative hypotheses for the deviating time trend on the west coast, adding economic, technical, and weather-related processes.

In 2007, the European Union adopted a recovery plan for the eel (Anonymous, 2007), obliging member States to develop national Eel Management Plans (EMPs). The goal of the EMPs is to reduce mortality so that the stock can recover to historical levels

(Anonymous, 2007). Sweden introduced severe restrictions on the commercial fishery (a licencing system, a limit on the number of days fishing, and an increased minimum size) and adopted its National Eel Management Plan in 2009 (Anonymous, 2008). In spring 2012, the eel fishery on the Swedish west coast was completely closed.

For management of the fishery, indicators of stock abundance (in numbers or biomass; current and pristine) and of human impacts are required. Now that this fishery is closed, those abundance indicators will be required to document the recovery process. As in many data-poor fish species, previous assessments of the Swedish eel stock relied on fishery-dependent catch data (Svedäng, 1999; Anonymous, 2008; Dekker, 2012). However, we question whether eel catch was indicative for the stock on the Swedish west coast. Fisheries catch data are notoriously difficult to interpret, due to underreporting (Deelder, 1984). For data-poor stocks, landings data may be the best data available (Pauly *et al.*, 2013), even though socioeconomic factors should be taken into account too (Branch *et al.*, 2011; Probst and Oesterwind, 2014). Landings data may have to be standardized before being used in stock assessments (Bishop, 2006). Nevertheless, catch trends can be consistent with trends in biomass data of fully assessed stocks (Froese *et al.*, 2012) and have recently been used to estimate stock depletion (Zhou *et al.*, 2017).

The aim of the current study is to evaluate whether the commercial catch can be indicative for the trend in the stock on the Swedish west coast, or to what degree other processes (economical, technical, and environmental) might have been influencing the trends.

Material and methods

The Swedish west coast and its eel fishery

The Swedish west coast is a 320-km long coastline bordering the Skagerrak and Kattegat (Figure 1). It is a productive environment with brackish surface water in the south, originating from the Baltic Sea, and an increasing salinity towards the north. The exposed sandy coastline in the southern parts is gradually replaced by a rocky, sheltered archipelago towards the north. The main rivers that feed into this area are Göta Älv (with a long recruitment series at Trollhättan), Viskan, Ätran, Nissan, Lagan, and Rönneå. The total surface area of coastal eel habitats in this area is estimated at 0.5×10^6 ha (Andersson *et al.*, 2019) to 10^6 ha (Dekker *et al.*, 2011).

The Swedish west-coast fishery comprises a sea fishery using large boats to catch herring, sprat, and cod, a coastal fishery using seine fishing and trawling boats to catch herring and sprat, and a near-shore fishery using nets, tins, cages, and fyke nets from smaller open boats to catch a wide range of species, including herring, sprat, mackerel, eel, and shell fish (Kustfiskeutredningen, 1982–1985; Lagenfelt and Svedäng, 1999; Neuman and Píriz, 2000). The economically most important species in the coastal fishery are herring, lobster, cod, mackerel, and eel (Kustfiskeutredningen, 1982–1985). Until the ban on eel fishing in 2012, the Swedish west-coast eel fishery (from Kullen up to Norway, i.e., excluding the Sound) targeted mainly yellow eel—the silver eel constituted only a few percent of the eel catch. It was a small-scaled seasonal fyke-net fishery, between May and October, by local fishers in small open boats (Kustfiskeutredningen, 1982–1985). The eel fishery was often combined with fisheries for other species in other seasons, and/or with agricultural activities and/or business related to fish and tourism. The eel fishery was regulated through a minimum of legislation, setting a minimal size (35 cm since 1907, 37 cm since the mid-1950, and 40 cm since 2007). In the early-1900s, the eel fishery was restricted by private fishing rights (linked to land ownership, Göteborgs och Bohus läns havsfiskeförening 1867–1912/13—although free by law since 1896, Fiskeristadga, 1932), but this was relaxed in 1928 when land owners were financially compensated for their loss of fishing rights (Fiskeristadga, 1932). In 2007, recreational eel fishing was banned and the professional fishery was limited to less than a hundred of licenced fishers (74–98 in 2007–2011), restricted fishing periods, and a maximum number of fishing gears (Bergenius *et al.*, 2018). In 2012, the eel fishery in this area was completely closed.

Data

Data on catch (1914–2006; Table 1 and Figure 2) and indices of effort [numbers of fishers (full-time and part-time fishers); numbers of small open boats (without motors 1914–1970, with motors 1914–1970, with and without motors combined 1971–2006), and fyke nets 1914–1979; Table 1 and Figure 3] were obtained from the Swedish statistical board (SCB, 2019). Due to changes in the registration system in the 1970s and 1980s, some catches from the west coast might have been landed on the south coast (and recorded there), while some south- and east-coast catches might have ended up on the west coast (which possibly inflated the peaks in mid-1980 and 1990). Illegal fishing and underreporting have undoubtedly occurred, but given the lower prices (see below) and the limited take-up of the local markets, it is unlikely to have had a considerable influence. These local markets might have changed over time, but without data, we presume that it did not affect the overall trends significantly. Over time, boats without motor were replaced by boats with motor; we used the number of small boats with motors as an index for technical development in the first half of the 20th century. In 2002, 72% of all small boats (with and without motors) were used for the main purpose of eel fishing, and another 15% for eel fishing in combination with other small-scaled fisheries (Fiskeriverket, 2010).

Indices of production and trade (Table 1 and Figure 4) included volumes (weight) of imported and exported eel (data from SCB, 1914–2006; Kommerskollegium, 1896–2006; FAO, 2011–2019), the volume of farmed eel (aquaculture in Sweden, Europe, and globally; data from SCB, 1914–2006; FAO, 2011–2019) and the volume of eel used for restocking (database at Swedish Agricultural University). Price indices (Table 1 and Figure 5) included eel price on the west coast (calculated from volume and value of the total landings on the Swedish west coast; SCB, 1914–2006) and relative price of eel versus other fish (mackerel, herring, and total fish; calculated from volume and value of eel, mackerel, herring, and total fish; SCB, 1914–2006, 1987). The price of eel at export exceeded the first-hand price to the fishers (Swedish landings), but the export price is not included in our analyses. All prices were corrected for inflation using historical consumer price indices and standardized to the year 2000 (using Consumer Price Index, CPI; from SCB, 2019). Supplementary information on eel fishery, market demand, and trade routes was obtained from historical archives of Swedish Newspapers (Kungliga biblioteket, 2019).

There is no direct index of the abundance of the eel stock covering the entire 20th century. Abundance indices from standardized fishery-independent surveys are available from 1976 onward

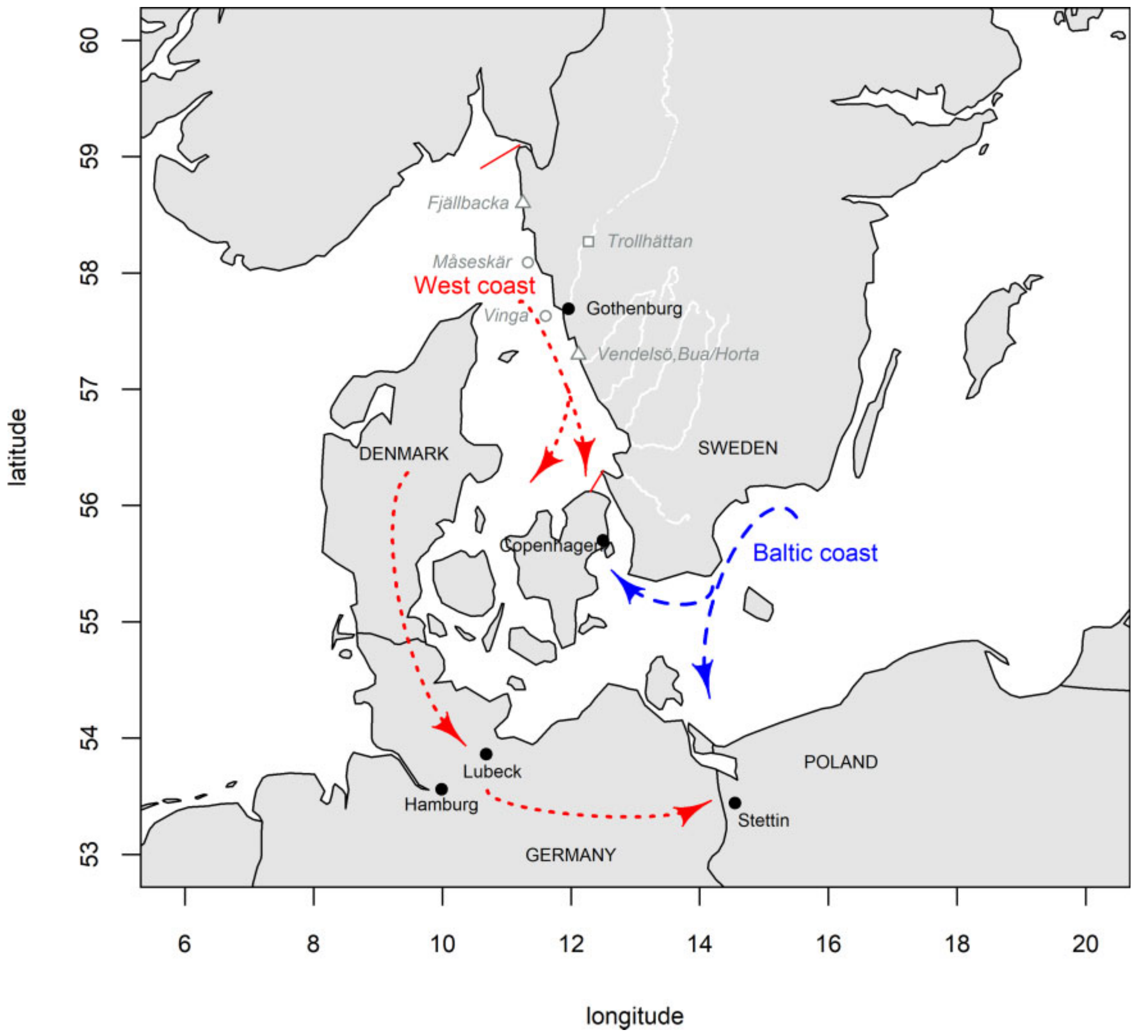

Figure 1. Map of the study area. Main trading routes for eel are indicated (from the Swedish west coast to Denmark, red and dotted arrows; from the Swedish Baltic coast to Denmark and Germany, blue and dashed arrows). Local weather stations are marked with open circles, test fishing areas with open triangles, and recruitment series with an open square. The northern and southern limits of the west coast are marked with thin red lines.

at one site (Vendelsö), and two additional sites from 1988 onward (Bua/Horta in August and Fjällbacka in October). Here, we use the mean CPUE from the three sites 1988–2006 (Figure 6, Andersson *et al.*, 2012). There were no time trends in mean body lengths of the eel in these surveys (Andersson *et al.*, 2019). These are the only series of fishery-independent data on CPUE for the west coast. In addition, an index of recruitment is available from Trollhättan, in the river Göta Älv on the Swedish west coast (annual values and 5 year moving average; Table 1 and Figure 6. Dekker *et al.*, 2018). Noting that different recruitment indices correlate reasonably well, within Sweden and between Sweden and the rest of Europe (Dekker *et al.*, 2018), we consider the Trollhättan data series indicative for the unknown recruitment to the west-coast eel stock.

Weather-related processes (Table 1) were represented by long-term homogenized time series of regional air temperature, precipitation, and wind and storms (annual and/or seasonal data; data from SMHI, 2017). Local weather data were available for the years 1950–2006 (at Måseskär 58°5′38.7”N, 11°19′49.4”E and Vinga 57°37′55.0”N, 11°36′2.5”E).

Logbook data from individual fishers were used to look at trends among fishers that fished regularly and those who fished occasionally (287 fishers along the coast in 1999–2006, data from HaV, 2017).

Statistical analysis

To evaluate which factors influence the eel catch, the historical catch in biomass (on log-scale) was related to indices of effort (i.e. number of fishers, boats, fyke nets), of market and trade processes (i.e. import, export, aquaculture, restocking, and price indices), of stock abundance indices (i.e. CPUE in test fishing, and recruitment indices), and of weather-related processes that may influence effort and catchability (i.e. temperature, precipitation, and wind; Table 1). Since the independent, explanatory variables show different long-term trends and vary independently over short time periods, this will enable us to select and quantify their effects on the catches.

Eel catch was modelled using a random forest regression (Breiman, 2001), which was run for the full set of explanatory

Table 1. Summary statistics for variables used in the catch models and variable importance measure (%IncMSE) before variable selection.

Variable name	Explanation (unit)	years	Mean	Min	Max	%IncMSE
Eel catch	Dependent variable (kg)	93	238 307	49 194	735 000	
Effort indices[1]						
Fishers	(Number)	93	4 827	881	7 923	3
Boats	(Number)	93	1 090	33	1 770	4
Motorboats	(Number)	93	499	16	1 688	7
Fyke nets[2]	(Number)	66	14 749	6 497	25 973	7
Market and trade indices[1]						
Export	(kg)	93	781 061	0	1 298 000	16
Import	(kg)	93	160 788	90	403 000	7
Aquaculture	Farmed eel in Sweden (kg)	93	44 021	0	311 000	1
Aquaculture EU	Farmed eel in EU (kg)	93	2 302 870	0	10 761 000	4
Aquaculture global	Farmed eel globally (kg)	93	58 396 365	0	420 109 000	5
Restocking	Yellow eel (kg)	93	19 133	0	104 163	6
Price (lag 0–1 year)	Eel price (SEK/kg)	93	36.44	14.31	67.11	10
Relative price (lag 0–1 year)	Price eel/total fish (no unit)	93	7.22	1.74	19.13	9
Relative price to herring	Price eel/herring (no unit)	93	9.95	2.16	25.91	8
Relative price to mackerel	Price eel/mackerel (no unit)	93	5.77	1.75	15.88	7
Price export	Eel export price (SEK/kg)	93	55.91	28.10	95.94	5
Stock abundance indices[1]						
Recruitment (lag 0–7 years)	Trollhättan (kg)	93	217	0	1129	0 – 3
Recruitment 5 year mean	Trollhättan, 5 year mean (kg)	93	223	21	720	6
CPUE[4]	Test fishing, 3 sites (kg/effort)	19	0.072	0.022	0.147	0
Regional weather[1]						
Air temp year (lag 0–3 years)	January–December (°C)	93	4.89	2.80	6.70	3
Air temp winter	December–February (°C)	93	−4.12	−9.80	−0.20	1
Air temp spring	March–May (°C)	93	3.23	0.30	6.00	0
Air temp summer	June–August (°C)	93	14.79	12.40	17.20	0
Air temp fall	September–November (°C)	93	5.61	3.40	8.00	2
Precip. year	January–December (mm)	93	635	481	866	1
Precip. winter	December–February (mm)	93	130	48	203	0
Precip. spring	March–May (mm)	93	110	49	174	0
Precip. summer	June–August (mm)	93	211	103	312	3
Precip. fall	September–November (mm)	93	182	93	278	1
Wind	January–December (m/s)	93	9.80	8.70	11.20	1
Storms	January–December (number)	93	19	6	46	0
Local weather[3,4]						
Local air temp	April–September (°C)	56	14.20	12.46	15.58	0
Local air temp 10	Temperature >10°C (% days)	56	83	74	91	1
Local air temp 20	Temperature >20°C (% days)	56	14	0	33	0
Local precip. year	January–December (mm)	56	624	433	933	1
Local precip. year (days)	Rain >0 mm (% days)	56	41	30	54	2
Local wind	April–September (m/s)	56	6.5	4.8	7.6	5
Local wind 5	Wind >5 m/s (% days)	56	58	34	68	6
Local wind 10	Wind >10 m/s (% days)	56	14	7	21	2
Local wind 20	Wind >20 m/s (% days)	56	1	0	5	0

[1,2,3,4]These (groups of) variables are used in models 1, 2, 3, and 4, respectively, as identified in Table 2.

variables (including lag of n years for selected variables, Table 1), as well as for the most important variables selected through a model selection procedure (Evans *et al*., 2011). Alternative models were selected using an iteration method where the least important variable was removed, and model selection was based on best fit (minimum model MSE and maximized percentage of variation explained) and minimum number of retained variables (Murphy *et al*., 2010). The main effects of the most important variables were visualized using accumulated local effect plots, which factors out the effect of the other variables in the model including interactions (ALE plots; Apley, 2018). The purpose being variable selection and not forecasting, and to study long-term processes rather than short term patterns, the data series were not de-trended prior analyses (nonetheless, Durbin Watson test for autocorrelation is presented alongside the model statistics; Durbin and Watson, 1950). There is no assumption on the distribution of residuals in random forest regression models. Nonetheless, residuals were visually inspected for normal distribution and homoscedasticity. Other relationships were analysed using linear regression.

The analysis model chosen actually comprises a more straightforward analysis of CPUE as a special case: we relate the catch (independent variable) to effort and other explanatory variables. If the relation between catch and effort is proportional (i.e. a linear relation of the logged variables, with slope 1), bringing the effort to the left side of the equation would transform our model into a relation of the CPUE (independent variable) to the remaining explanatory variables. By using our more generic model, we allow more flexibility; there seems to be no need to fix the simpler

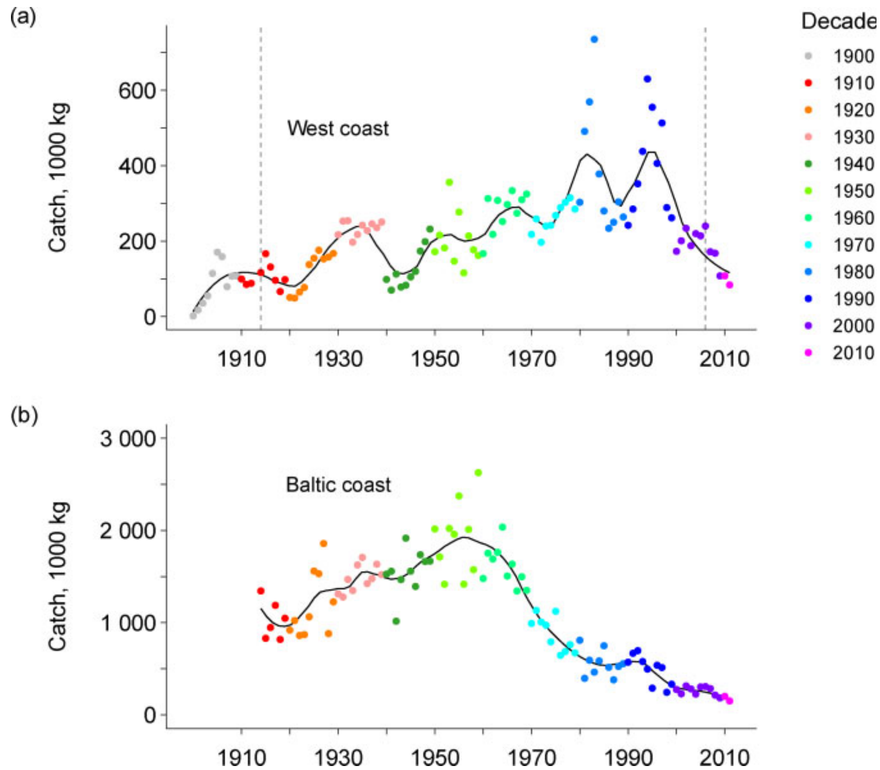

Figure 2. Time series of Swedish eel catch by coastal area: (a) for the west-coast (*Eel catch*), vertical lines mark the start (1914) and end (2006) of the modelled time period, and (b) the Baltic coast. Annual values are shown as coloured dots together with a locally estimated scatterplot smoothing line.

CPUE model at forehand. Actually, our data show no perfectly linear relation between catch and effort (Figure 7b, last panel, number of fyke nets), discrediting a straightforward analysis of CPUE.

All analyses were implemented in R Stats Package version 3.4.0 (R Core Team, 2019), using packages *randomForest* 4.6-14 by Liaw and Wiener (2002, 2018) for the random forest models; *rfUtiliies* 2.1-4 by Evans and Murphy (2018) for the variable selection (function *rf.modelSel*) and model statistics (functions *rf.significance* and *rf.regression.fit*); the package *car* 1.2.6 by Fox (1997) for Durbin Watson statistics; the package *ALEPlot* 1.1 by Apley (2018) for producing ALE plots; and the package *ggplot2* by Wickham (2016) for all other plots (local estimated scatterplot smoothing lines was created using the function *geom_smooth* with span = 0.2).

Results

Catch

Reported eel catches on the Swedish west coast increased from almost nil to 95 t in 1900–1910, gradually increasing further to 390 t in 1991–2000 (with higher peaks in the mid-1980 and mid-1990) but declined to 216 t in 2001–2006 (Figure 2a). This is in contrast to the Swedish eel catch on the Baltic coast, which also increased in the first half of the century, but dropped considerably already after the 1960s (Figure 2b). Hence, the relative contribution from the west coast to the total Swedish catch increased from 5–15% before 1960 to 25–65% after mid-1970.

Effort

The fishers on the Swedish west coast numbered around 7000 in the first half of the 20th century, but their numbers declined consistently during the second half, to about 1500 at the end (*fishers* in Figure 3a). A similar trend appeared in the number of small open boats (*boats* in Figure 3b). Motorboats increased in numbers from 1910 to 1970 but then declined considerably (*motorboats* in Figure 3b). Fyke nets were common in early-1900, dropped during World War I (WWI) (equipment in poor quality were discarded and not replaced due to the high price, SCB, 1914–2006) and World War II (WWII), and increased from 1960 onwards (no data after 1979, *fyke nets* in Figure 3c). The number of fyke nets was positively correlated with the price of the eel (lag1) 1914–1979 (log-scale, $r = 0.29$, $p < 0.001$).

Economic indicators

The first group of market indicators includes production and trade (Figure 4). The total Swedish eel export in 1914–2006 ranged from 0 to 1300 t (*export* in Figure 4), corresponding to 40–80% of the available eel in all of Sweden (fishery, imported, and farmed), except during the WWI and WWII. The bulk of the eel was exported to Denmark and Germany: German companies visited the larger harbours on the Swedish east coast, whereas Danish companies mainly visited the south and west coasts. Germany imported eel for smoking and local consumption, whereas Denmark was largely a transit country, re-exporting the (processed) imports to Germany and other countries. The Swedish eel export was 785 t in 1908, the first year that eel was

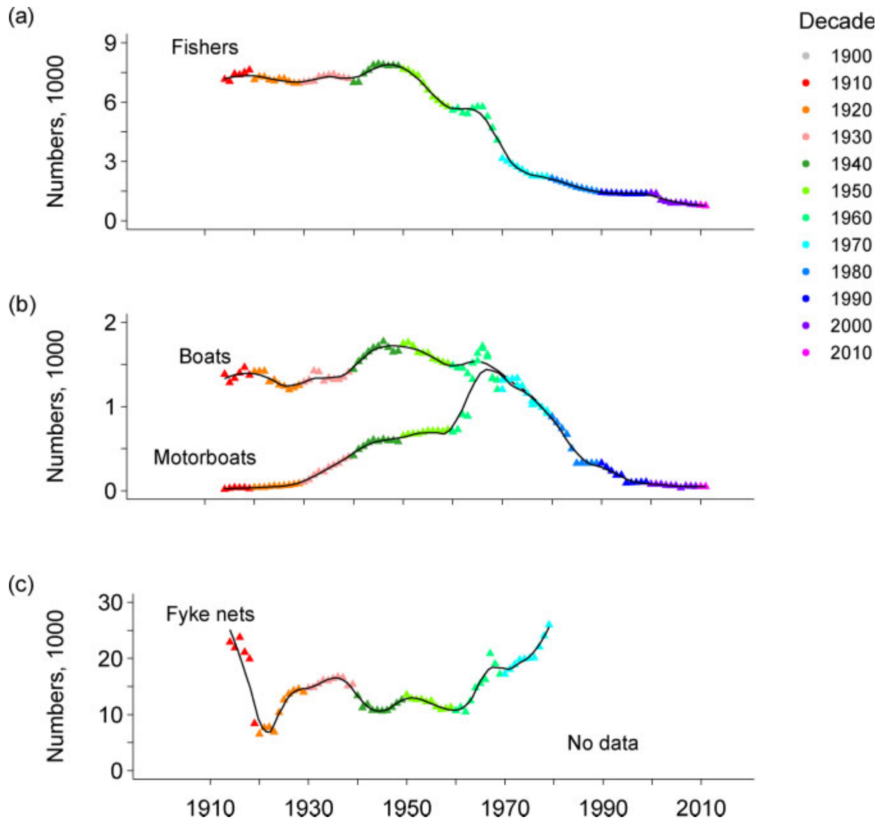

Figure 3. Time series of effort: numbers of (a) *fishers*, (b) small open *boats* and *motorboats* (boats with and without motors are separated until 1970), and (c) *fyke nets*. Annual values are shown as coloured dots together with locally estimated scatterplot smoothing line.

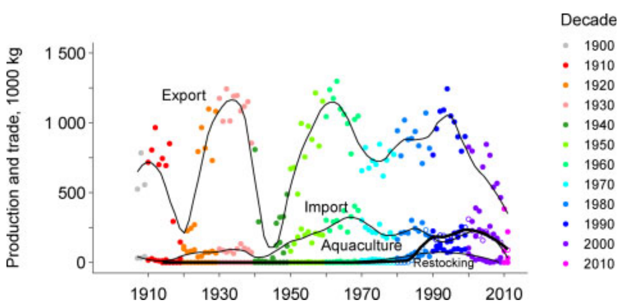

Figure 4. Time series of production and trade: weight of Swedish eel *export*, *import*, *aquaculture* (open circles), and *restocking*. Annual values are shown as coloured dots together with locally estimated scatterplot smoothing line.

separately reported in the export statistics (Kommerskollegium, 1896–2006). Volumes of eel might have been exported before, as Swedish fish export (all species) developed in the late-1800s (<10 t of fish in 1866, rising to >100 000 t fish before the turn of the century).

Imports of eel were <100 t shortly after WWII and peaked in the late-1960s at about 400 t, exceeding the volumes imported in later years (*import* in Figure 4). Eel farming in Sweden started in early-1980 and peaked with 300 t in 2000 (*aquaculture* in Figure 4), showing a similar temporal trend to the farming of European eel within the EU (*aquaculture EU*; $r = 0.95$, Pearson correlation). Globally, farming of different eel species (*Anguilla* sp.) increased considerably from 500 t in 1950 to >420 000 t in 2006 (*aquaculture global*; Table 1). Restocking of yellow eel started shortly after WWII and peaked in early-1990 when >100 t of yellow eel (50–90 g individual weight, Dekker, 2012) was restocked along the coasts and in inland waters (*restocking* in Figure 4). After the mid-1990s, the restocking of yellow eel was replaced by the restocking of glass eel (individual weight ~1 g, imported).

The second group of market indicators includes eel price and relative price of eel (Figure 5; we adjusted all prices for inflation, to year 2000). The eel price ranged from 18 to 66 SEK/kg (SEK = Swedish crowns, 10 SEK ~1 euro), and peaked in 1980s (Figure 5).. The price of eel at export was on average 59% higher than the price paid to the fisher at the west coast because the export also included the higher priced silver eel from the Baltic coast, and due to added costs of transport and handling (for Sweden as a whole, export price was 8% above the price of landing). The relative price of eel showed a similar temporal pattern as the eel price, but with a pronounced dip after WWII, and a peak in 1990s (Figure 5b). The dips in eel price at the end of WWI and during WWII were evidently related to the export being prohibited. The declining eel price in recent years likely reflects an increasing availability of farmed eels (correlation of eel price and worldwide production of farmed European eel in 1980–2000; $r = -0.70$) and an increasing demand for smaller sized eel for restocking purposes (peaking in 1990s when 1 million small eel from the west coast were restocked every year, expressed in biomass in Figure 4; these smaller eel was less expensive than larger eel). In

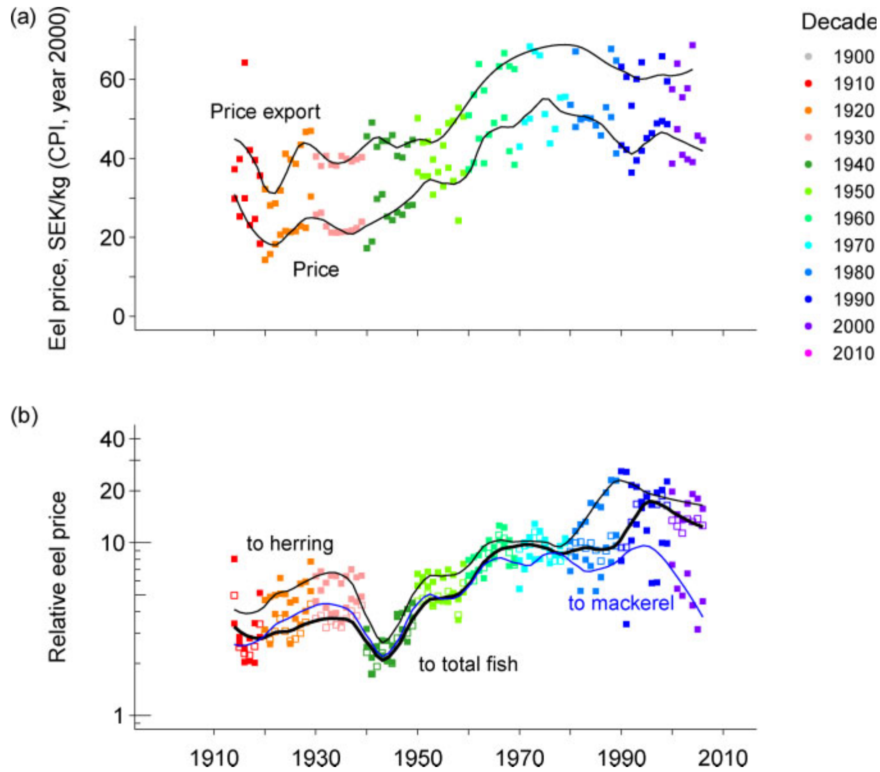

Figure 5. Time series of eel price: (a) price for landed eel on the Swedish west coast (*price*) and exported eel (*price export*) and (b) the price of eel relative to the price of all fish (*relative price*; thick line and open rectangles), relative to the price of herring (*relative price to herring*), and relative to the price of mackerel (*relative price to mackerel*; blue line) (note log-scale on *y*-axis). Annual values are shown as coloured dots together with locally estimated scatterplot smoothing line. All prices are inflation-adjusted to year 2000.

addition, there might have been a drop in market demand, due to media campaigns calling to end eel consumption, in relation to the bad state of the eel stock.

Stock abundance indices

Recruitment of young eel to Göta Älv (Trollhättan) peaked in 1930–1940 and decreased ever since (Figure 6a). In addition, the fishery-independent surveys at three sites along the west coast showed mean eel catches fluctuating between 0.02 and 0.15 kg per fyke net and night (*SD* 0.004–0.17), and no apparent temporal trend in the mean values (Figure 6b).

Weather processes

Indices of weather conditions (annual and/or seasonal air temperature, precipitation, wind speed, and number of storms; Table 1) fluctuated over the years but showed no long-term temporal trends.

Catch models

From 1914 to 2006, eel catches on the Swedish west coast were primarily related to trade and price (main model, pseudo-R^2 = 73%, $p < 0.001$, Table 2), in particular to total Swedish export of eel (*export*) and eel price in the previous year [*price* (*lag1*) and *rel. price* (*lag0–1*), Figure 7a]. Though west-coast catches contributed to the eel export, their contribution must have been relatively small (max 25%, if all catches would have been exported)—that is: the west-coast catches and the export are not fully independent statistically, but nearly so. Environmental processes and regional weather indices were less correlated to the variation in catch in the 1914–2006 period (none of the environmental or weather indices was kept after variable selection; main model, Table 2).

Over the 1914–1979 period, the number of fyke nets, together with variables of trade and price, was well correlated (Figure 7) with the temporal pattern in eel catches (main model + fyke nets, pseudo-R^2 = 80%, $p < 0.001$, Table 2). Other variables of effort (number of boats with and without motor and number of fishermen) were not (these variables were not kept in the final model, Table 2).

The addition of local weather variables to the main model for the 1951–2006 data shows that wind and relative price correlated with the temporal pattern in eel catch (main model + local weather, pseudo-R^2 = 39%, $p < 0.001$, Table 2 and Figure 7c). For the 1988–2006 data, adding CPUE and local weather to the main model, indicates that CPUE was not correlated with eel catch (main model + local weather + CPUE, pseudo-R^2 = 75%, $p < 0.001$, Table 2). High winds had a negative effect on eel catch in both periods (number of days with high winds *local wind5* in Figure 7c–d, and average wind speed *local wind*, Figure 7d), while price generally had a positive effect on eel catch in both periods (*rel. price* in Figure 7c–d).

The models explained 39–80% of the variation in the eel catch. Remaining variation might be related to other factors, such as changes in vegetation structure, nutrient levels, currents, and predators (seals and cormorants). Nutrient input has changed the vegetation structure along the western coast, with a severe decrease in coverage of eel grass (Nyqvist *et al.*, 2009), and increasing occurrence of fine-threaded algae in shallow bays (Pihl *et al.*, 1995), which

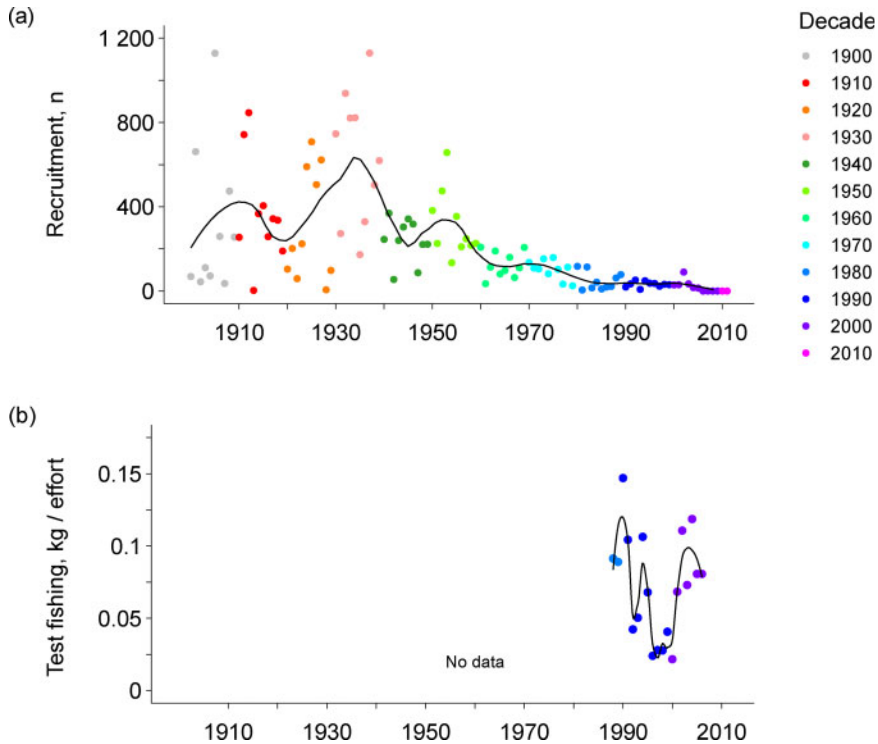

Figure 6. Time series of stock abundance indices: (a) *recruitment* of eel at Trollhättan and (b) catch of yellow eel per unit effort (*CPUE*) at three test fishing locations (mean values). Annual values are shown as coloured dots together with locally estimated scatterplot smoothing line.

may affect the eel stock and catch. Fishers report, for example, that algae cause clogging of the nets (a problem that was particularly prominent in the late-1990s, personal communication with a west-coast eel fisher), and that available fishing areas have decreased due to general exploitation of the coastal zone (dredging, filling, and building small marinas; Kustfiskeutredningen, 1982–1985).

Log books

Over the period 1999–2006, a total of 260 fishers reported their eel catches in logbooks for a shorter or longer period, varying from a single year of reporting (69 fishers), to all years being reported (68 fishers), with a mode of 132 fishers per year. Two-thirds of the fishers reported relatively small catches (<1000 kg per fisher per year on average). Fishers reporting catches for every year accounted for 70% of the total catch. Most eel was caught in Skagerrak (80–90%), the remaining part in Kattegat (10–20%). From 1999 to 2010, the number of active fishers decreased by >50% (from 172 fishers to 76 fishers). The economic value of the eel catch per fisher ranged from 1000 to 1 033 000 SEK per fisher per year (68 000 SEK per fisher per year, on average), amounting 92 000 SEK for the fishers reporting logbooks every year, and over 200 000 SEK for the top-seven fishers.

The positive relation between eel catch and eel price (see ALE plots from random forest regression, Figure 7, and linear regression, Figure 8a) was also observed in the logbook data (1999–2006), where the total catch was positively correlated to eel price (lag0, $r^2 = 0.55$, $p = 0.036$, linear regression model). This relationship occurred for fishers reporting all years ($r^2 = 0.27$, $p = 0.19$, Figure 8b) and was even stronger for fishers reporting some years only ($r^2 = 0.59$, $p = 0.025$, Figure 8b). This indicates that in years with high prices, both the number of fishers targeting eel and their individual catch increased.

Newspaper clips

We identified about 230 newspaper clips describing the Swedish eel fishery and trade routes for the years 1854–1996 from historical archives (Kungliga biblioteket, 2019). A majority of these was from the period before 1960 and describe the emerging eel fishery on the Swedish west coast. For example, newspapers reported in late-1800s that the eel fishery could generate great profits and that German boats visited the Swedish south and east coasts to buy the available eel, at a good price (e.g. Aftonbladet, 1882-10-09). In this context, the Swedish west coast was mentioned for the first time around 1890, reporting that eel may be more common on the west coast than on the east coast and that the Germans would surely find their way to the Swedish west coast to collect eel if sufficient volumes could be made available (e.g. Göteborgs handels och sjöfartstidning, 1890-07-23). This was followed shortly after (at the turn of the century) by reports that it was desirable to develop the eel fishery on the Swedish west coast for export to Germany, where there was shortage of meat (e.g. Svenska Dagbladet, SvD, 1902-11-17; 1905-11-22). In these same years (Göteborgs aftonblad, 1900-05-22), fishermen on the Swedish west coast started to use fyke nets for eel.

Discussion

In the late-1800s, a profitable commercial eel fishery developed on the Swedish Baltic coasts (Trybom and Wollebæk, 1904). On

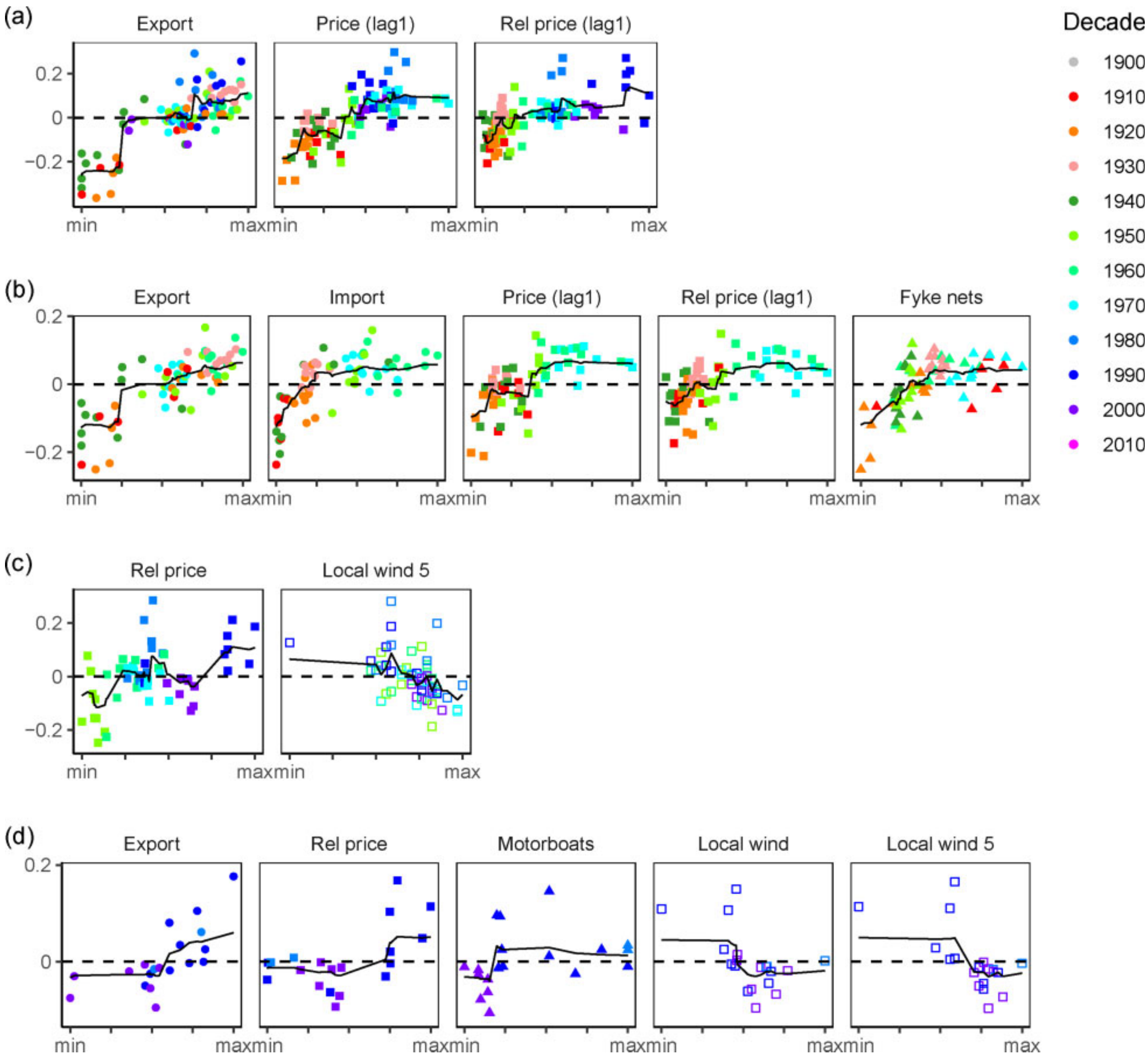

Figure 7. Plots of the effects of the most important variables on eel catch (lines for accumulated local effects) together with model residuals (added to the predictor effect; coloured dots) for (a) the main model (1914–2006), (b) the main model + fyke nets (1914–1979), (c) the main model + local weather (1951–2006), and (d) the main model + local weather + CPUE (1988–2006). The vertical axes of each sub-plot have been scaled from minimum to maximum estimated effect. The horizontal axes are scaled from minimum to maximum value of the predictor.

the Swedish west coast, however, a commercial fishery targeting eel was virtually nonexistent at that time. An unknown amount of eel was caught in subsistence/artisanal fishing or as a bycatch in other fisheries, but that catch was certainly not marketed. At the turn of the century, the commercial eel fishery on the Swedish west coast developed, rising from almost zero catch reported in 1900 to >100 t only 5 years later. This initial period was followed by a 50-year long period of slowly increasing catches, reaching 300 t in 1960s (interrupted only by the WWI and WWII). Catches peaked as late as the 1980–1990s, before fishing restrictions in the 2000s resulted in severe reductions, and eventually, the fishery was completely closed in spring 2012.

Our results show that the development of the Swedish west-coast eel fishery in the first half of the 1900 (increasing effort and catch) was driven by commercial factors (price and trade), facilitated by technical development. No indications were found of an increasing biomass of the stock driving this development. The technical development encompassed better (nylon instead of cotton) and cheaper nets (commercially made instead of hand-made nets) and better (plastic instead of wooden) and faster boats (increase in number of motors), which made it easier to maintain the equipment and to extend the geographical area used for fishing. The main commercial factors driving the west-coast eel catch in 1914–2006 included the export and the price paid (particularly in the year preceding the catch).

These results fit in with findings by Dekker (2019a), reporting about deliberate development programmes for commercial eel fishing throughout Europe, in the early-1900s (the late-1800s until 1950). The small-scaled subsistence/artisanal fisheries for eel in several countries expanded from a localized market into a flourishing commercial fishery that provided luxury foods to new customers via new international markets, exploiting new areas, new fishing methods, and new processing techniques (Dekker, 2019a, b). The development of the eel fishery on the Swedish west coast occurred later than for the Swedish south and east coasts (Göteborgs handels och sjöfartstidning, 1889-01-28; Göteborgs aftonblad, 1900-05-22) and was driven by export (Kungliga biblioteket, 2019). The yellow eel was lower priced and less desirable for the local market than the larger silver eel (SvD, 1941-06-14), and therefore likely more susceptible to changes in trade and price. For example, the lower price following WWI was reported to result in suppressed catches, and the excess eel was prepared for the local Swedish market (SvD, 1917-01-01). During WWII, eel export was prohibited, the price of west-coast eel was low, and there was an excess of yellow eel that could not be sold within the country (SvD, 1941-06-14), which also affected the west-coast catch (low catch 1942–1948). In summary: anecdotal evidence from the newspapers confirms our interpretation that economic processes affecting the fishing, rather than biological processes affecting the stock, have determined the development of this fishery over time.

The ever-rising catch trend on the Swedish west coast throughout most of the 20th century, as influenced by short- and long-term variation in eel price and market demand, implies that the biological production from the stock has not been limiting the catch (at least not until the final peaks in 1980 and 1995), and hence, that the fishery has not fully exploited the biological production. This is in line with the study by Andersson *et al.* (2012) analysing eel catch and effort from the early-1980s onwards, who found that the CPUE on the Swedish west coast was relatively stable, but this deviates from the view expressed by Westerberg (1987) and Svedäng (1999) that stock abundance on the Swedish west coast is limited by density-dependent settlement of recruits, and heavy over-exploitation of the yellow eel phase. Though economic and biological processes might have been operating in parallel, our economic hypothesis considers that the stock is at the lower end of the profitability range, while the biological hypothesis considers that the stock was at the upper carrying capacity of the ecosystem. The catch, ranging from 100 to 400 t per year over the 20th century, corresponding to ~0.5–4 million eels per year, was derived from a productive area of 0.5–1 million ha (Dekker *et al.*, 2011; Andersson *et al.*, 2019). That corresponds to a catch of 0.1–0.8 kg per hectare per year, respectively, 100–1000 individuals per km^2 per year. This is at the very lower end of catch densities reported in literature (Tesch and Thorpe, 2003, p. 240: range <1–10 kg per hectare per year; Dekker, 2003b, Fig. 5b: range 100–40 000 individuals per km^2 per year for yellow and silver eel). Hence, it is more likely that economic processes have limited the development of the fishery, at the lower end of the profitability range. Moreover, at a catch density of 100–1000 individuals per km^2 per year, most eel fisheries in fresh waters would harvest ~50% or more of their catch as silver eel (Dekker, 2003b, Fig. 5b), that is: focusing efforts on the part of the stock that is concentrated in time and space. On the Swedish west coast, however, silver eels do not concentrate in space, and hence, the catch of silver eel is practically zero—almost any silvering eel will escape towards the ocean. This "loss" (in an economic sense) of biological production will have reduced the profitability of this fishery even further.

For the relation between price and quantity, we found a positive correlation—for individual fishers reporting in logbooks in 1999–2006 (Figure 8b), as well as for the market as a whole over most of the 20th century (Figure 8a). In general, markets supplied by wild fisheries show a negative correlation between price and quantity, known as "an inverse demand system", while aquaculture-supplied markets more often show "an ordinary demand system" with a positive correlation between price and quantity (Barten and Bettendorf, 1989; Nielsen *et al.*, 2011). The quantities of fish caught by wild fisheries are set predominantly by external factors, including stock abundance, governmental restrictions, and weather conditions—the price then adjusts to this externally determined supply. In aquaculture, in contrast, quantities produced often relate primarily to the (expected or observed) price in the market, and much less so to external conditions—extra production capacity can be switched on or off relatively easily, adjusting the quantity produced to the (expected) price. Remarkably, our eel fishery on the Swedish west coast shows a positive relation between price and quantity as is characteristic for an aquaculture-dominated market—while it is undoubtedly a fishery on a wild stock. We consider that this extraordinary economic behaviour is related to four factors: (i) prices are set by external factors; (ii) the fishery is limited by (lack of) profitability; (iii) the individual fisher can afford to adjust his fishery to economic circumstances, and (iv) the local eel stock has spare production capacity available.

As for the price-formation process, the eel fisheries on the west coast have produced 100–400 t per year, predominantly for export to an international market handling a total of up to 20 000 t per year (Dekker, 2019a). Even though the Swedish west-coast fisheries contributed to this international market, other factors (related to supply elsewhere and demand-related factors) have overshadowed any ordinary demand system on the west coast itself. During both WWI and WWII, the export market was unavailable, and the local market set a price much lower than before and after, apparently through a normal "ordinary demand system". Though local factors, such as a gradual increase in mean size of the eel in the catch (which comes with a higher price; Kustfiskeutredningen, 1982–1985), might have affected the price formation too, the abrupt and repeated price drop during the wars indicate that price formation was largely an international process. During the developmental years of this fishery, and throughout the 20th century, however, the price was set by the international market, far beyond the control of the west-coast fishers.

Regarding the profitability of the fishery on the west coast, no detailed information on the costs related to eel fishing was available, not for the individual companies reporting their logbooks in 1999–2006, and certainly not for the sector as a whole, throughout the 20th century. However, it seems highly unlikely that fishers restricted their efforts at low eel price, if they would still have made a profit. More likely, during periods of low market prices for eel, individual fishers gave up the least-profitable fishing sites first, and the least-profitable fishers stopped altogether. And vice versa: increased prices enable the fishery at less profitable places, as reflected in the concave relation between catch and effort (Figure 6b, last panel). In the early years (1900–1910), fisheries in the most northern part of the west coast (north of Gothenburg) were paid an equal price as to those in the south. Due to the longer transport routes (and possibly a lower stock abundance locally), costs were higher in the north, and hence, these fishers produced a much smaller catch then further south—these areas came to full development only after prices had risen to a more

Table 2. Model summary of each catch model (main model 1914–2006 includes indices for demand, market and trade, recruitment, and regional weather; the next three models include same variables as the main model plus additional variables listed in Table 1).

	RF models			
Model description	**Main model[1]**	**Main model[1] + fyke nets[2]**	**Main model[1] + local weather[3]**	**Main model[1] + local weather[3] + CPUE[4]**
Years	1914–2006	1914–1979	1951–2006	1988–2006
Observations (number)	93	66	56	19
Full model (all variables)				
Variables (number)	40	41	49	50
Pseudo-R^2 (%)	71	75	28	62
Final model (selected variables)				
Variables (number)	3–5	5	2	5
Pseudo-R^2 (%)	73	80	39	75
Overfitting ratio	19	13	28	4
RMSE	0.11	0.10	0.12	0.08
p-Value	<0.001	<0.001	<0.001	<0.001
Durbin Watson test	1.3	2.0	1.7	1.6
Variables in decreasing order of importance	Export	Import	Rel. price	Local wind 5
	Price (lag1)	Export	Local wind 5	Boats
	Rel. price (lag1)	Price (lag1)		Rel. price
	Rel. price	Fyke nets		Export
	Rel. price herring	Rel. price (lag1)		Local wind

For each model, a full model of all variables was fitted, and a reduced model, based on automatic variable selection. RMSE = root mean square error (smaller is better model fit); overfitting ratio = overfit risk (values <10 denote overfit model); *p*-value = significance test for model (critical alpha = 0.05); Durbin Watson test = autocorrelation test for the model residuals (0–4; 2 = no autocorrelation).
[1,2,3,4]These models contain the variables as indicated in Table 1.

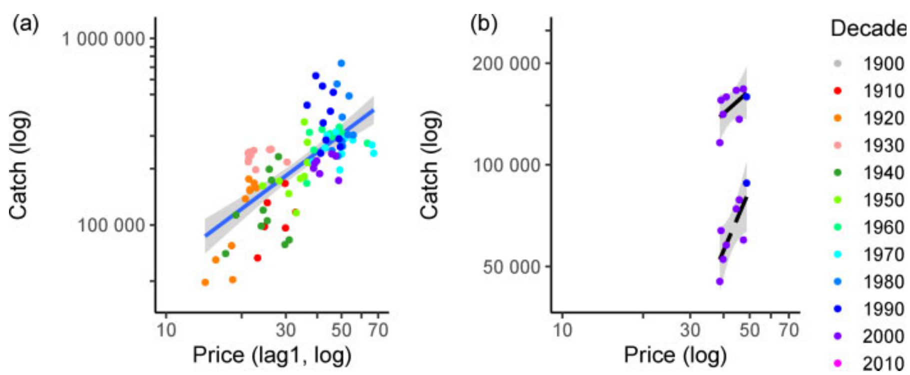

Figure 8. Relationships between eel catch and price for (a) total catch per year in 1914–2006 and (b) fishers reporting catch in log books 1999–2006 (dotted regression line for occasional fishers and solid regression line for fishers reporting catch every year). Annual values as coloured dots.

profitable level. Overall, it seems quite plausible that the west-coast fishery—at the northern end of the commercial eel fisheries (Dekker, 2003a), exploiting a stock density at the lower end of conventionally exploited densities (discussed above), lacking the opportunity to give up on yellow eel to target silver eel instead—was making only a small income, the marginal fisher making no profit at all.

For the individual fisher, reducing the eel fishery at low price will have meant a loss of income but a loss of related costs too. We observed that fishers reduced or ceased their eel fishing operations when low prices prevailed, reacting to the market forces at relatively short notice. This is in contrast to the Swedish eel fisheries on the Baltic coasts (Björkvik *et al.*, 2020), where fishers continued, even when catches (and profitability) declined considerably. While the eel constituted a major part of income for the Baltic fisheries (eel contributing on average 13% of the total landed value), it was just one out of a mixed bag of many species for the west-coast fishers (considering both the small-scaled fisheries and the larger seine and trawl fisheries, eel constituted on average 1.5% of the total landed value). While the Baltic fishers possibly could not afford to reduce/close their eel fishing operations, those on the west coast might have actually improved their overall-profitability by doing so—keeping a slightly lower, but more profitable turnover from other species or business activities.

For the production capacity, we note that higher prices came with a higher catch per fisher, as well as with a higher number of fishers targeting eel (in the logbook data). This implies that at lower prices, those catches have not been made, even though the eel must have been available—remaining unexploited. In biological terms, the stock apparently was less than fully exploited during most of the 20th century, leaving spare production capacity available. A fortiori, it seems plausible that, even at high price levels, this fishery never reached full exploitation. The increasing exploitation over the 20th century, however, will have reduced the local spawner production, contributing to the overall decline in the eel population across Europe.

While it is clear that catch volumes generally relate to stock abundance and fishing effort, our results indicate that (international) market price and local environmental variables have a major, even larger influence on the catch. The relation between effort (number of fyke nets) and catch (Figure 7b, last panel) is clearly not linear but concave, indicating a diminishing catch per unit of effort at higher effort levels. This complicates the relation between abundance, catch, and effort considerably and blocks the straightforward interpretation of CPUE from this commercial fishery as an index of abundance, as for instance done by Andersson *et al.* (2012) for their logbook data. Obviously, scientific survey CPUE is to be preferred where available, relying on a standardized effort. For the nearby Norwegian coast, such a scientific survey index is available indeed (Durif *et al.*, 2011), catching a comparable age-range as our commercial fishery. That index shows a low in abundance around 1925, 1970, and towards the end of their data series (2007), each lasting for about 20 years. This last minimum (at the end) occurs in both the Norwegian and our Swedish data, which might well indicate a common origin in the diminishing recruitment found all over Europe. The two earlier Norwegian minima are not reflected in our Swedish data, which confirms our observation that other factors (price) likely have determined the development of the Swedish fishery. Since the scientific surveys on the Swedish west coast run for much shorter periods only (Andersson *et al.*, 2012), it remains unclear whether the Norwegian survey is fully representative for the abundance in Sweden too.

At the bottom line, our results indicate that the eel stock on the Swedish west coast probably was never fully exploited during most of the 20th century, before the government imposed restrictions on the fishery (since 2006) and closed it (in 2012). Catches (and fishing effort) increased slowly throughout most of the 20th century, in relation to slowly rising market prices. Over the second half of the 20th century, landings across Europe were diminishing (Dekker, 2003b; Aalto *et al.*, 2016), while during the first half of the century, the stock might well have been in decline already (Dekker, 2019a). That is: the eel fisheries on the Swedish west coast developed, driven by economic factors (price), in times of biological population decline.

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Data availability statement

The data underlying this article will be shared on reasonable request to the corresponding author.

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