Aquat Sci (2015) 77:411–425
DOI 10.1007/s00027-014-0389-9

Aquatic Sciences

RESEARCH ARTICLE

Dynamics of fish catches in the eastern Gulf of Finland (Baltic Sea) and downstream of the Neva River during the 20th century

Dmitry Lajus · Jekaterina Glazkova · Dmitry Sendek · Vadim Khaitov · Julia Lajus

Received: 18 February 2014 / Accepted: 28 November 2014 / Published online: 16 December 2014

Abstract The paper describes changing patterns of commercial fish catch in the downstream part of the Neva River and the eastern Gulf of Finland and analyzes drivers of these changes for the period 1929–1995. We summarize catch data on 20 species and species groups of fishes and lamprey, as well as available abiotic data (salinity, temperature and water transparency). Water transparency gradually decreased during the 20th century being inseparable from a number of non-quantified anthropogenic factors, thus it can be used as an integral index of anthropogenic loading on the ecosystem. Because fisheries statistics were not published regularly, catch data were extracted from archives and various publications. Fishing locations, gear and target species changed over time in relation to each other, reflecting technological developments in fisheries, commercial demands for fishery products and the abundance of fish populations. Until the 18–19th centuries, fisheries took place mostly in rivers where weirs and set nets targeted sturgeon, salmon and whitefish. By the end of the 19th century, herring and smelt were the main targets of fixed nets in coastal areas. A century later, the main commercial species, herring, was harvested with pelagic trawls operating offshore in the Gulf. This evolution in fisheries, along with other anthropogenic activities, caused severe declines in diadromous species. Spawning migrations that make them easy to catch, and their high market value, make diadromous fish more vulnerable than other groups. Canonical correspondence analysis showed that catches of most diadromous species decreased with increasing transparency, which may reflect their response to anthropogenic pressure. Marine and freshwater fish suffered from anthropogenic pressure, but to a lesser extent probably because of a wider distribution and dispersal, and more capital-intensive fishing methods. Catches of marine species, except herring, significantly increased in the 1970–1980s when salinity was comparatively high. We found no correlation of fish catches with temperature.

Keywords Baltic Sea · Gulf of Finland · History of fisheries · Historical ecology

This article is part of the special issue 'Historical ecology of riverine fish in Europe'.

D. Lajus (✉) · J. Glazkova · V. Khaitov
St. Petersburg State University, 16 Linia V.O., 29. 199178, St. Petersburg, Russia
e-mail: dlajus@gmail.com

D. Sendek
State Research Institute for Lake and River Fisheries, Makarova Embankement 26, St. Petersburg, Russia

J. Lajus
National Research University Higher School of Economics, St. Petersburg, Russia

Introduction

Information about past ecosystems and the changes they underwent allows us to predict how they will look in the future and how we might change them in a direction we would like. Fisheries statistics are an important source of knowledge about past ecosystems because these data usually pre-date many other types of ecosystem information. Thus they attract attention from aquatic historical ecologists. Because catches reflect not only population abundance but also fishing effort, catch data are not easy to interpret in terms of ecosystem changes. Nevertheless, they are often used in historical studies despite, or perhaps because of, the fact that fishing effort is difficult to quantify (Haidvogl et al. 2014). To fully use their potential, fisheries data must be sufficiently detailed to quantify environmental variables that may influence population abundance.

In estuaries, fish abundance and community structure is affected by a strong gradient of natural environmental factors. In addition, estuarine organisms are subjected to serious human-induced effects: contamination from domestic and industrial discharges, alterations resulting from agricultural, industrial and engineering projects, and overfishing (Haedrich 1983). Studies with a long-term perspective on processes occurring in fish communities in estuarine areas increasingly attract the attention of researchers (Cabral et al. 2001; Potter et al. 2001; Shan et al. 2013).

The eastern part of Gulf of Finland and the Neva River estuary are situated downstream on the Neva River near St. Petersburg, with five million inhabitants, one of the largest cities in Europe. The economic situation in this area has been quite unstable during the last few decades, which has noticeably changed human-induced pressure on ecosystems. Hydrological conditions also exhibit high natural variability (Alenius et al. 1998). The fish community, which includes 54 species (Kudersky 1996), is quite heterogeneous and includes marine, freshwater and diadromous components. Therefore, changes in this complex fish community are driven by multiple exogenous factors interacting with each other and causing both direct effects on species and indirect effects via factor interaction.

With such high complexity, identifying factors and mechanisms that cause change in ecosystems is difficult. Yet this knowledge is essential for forecasting future conditions and promoting sustainable use. Identifying ecosystem drivers is much easier using longer time-series because, in shorter time-series, noise and the greater contribution of non-control factors confound the signal. As a result, studies of long-term ecosystem change using historical approaches have become more common. The Baltic Sea ecosystem has received scrutiny (MacKenzie et al. 2002, 2011; Eero et al. 2007, 2008), as have fishes in the Gulf of Finland, particularly in the eastern part (Ilienkova et al. 1978; Kudersky 1999; Lajus et al. 2013).

Ilienkova et al. (1978) revealed the effect of temperature and river discharge on the abundance of major commercial fishes in Neva Bay during the period from the 1960s (in some cases from the 1930s) to the 1970s. The authors identified two groups of species which responded differently to hydrometeorological processes. Kudersky (1999) focused on changes in fish catches and communities from the mid-1940s to mid-1990s and found that the declines in fish populations in the area were mostly caused by fishing as well as pollution and altered spawning grounds in Neva Bay. These studies, however, were to a great extent descriptive because of lack or only simple statistical analyses, which considerably limits formal data interpretation.

Recently, we summarized the available sources on changes in fish populations in the Neva region from the 15th–early 20th century, most from historical archives (Lajus et al. 2013), but analytical possibilities for very old catch data are limited due to its fragmentary nature. Continuous long-term time series of catches and environmental variables would strengthen interpretations of historical data and better explain processes currently occurring in this ecosystem. Here, the objective was to describe changes in abundance and distribution of fish in the eastern Gulf of Finland and the Neva River estuary in the 20th century and, using statistical analysis, to reveal which environmental factors are correlated with population abundance.

Materials and methods

Study area

Gulf of Finland extends in length 420 km from east to west, its width grows from 70 km in the east to 130 km in the west. This results in a surface area of 29,500 km^2, and water volume of 1,120 km^3 (Alenius et al. 1998). The Gulf's hydrological regime is determined by its connection to the Baltic Sea and inflow from the Neva River. It is common to consider the eastern part of the Gulf of Finland as a separate region for political reasons. In the 17th century this area belonged to Sweden, and between World War I and II its northern coast belonged to Finland. Otherwise, the eastern Gulf of Finland extending from the Neva River to include Koporye, Luga and Narva bays has been Russian since the Middle Ages and belongs entirely to Russia today (Fig. 1). Administratively, it is part of the Leningrad *oblast* administrative division. Near Seskar Island, the width of the Gulf increases considerably, which slows the Neva's current and increases local sedimentation. Thus it is a buffer for pollutants transported down the Neva River, which flows through the heart of St. Petersburg.

The coastal zone of the eastern Gulf of Finland is usually shallow with bottoms consisting of sand, sandy silt and clay. A constant current runs through the Gulf due to river outflow. Before the St. Petersburg dam's construction completed in 2011, current velocity near Kotlin Island ranged from 10 to 32 cm/s (Smirnov 1973). The Neva is the largest river flowing into the Gulf of Finland (average annual discharge = 2,400 m^3/s), and the second largest is the Narva River (discharge = 357 m^3/s). These two rivers provide more than 70 % of the total river inflow into the Gulf of Finland.

Ice usually covers the eastern Gulf of Finland from November to May. Near the mouth of the Neva the frozen

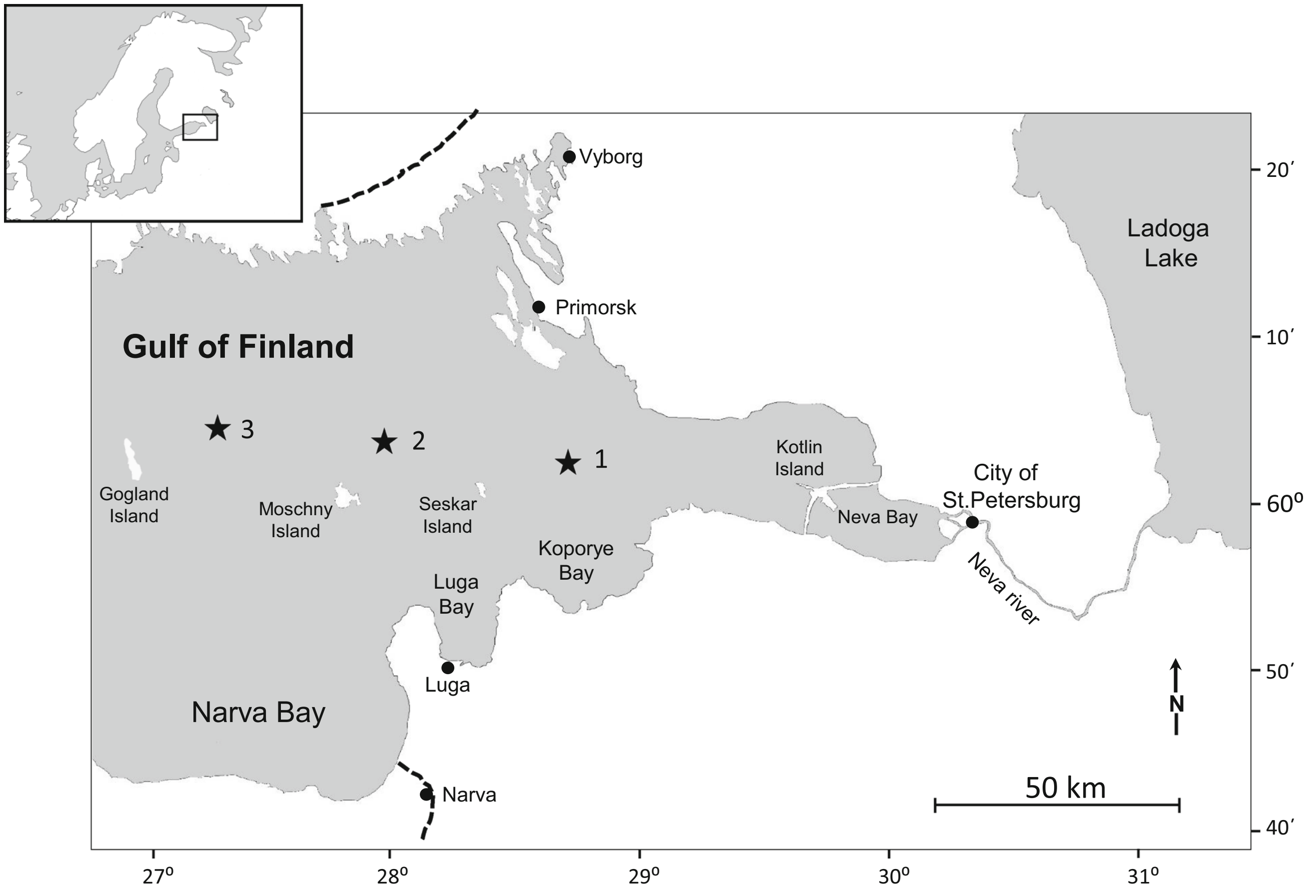

Fig. 1 Study area—the eastern Gulf of Finland. *Asterisks* designate stations with salinity time series (*1, 2* and *3* designate *2, 3* and *4*, respectively, from Davidan and Savchuk 1997). *Dash line* designates current border of Russia

period lasts from 141 to 185 days (Alenius et al. 1998), and ice thickness varies from 30 to 100 cm (Smirnov 1973). Average surface temperature in August, the warmest month, fluctuates between 15 and 20 °C; below 30–50 m depth, temperature varies from 2 to 4 °C during the year.

Overall, salinity increases westward from completely fresh water to 3–4 PSU at the surface and 6–7 PSU on the bottom near Gogland Island. Changes in salinity depend upon saltwater inflow from the North Sea to the Baltic, and relate to general atmospheric circulation, fluctuations in river flow and moisture exchange. Nonetheless, salinity values are still below the critical threshold for freshwater organisms, 5–8 PSU (Khlebovich 1969), thus the area is inhabited by freshwater and migrating fish species typically found in the Neva River, as well as some marine species that tolerate low salinity.

Environmental variables

Temperature data were obtained from the ICES web site (https://www.ices.dk). Because data for the study period, 1929–1995, and study area, east of 25°E, were not available, we used data from the closest areas—in most cases from the northwestern part of the Gulf of Finland. Only surface temperatures were used. When multiple data points were available for the same day, we averaged them, and then determined the monthly mean based on available daily data. Data for the warmest month, August, and the coldest month, February, were used. Salinity data were obtained from work by Davidan and Savchuk (1997) by averaging integral values from surface to bottom (40–60 m) from three stations situated in the eastern Gulf of Finland (Fig. 1). Since salinity records for 1944–1952 and 1994–1995 were absent from this dataset, missing data were estimated via calculations that assumed a constant ratio with salinity values from the ICES database from the locations described above (average between winter and summer salinity). Information on water transparency measured as annual average Secchi depth was obtained from the Helsinki Commission web site (https://www.helcom.fi). Because data were presented only in the form of a graph, the program UTHSCSA ImageTool (available online from https://www.uthscsa.edu) was used to trace the graph and obtain numerical values. Data on environmental variables are presented in Fig. 2.

Catch data

In this study, we used catch data for the period from 1929 to 1995 because later data became unsatisfactory due to the crash of the Soviet fisheries statistics system. Catch data were obtained from published papers and unpublished reports of the State Lake and River Fishery Research Institute in St. Petersburg (GosNIORKh). Most documents refer to Sevzaprybvod, a state agency responsible for collecting fishery statistics, as the source of data, although a few authors do not specify their source (Tiurin 1949; Bykova 1960).

In total, we obtained data on 17 individual species and on 3 species groups: (a) salmonids, including Atlantic salmon (*Salmo salar*), and anadromous brown trout (*S.trutta*), with salmon dominating (see Lajus et al. 2013); (b) tiddler, which included roach (*Rutilus rutilus*), sichel (*Pelecus cultratus*), ruff (*Gymnocephalus cernuus*), bleak (Alburnus alburnus), juveniles of common perch (*Perca fluviatilis*), bream (*Abramis brama*), *pikeperch* (*Sander lucioperca*), and; (c) sticklebacks, including two species—three-spined stickleback (*Gasterosteus aculeatus*) and nine-spined stickleback (*Pungitius pungitius*).

Telegin (1944) provided total annual catches from 1929 to 1939, as well as the average ratio of individual species for this period. Assuming a constant ratio, we calculated the catch of each species in each year if data from other sources were not available. This was the case for vendace [data for 1936–1943 from Bykova (1960)], and lamprey (*Lampetra fluviatilis*) [data for 1935 and 1936 from Tiurin (1949)]. Telegin (1946) provided only pooled data on pike, burbot, ide and vimba bream (*Vimba vimba*). Individual catches of these species were estimated based on the ratios of these species within catches from adjacent periods found in other sources. When only averaged data for a five-year period were available, we used the average for each individual year during that period (eel (*Anguilla anguilla*) and burbot (*Lota lota*) catches for 1946–1970 and flounder (*Pleuronectes flesus*) for 1966–1985, which is about 7 % of all catch data. When different papers by the same authors for the same year gave different data (for instance, Popov et al. 1982; Popov 1983), preference was given to the latest data of publication. Tiurin (1949) provided pooled catch data on river lamprey from 1933 to 1944, which suggested that fishing occurred each year. Given the absence of regular fishing in Leningrad (now St. Petersburg) during the Siege (1941–1943), we assumed that all catch was obtained in the years 1933–1939 and 1944. With this assumption, the results coincided with data from other sources (Telegin 1946; Kudersky 1999). Absence of data was interpreted as zero catches since any significant catches would have been reflected in the fishery statistics.

Statistical treatment

For statistical analysis, we used only data from 1944 to 1995 to avoid the gap between 1941 and 1943 caused by

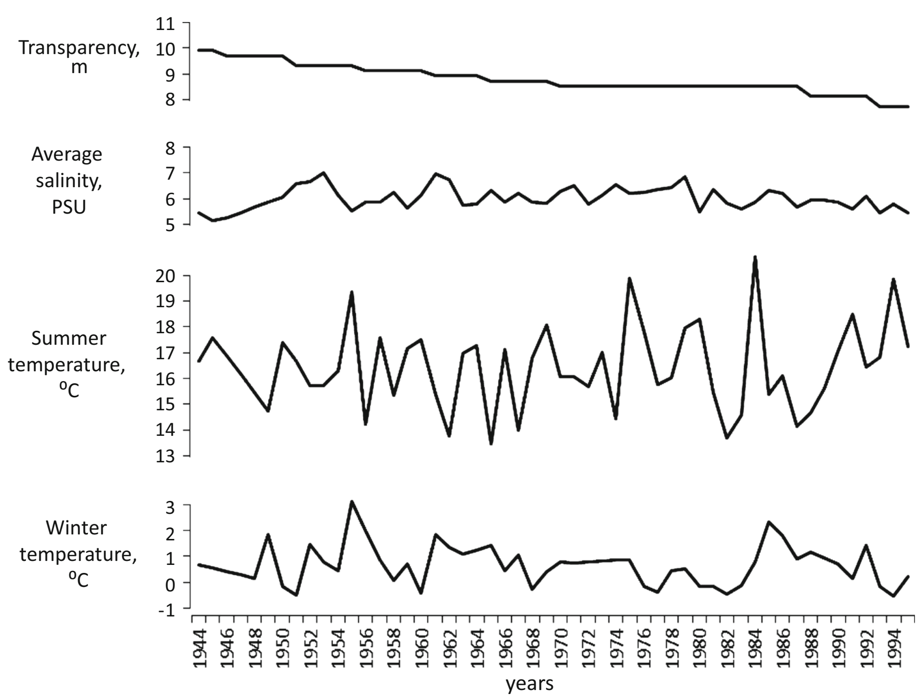

Fig. 2 Environmental variables (*from bottom*): Winter (February) surface temperature near the study area from ICES database (NW Gulf of Finland, about 60°N, 24–25°E); summer (August) surface temperature; salinity in the study area—average from salinity at stations 2, 3 and 4 (according to Davidan and Savchuk (1997), see also Fig. 1 and explanations in text); annual average water transparency measured as Secchi depth from HELCOM site (helcom.fi)

World War II. Although some fishing is known to have occurred during the war, information on landings during that period was unsatisfactory. The period 1929–1940 was excluded because data were not available for the northern coast, which belonged to Finland at that time.

R programming language (R Core Team 2014) was used for all data processing. We used R-package "vegan" (Oksanen et al. 2013). Prior to statistical analysis, all catch values were log-transformed. To explore the effect of environmental factors on catches, we performed canonical correspondence analysis, CCA (ter Braak 1986; Legendre and Legendre 2012). The matrix of catch values of each particular species was considered as a dependent data and matrix of environmental variables as independent predictors. The significance of the analysis was assessed by permutation method as described in Legendre and Legendre (2012).

For the analysis of general trends in catch composition, individual species and species groups were considered as variables and years as samples, and a matrix of Bray-Curtis dissimilarity (BCD) coefficients comparing each pair of samples was calculated (Clarke and Gorley 2006). To reveal trends, we used a model-matrix technique (Clarke and Gorley 2006; Legendre and Legendre 2012). Briefly, this analysis includes the calculation of a gradient model-matrix—a matrix of Euclidean distances (ED) between points evenly distributed along a line (in fact, we calculated an ED matrix between years, i.e., for example, 1944 vs 1945 or 1995 vs. 1971). This gradient model matrix was compared with the BCD matrix using a Mantel correlation, the significance of which was assessed through 999 permutations of the initial matrix (Legendre and Legendre 2012).

To address variables which are not controlled in the study and thus are not accounted for in the CCA model, but could also affect catches, we performed analysis of residuals. For that, we calculated a matrix of Euclidean distances between years based on residuals for each species. This matrix was used for multidimensional scaling (MSD) ordination.

Results

Temperature during our study period did not show clear trends, whereas salinity showed two spikes, one around 1960 and a larger one around 1980 (Fig. 2). Winter and summer temperature did not correlate with each other. Salinity across different locations (stations 1, 2 and 3, Fig. 1) showed, positive correlations (average $r = +0.669$), while transparency (Fig. 2) was very highly correlated with year serial number ($r = 0.936$, $P < 0.01$).

Catches of 20 species and species groups are provided in Table 1. Figure 3 shows long-term changes in catch size and in composition of principal species and species groups.

Evidence of a strong trend in temporal changes of catch composition was provided by comparing the BCD matrix with the gradient model matrix. The Mantel correlation between BCD matrix and gradient model matrix was 0.72 (permutation p level <0.01).

Canonical correspondence analysis showed that constrained ordination of objects in four canonical correspondence axes (CCA) explained 31.5 % of the total variance of catches (in terms of inertia). The two first CCA were significant ($F_{CCA1} = 12.36$; $F_{CCA2} = 8.34$, permutation p value <0.05 in both cases, 199 permutations). Two of four environmental variables showed significant effects on constrained object ordination—water transparency and salinity (Table 2). At the same time, almost 70 % of catch variation was explained by variation of factors that were not quantified. Some of them may be estimated qualitatively and will be addressed in the Discussion section. As in three species, we had only average data for some periods (see "Materials and methods" section) which may result in false correlations due to pseudoreplication, we also performed an analysis excluding these three species. According to this analysis, four CCA explained 29.5 % of total catch variance, which we considered to be a very similar result and in future analyses use of the entire dataset.

The ordination of species in the space of two first CCAs showed clear association of most marine species with the Salinity axis, and migratory species, except smelt and lamprey, with the Transparency axis (Fig. 4). Other species, excluding sticklebacks did not show strong correlation with environmental variables.

The ordination in constrained CCA revealed an obvious pattern: points corresponding to different years changed their position gradually. They moved along the Transparency axis at the end of the study period (after 1985) (Fig. 5). For the whole period, there was a large loop in direction of the Salinity axis in the 1950–1980s (Fig. 5), which showed high dependence of catch composition on salinity.

MSD ordination of residuals (Fig. 6) showed that most years cluster together with quite uniform residuals. However, years from 1973 to 1977 form a loop which considerably deviates from other years. This period coincides quite well with peak catches for a majority of species over the entire period of our study (Table 1). Analysis of trends performed in a similar way as with the CCA model showed absence of any trend–Mantel correlation was $= -0.07$ (permutation p level >0.05).

Table 1 Catch data (metric tonnes) for fish and lamprey in the Neva River and the eastern Gulf of Finland for the periods 1929–1940 and 1944–1995

Years	Herring	Sprat	Cod	Eelpout	Flounder	Lamprey	Eel	Salmonids	Vendace	Whitefish	Smelt	Bream	Pike	Burbot	Ide	Vimba bream	Sticklebacks	Pikeperch	Perch	Tiddler
1929	2,718.89	0.00	0.00	0.00	0.00	24.70	7.56	12.95	0.00	15.63	723.32	32.64	11.30	2.82	3.49	25.79	0.00	42.87	179.32	426.97
1930	2,346.52	0.00	0.00	0.00	0.00	21.20	6.52	16.61	0.00	13.49	624.25	28.17	9.75	2.44	3.01	22.26	0.00	37.00	154.76	368.50
1931	4,098.37	0.00	0.00	0.00	0.00	37.40	11.39	29.02	0.00	23.56	1,090.30	49.20	17.03	4.26	5.25	38.89	0.00	64.63	270.30	643.61
1932	2,620.18	0.00	0.00	0.00	0.00	23.70	7.28	18.55	0.00	15.06	697.06	31.45	10.89	2.72	3.36	24.86	0.00	41.32	172.81	411.47
1933	4,429.01	0.00	0.00	0.00	0.00	40.20	12.31	31.36	0.00	25.46	1,178.26	53.17	18.40	4.60	5.68	42.02	0.00	69.84	292.11	695.53
1934	5,153.65	0.00	0.00	0.00	0.00	46.70	14.32	36.49	0.00	29.63	1,371.04	61.86	21.41	5.35	6.61	48.90	0.00	81.27	339.90	809.33
1935	4,750.73	0.00	0.00	0.00	0.00	73.10	13.20	33.64	62.70	27.31	1,263.85	57.03	19.74	4.93	6.09	45.08	0.00	74.91	313.33	746.06
1936	4,248.68	0.00	0.00	0.00	0.00	76.60	11.81	30.08	22.30	24.42	1,130.29	51.00	17.65	4.41	5.45	40.31	0.00	67.00	280.22	667.21
1937	5,286.60	0.00	0.00	0.00	0.00	66.70	21.20	24.90	0.00	26.98	1,514.30	57.20	10.48	2.62	6.41	47.46	0.00	80.60	340.70	726.70
1938	5,345.90	0.00	0.00	0.00	0.00	80.20	13.70	25.80	4.30	76.30	688.20	131.80	24.64	6.16	5.95	44.04	0.00	86.60	230.10	691.00
1939	3,905.40	0.00	0.00	0.00	0.00	15.90	13.80	23.40	0.50	45.00	847.80	174.30	16.56	4.14	5.13	37.97	0.00	114.60	318.00	703.20
1940	3,920.30	0.00	0.00	0.00	0.00	19.10	9.70	12.70	0.80	6.00	490.90	222.30	20.32	5.08	5.13	37.97	0.00	110.70	373.90	675.50
1944	1,082.30	0.00	0.00	0.00	0.00	24.80	1.00	0.60	8.50	0.00	295.50	56.60	12.64	3.16	0.61	6.17	0.00	16.60	93.40	299.30
1945	1,711.60	0.00	0.00	0.00	0.00	21.70	2.20	9.00	17.50	0.30	588.20	38.60	7.92	1.98	0.38	3.87	0.00	30.00	60.90	194.20
1946	2,388.97	4.00	0.00	0.00	0.00	41.50	2.00	14.18	21.39	0.75	985.45	40.00	17.21	5.00	0.86	8.68	0.00	22.20	42.44	354.35
1947	3,153.77	4.00	0.00	0.00	0.00	39.40	2.00	26.98	8.91	5.45	1,002.72	70.40	25.54	5.00	1.18	11.93	0.00	39.40	57.07	476.43
1948	3,614.41	4.00	0.00	0.00	0.00	86.70	2.00	26.49	19.61	2.36	1,339.46	75.20	18.31	5.00	0.90	9.10	0.00	48.40	52.74	440.32
1949	5,320.00	4.00	0.00	0.00	0.00	25.60	2.00	36.02	17.83	9.00	1,002.21	115.19	27.29	5.00	1.25	12.61	0.00	56.70	68.77	574.09
1950	6,130.00	4.00	0.00	0.00	0.00	41.98	2.00	33.53	19.61	26.30	1,457.53	97.59	10.20	5.00	0.59	5.94	0.00	60.80	73.14	610.60
1951	5,360.00	23.00	0.00	0.00	0.00	33.79	1.00	23.29	64.18	32.40	1,819.78	108.79	20.83	9.00	1.15	11.65	44.23	64.40	77.54	647.36
1952	5,980.00	0.00	0.00	0.00	0.00	60.42	1.00	20.12	19.61	97.00	1,195.99	108.79	16.33	9.00	0.98	9.90	0.00	67.60	106.82	891.80
1953	6,060.00	0.00	0.00	0.00	0.00	67.93	1.00	18.03	12.48	23.50	1,212.84	115.19	16.44	9.00	0.98	9.94	70.77	66.90	103.90	867.38
1954	5,800.00	0.00	0.00	0.00	0.00	79.18	1.00	16.94	281.68	22.60	2,350.39	98.13	22.91	9.00	1.23	12.46	79.62	37.50	79.00	659.57
1955	7,190.00	0.00	0.00	0.00	0.00	52.57	1.00	16.24	135.40	6.50	2,847.30	147.19	44.50	9.00	2.07	20.90	53.08	45.50	102.49	855.61
1956	8,120.00	0.00	0.00	0.00	0.00	53.25	2.00	14.46	82.20	29.60	1,895.32	150.40	46.59	9.00	2.15	21.71	124.17	61.90	76.19	636.08
1957	7,060.00	203.38	0.00	0.00	0.00	52.22	2.00	10.30	118.30	6.70	715.88	78.93	19.84	9.00	1.11	11.27	97.31	32.50	57.05	476.27
1958	8,920.00	378.86	52.50	0.00	0.00	80.90	2.00	4.65	263.85	3.10	1,128.54	58.66	11.84	9.00	0.81	8.14	300.90	38.30	51.22	427.58
1959	10,847.47	639.18	0.00	0.00	0.00	89.78	2.00	3.86	1,028.79	1.50	1,937.26	60.80	20.83	9.00	1.15	11.65	419.00	15.30	52.68	439.79
1960	12,615.84	987.82	0.00	0.00	0.00	63.15	2.00	3.95	328.04	11.10	1,802.73	87.46	22.14	9.00	1.20	12.16	390.00	16.00	21.99	183.59
1961	14,155.42	465.73	0.00	0.00	0.00	109.58	2.00	5.04	66.20	11.50	1,870.06	124.79	14.03	7.00	0.81	8.21	962.20	10.10	23.45	195.76
1962	13,232.98	1,714.46	0.00	0.00	0.00	81.59	2.00	2.67	35.10	2.80	1,372.81	94.93	15.57	7.00	0.87	8.81	1482.10	10.60	24.91	207.97
1963	5,385.47	697.29	0.00	0.00	0.00	79.19	2.00	4.05	17.60	4.00	1,078.01	97.06	14.58	7.00	0.83	8.43	448.50	19.60	39.60	330.62
1964	8,320.00	87.16	0.00	0.00	0.00	49.83	2.00	3.95	14.90	0.50	1,078.09	133.33	13.48	7.00	0.79	8.00	1,187.70	18.60	60.00	1172.60
1965	14,320.00	1,743.51	0.00	0.00	0.00	52.23	2.00	3.56	189.01	0.20	2,265.54	195.30	13.15	7.00	0.78	7.87	369.20	27.20	54.10	1392.37
1966	17,360.00	3,835.52	0.00	0.00	2.00	51.89	1.00	4.55	17.60	6.50	2,130.75	173.20	18.86	10.00	1.12	11.27	192.80	35.30	124.90	2100.79
1967	17,120.00	2,440.65	0.00	0.10	2.00	46.76	1.00	3.36	6.80	0.40	1,911.70	144.80	11.40	10.00	0.83	8.36	0.00	74.40	145.40	2516.16
1968	23,940.00	1,191.20	0.00	0.30	2.00	68.95	1.00	6.92	20.30	1.30	4,202.42	142.80	16.55	10.00	1.03	10.37	13.90	151.50	160.20	2357.40
1969	15,930.00	1,249.31	0.00	0.00	2.00	46.76	1.00	5.34	19.10	1.60	2,703.33	156.80	15.68	10.00	0.99	10.03	0.00	186.10	157.00	2235.33
1970	23,580.00	1,627.30	0.00	0.00	2.00	74.41	1.00	6.43	39.40	9.40	2,452.67	193.30	12.93	10.00	0.89	8.96	0.00	207.70	88.40	4091.47
1971	21,420.00	2,033.90	0.00	3.30	0.00	90.45	0.00	11.77	103.70	14.10	1,372.76	243.20	14.91	7.00	0.85	8.56	0.00	164.20	90.30	3261.42
1972	17,000.00	3,341.61	0.00	3.20	0.00	60.00	0.90	15.00	124.90	31.70	1,917.00	309.60	16.00	8.00	1.70	17.00	901.00	289.50	195.00	1392.21

Table 1 continued

Years	Herring	Sprat	Cod	Eelpout	Flounder	Lamprey	Eel	Salmonids	Vendace	Whitefish	Smelt	Bream	Pike	Burbot	Ide	Vimba bream	Sticklebacks	Pikeperch	Perch	Tiddler
1973	21,000.00	5,549.98	0.00	1.40	0.00	76.00	1.00	12.00	79.30	15.20	2,254.00	383.80	16.00	6.00	1.00	17.00	1,351.00	229.80	261.90	830.78
1974	20,800.00	14,324.47	0.00	28.80	0.00	81.00	0.50	10.00	50.50	13.60	2,497.00	453.80	20.00	6.00	1.80	11.00	735.00	323.40	216.00	3,090.00
1975	13,300.00	9,762.47	111.57	3.30	0.00	96.00	6.40	11.00	6.00	6.00	2,426.00	414.00	22.00	8.00	0.60	20.00	2,207.00	239.30	231.00	1,831.96
1976	10,400.00	13,917.14	0.00	6.00	28.00	128.00	5.10	3.00	20.00	4.00	1,942.00	399.00	32.00	16.00	1.40	23.00	209.00	358.50	227.00	4,506.84
1977	13,900.00	15,370.11	0.00	6.00	28.00	61.00	3.50	4.00	6.00	0.60	1,182.00	389.00	29.00	8.00	1.00	15.00	848.00	258.00	207.00	3,615.08
1978	20,600.00	9,093.94	72.19	6.00	28.00	46.00	2.50	6.00	13.00	0.30	1,781.00	320.00	23.00	8.00	0.60	10.00	1,548.00	220.00	173.00	2,919.08
1979	15,700.00	5,665.61	452.85	6.00	28.00	10.00	0.80	6.00	6.00	1.00	8,10.00	278.00	22.00	3.00	1.90	13.00	1,916.00	134.00	183.00	2,027.52
1980	16,300.00	1,191.20	3,416.19	6.00	28.00	15.00	0.20	17.00	3.00	2.10	1,372.00	288.00	15.00	2.10	1.20	3.60	2,292.00	144.00	145.00	1,233.66
1981	16,700.00	2,382.40	859.85	0.00	5.00	28.00	0.00	2.00	3.00	1.00	1,400.00	373.00	20.00	3.60	0.10	1.80	2,756.00	165.00	95.00	903.77
1982	15,100.00	493.91	249.39	0.00	5.00	19.50	0.00	1.00	6.50	16.00	2,176.00	370.00	14.00	3.20	0.30	2.00	1,956.00	173.00	82.00	818.29
1983	16,400.00	0.00	0.00	0.00	5.00	30.00	0.00	8.00	4.60	27.00	2,470.00	353.00	11.00	2.10	0.10	1.70	3,783.00	142.00	83.00	390.99
1984	14,000.00	0.00	0.00	0.00	5.00	34.00	0.00	13.00	3.00	11.00	2,402.00	491.00	28.00	3.20	1.20	2.10	2,943.00	182.00	187.00	1,489.90
1985	14,000.00	0.00	144.39	0.00	5.00	23.00	0.00	22.00	1.00	5.00	2,515.00	413.00	24.00	2.00	2.00	3.10	3,710.00	148.00	191.00	1,038.10
1986	15,000.00	0.00	0.00	0.00	0.00	44.00	0.00	0.00	0.00	8.00	3,122.00	497.00	0.00	4.00	0.00	0.00	3,698.00	215.00	169.00	1,135.72
1987	12,300.00	0.00	0.00	0.00	0.00	41.00	0.00	5.00	7.00	1.00	3,614.00	472.00	20.00	3.00	2.00	4.00	3,271.00	268.00	297.00	1,526.54
1988	12,800.00	0.00	0.00	0.00	0.00	44.00	0.00	8.00	30.00	7.00	2,715.00	539.00	26.00	4.90	0.80	9.00	2,250.00	127.00	265.00	1,954.08
1989	11,228.13	0.00	0.00	0.00	0.00	77.13	0.00	6.13	4.46	0.91	3,495.34	512.00	19.30	1.50	0.00	0.00	2,568.88	309.87	54.10	1,184.65
1990	13,690.55	0.00	0.00	0.00	0.00	64.50	0.00	4.54	4.46	3.62	2,922.51	388.25	14.36	1.50	0.00	0.00	3,410.95	263.40	297.00	561.75
1991	14,689.12	0.00	0.00	0.00	0.00	45.40	0.00	3.46	14.26	0.00	2,644.72	524.79	1.21	1.00	0.00	0.00	2,516.37	277.86	167.84	1,099.16
1992	16,765.49	0.00	0.00	0.00	0.00	22.18	0.00	0.92	0.00	0.00	1,533.11	265.59	7.56	1.00	0.00	0.00	1,772.47	144.61	0.00	720.51
1993	9,920.79	0.00	0.00	0.00	0.00	12.63	0.00	1.78	9.09	0.00	1,364.55	199.46	4.17	1.00	0.00	0.00	779.75	104.32	0.00	598.39
1994	7,613.72	0.00	0.00	0.00	0.00	19.80	0.00	1.38	0.00	0.00	1,111.95	201.59	6.69	1.00	0.00	0.00	612.00	97.10	0.00	464.22
1995	9,766.99	522.97	0.00	0.00	0.00	18.44	0.00	2.17	0.00	0.00	808.64	196.26	2.96	1.00	0.00	0.00	550.25	57.85	0.00	427.58

Sources of catch data are the following: Herring (*Clupea harengus*): Telegin (1944) for 1929–1936, Telegin (1946) for 1937–1945, Telegin (1961) for 1949–1958, Smirnov (1977a) for 1964–1974, Popov (1983) for 1975–1981, Schaschaev et al. (1989) for 1982–1988, Kudersky (1999) for 1946–1948, 1959–1963 and 1989–1995; Cod (*Gadus morhua*): Kudersky (1999); Sprat (*Sprattus sprattus*): Kudersky (1999); eelpout (*Zoarces viviparus*): Shirokov et al. (1975) for 1967–1974, Kudersky (1999) for 1975–1995; flounder (*Pleuronectes flesus*): Kudersky (1999); salmonides [Atlantic salmon (*Salmo salar*) and brown trout (*S. trutta*)]: Telegin (1944) for 1929–1936, Telegin (1946) for 1937–1945; Schaschaev et al. (1989) for 1972–1988, Kudersky (1999) for 1946–1971 and 1989–1995; vendace (*Coregonus albula*): Telegin (1944) for 1929–1935; Bykova (1960) for 1936–1943, Telegin (1946) for 1937–1944, Shirokov et al. (1975) for 1966–1971, Smirnov (1973) for 1955–1964, Smirnov (1977b) for 1965–1972, Schaschaev et al. (1989) for 1972–1988, Kudersky (1999) for 1946–1971 and 1989–1995; lamprey (*Lampetra fluviatilis*): Telegin (1944) for 1929–1934, Tiurin (1949) for 1935 and 1936, Telegin (1946) for 1937–1945, Schaschaev et al. (1989) for 1972–1988, Kudersky (1999) for 1948–1971 and 1989–1995; whitefish (*Coregonus lavaretus*): Telegin (1944) for 1929–1936, Telegin (1946) for 1937–1945, Smirnov (1972) for 1937–1940 and 1949–1971, Smirnov (1977c) for 1972–1974, Schaschaev et al. (1989) for 1972–1988, Kudersky (1999) for 1945–1948 and 1989–1995; vimba bream (*Vimba vimba*): Telegin (1944) for 1929–1939, Schaschaev et al. (1989) for 1972–1988; European eel (*Anguilla Anguilla*): Telegin (1944) for 1929–1936, Telegin (1946) for 1937–1945, Schaschaev et al. (1989) for 1972–1988, Kudersky (1999) for 1946–1971 and 1989–1995; European smelt (*Osmerus eperlanus*): Telegin (1944) for 1929–1936, Telegin 1946 for 1937–1945, Schaschaev et al. (1989) for 1972–1988, Kudersky (1999) for 1946–1971 and 1989–1995; tiddler [juvenile common perch (*Perca fluviatilis*), roach (*Rutilus rutilus*), sichel (*Pelecus cultratus*), ruffe (*Gymnochephalus cernuus*) etc.]: Kudersky (1999); sticklebacks (three–spined stickleback (*Gasterosteus aculeatus*) and nine–spined stickleback (*Pungitius pungitius*): Shirokov et al. (1975) for 1966–1973, Smirnov (1977c) for 1959–1966 and 1972–1973, Schaschaev et al. (1989) for 1972–1988; Kudersky (1999) for 1946–1958 and 1989–1995; bream (*Abramis brama*): Telegin (1944) for 1929–1936, Telegin (1946) for 1937–1945, Smirnov (1973) for 1965–1972, Shirokov et al. (1976) for 1965–1974, Schaschaev et al. (1989) for 1972–1988, Kudersky (1999) for 1946–1964 and 1989–1995; pikeperch (*Sander lucioperca*): Telegin (1944) for 1929–1936, Telegin (1946) for 1937–1945, Shirokov et al. (1976) for 1932–1976, Schaschaev et al. (1989) for 1972–1988, Kudersky (1999) for 1946–1971 and 1989–1995; pike (*Esox lucius*): Telegin (1944) for 1929–1936, Telegin (1946) for 1937–1945, Schaschaev et al. (1989) for 1972–1988; Kudersky (1999) for 1946–1971 and 1989–1995; perch (*Perca fluviatilis*): Telegin (1944) for 1929–1936, Telegin (1946) for 1937–1945, Shirokov et al. (1975) for 1965–1974, Schaschaev et al. (1989) for 1972–1988; ide (*Leuciscus idus*): Telegin (1944) (1929–1939), Schaschaev et al. (1989) for 1972–1988; burbot (*Lota lota*): Telegin (1946) for 1937–1945, Schaschaev et al. (1989) for 1972–1988, Kudersky (1999) for 1946–1971 and 1989–1995

The following data are absent: cod, sprat, flounder, eelpout, vendace for period 1929–1934, ide for 1989–1995. Absence of data were interpreted as absence of catches, assuming that any significant catch would be reflected in statistics

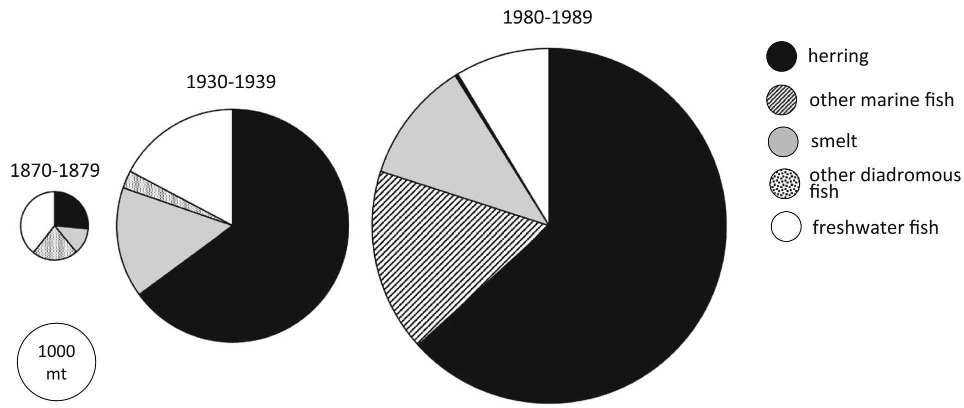

Fig. 3 Annual catch size of different species and species groups during different periods, with circle sizes proportional to landings. Data for 1870–1879 are based on Lajus et al. (2013)

Table 2 Permutation test for significance of effect of environmental variables used in canonical correspondence analysis

Term in model	df	Chi square	F	Number of permutations	P-level
Winter temperature	1	0.0097	2.8126	99	0.08
Summer temperature	1	0.001	0.29	99	0.95
Transparency	1	0.0344	10.0178	99	0.01
Salinity	1	0.029	8.4471	99	0.01
Residual	47	0.1614			

Discussion

The Baltic Sea is an inland sea with a large river inflow and a weak exchange with the ocean, conditions that have redoubled centuries of anthropogenic pressure and considerably transformed the environment (Lotze et al. 2006). Now increasing international efforts seek to improve the situation, and some successes are already evident (HELCOM 2010). However, limited data on Gulf of Finland are an obstacle to the management of ecosystems in this area.

Quantification of environmental variables

Many authors have attributed changes in fish abundance and catches to natural or anthropogenic factors (Koliushev and Podarueva 1969; Ilienkova et al. 1978; Popov 1983; Kudersky et al. 2008), however, these conclusions usually are not supported by statistical analyses. In order to reveal relationships between catch sizes and environmental variables in a more formal way, in this study, we applied multivariate statistical techniques. For that, it was necessary to quantify environmental variables. The most important environmental variables influencing catch variation in the eastern Gulf of Finland were water transparency and salinity (Fig. 5). Temperature did not influence catch composition notably. This might be because during the study period temperature only slightly fluctuated around the mean without clear trends (Fig. 2). In our analysis, we had to use temperature data from a location situated about 200 km to the west from the area of our research, where relevant temperature data were not available. Temperature regime can differ between the more shallow and brackish eastern part of the Gulf and deeper western part, which is closely connected to the Baltic proper. These differences are especially pronounced in warm periods due to coastal upwellings caused by cumulative wind stress (Uiboupin and Laanemets 2009). This, however, probably does not influence notably conclusions of the study because results of statistical analyses are based on correlations and thus depend not on absolute temperature, but on its year-to-year dynamics. Because surface water temperature strongly depends on air temperature which is usually quite uniform on the scale of thousand km, according to typical length of extratropical cyclones (Holton 1979), and there are no topographically-isolated water masses in the gulf (Alenius et al. 1998), dynamics of temperature must be similar in our study area and the western part of Gulf of Finland.

Transparency gradually decreased during second half of the 20th century (Fig. 2). In the Baltic Sea, it showed a positive and very high correlation with chlorophyll a, thus it proved to be a good eutrophication indicator (HELCOM 2009). Detailed analysis of long-term trends in transparency and its relation to loading of phosphorus and nitrogen in Gulf of Finland is provided by Hakanson (2011). While our study did not quantify human-induced factors such as pollution, fishing effort, and habitat degradation that increased over time and thus being statistically inseparable from transparency, they are correlated with serial number of a year. These factors are, however, known to influence

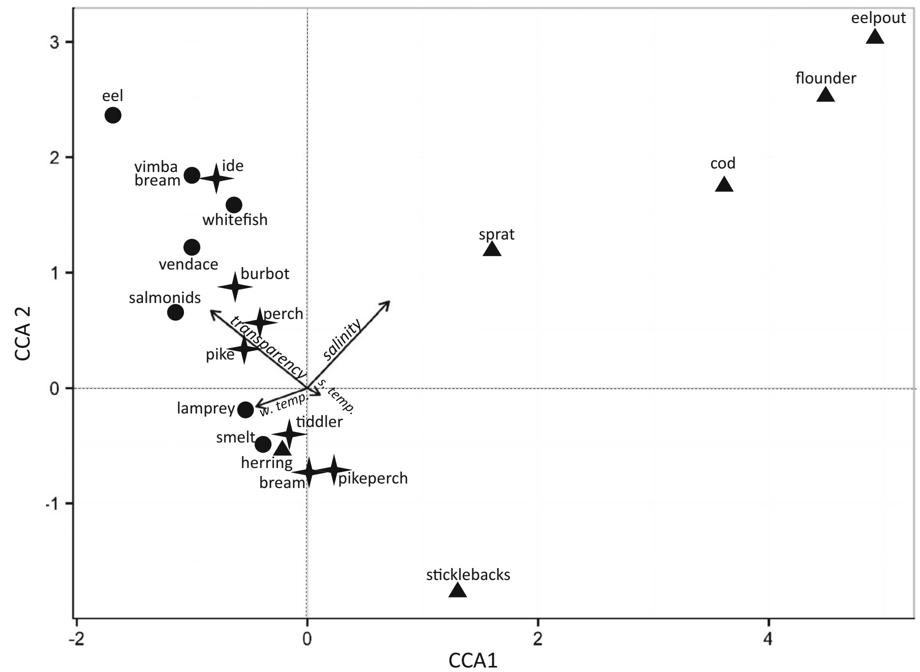

Fig. 4 Position of different species (based on their catches) in coordinates of two *canonical axes*. Freshwater species are designated with *asterisks*, diadromous with circles and marine with *triangles*

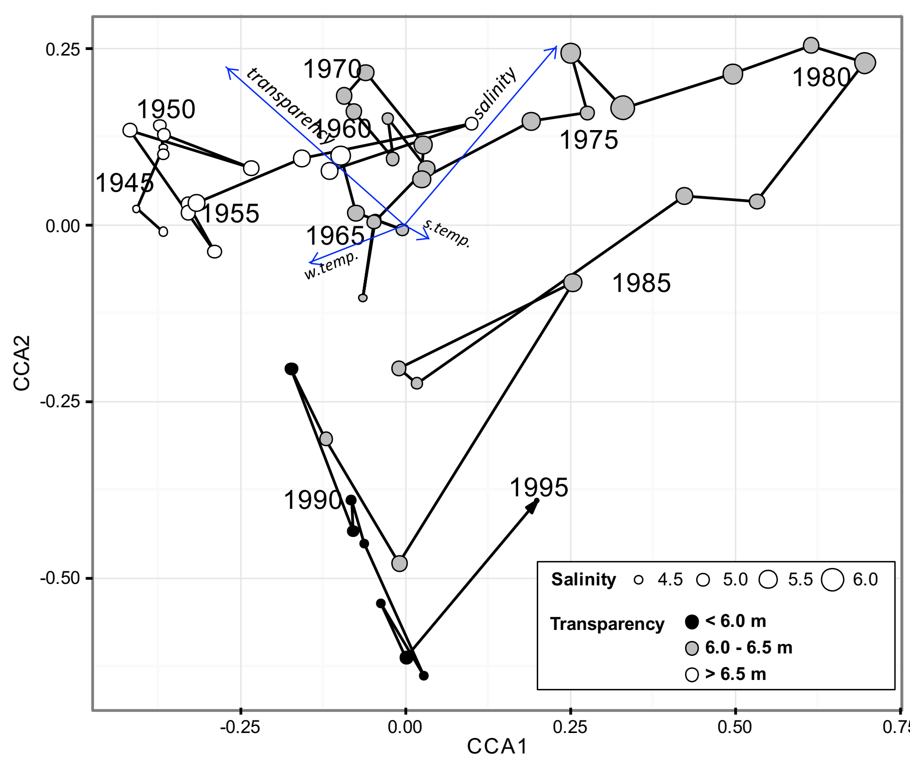

Fig. 5 Trajectory of changes of catch composition during 1944–1995 in two *canonical axes*. Transparency is shown by the intensity of *grey color* and salinity by size of *circles*

fish populations and we, where possible, will take into consideration qualitative data while interpreting the results. Similarly, Lappalainen et al. (2000) who studied spatial heterogeneity of fish communities along the northern coast of the Gulf of Finland, were unable to relate observed differences to eutrophication. The authors concluded that the abundance of fish is determined by fishing pressure rather than by eutrophication.

Cumulative effect of various environmental factors on populations very much depend on their interaction, especially given that in the Gulf of Finland fish often live near tolerance levels, especially in terms of salinity. In

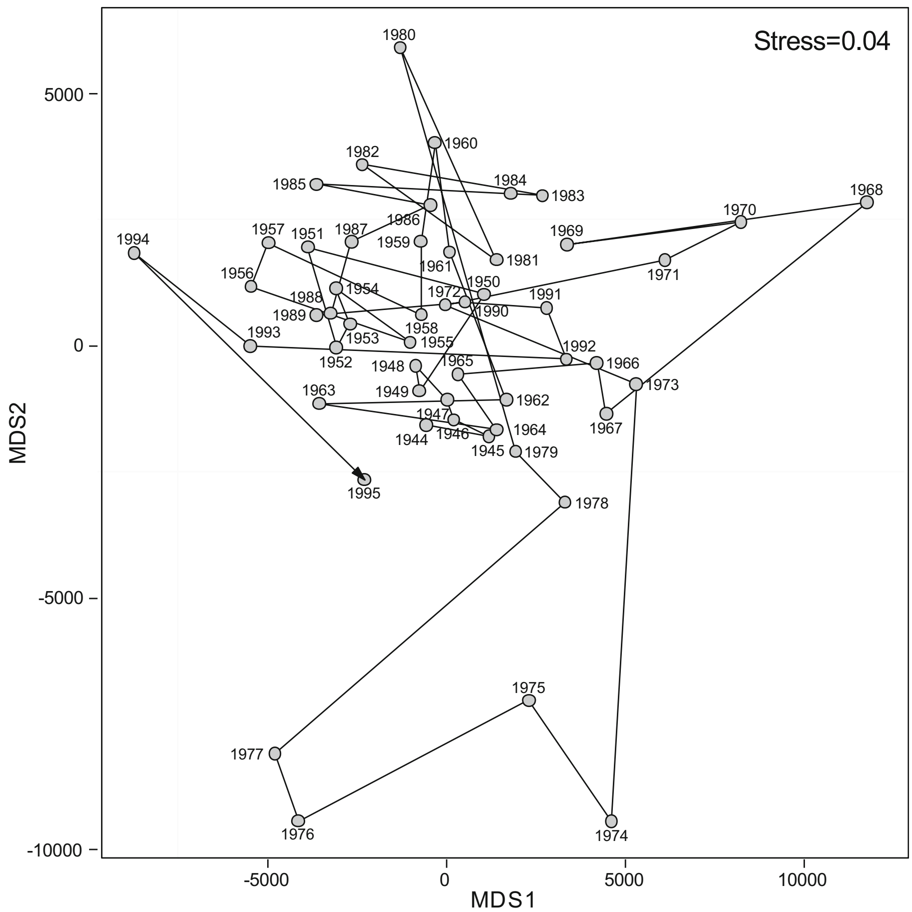

Fig. 6 Multidimensional ordination of years based on Euclidian distances of residuals from CCA model for individual species for period 1944–1995

particular, hazardous substances may cause extra stress on organisms which live close to their low- or high- salinity limits; their effect may be modified also by predicted increase of temperature (Heugens et al. 2001). Moreover, eutrophication depends not only on the input of biogenes, but also on their distribution, which may be strongly modified by salinity. It is known that inflow of saline waters causes stratification, which results in hypoxia in lower layers resulting in increases of sediment phosphorus release. This leads to further eutrophication (HELCOM 2009). At the same time, stratification and anoxia may prevent release of pollutants from sediments (HELCOM 2009). All these effects are highly non-linear and thus are very difficult to capture by statistical analyses.

Catch dynamics of particular species and species groups

Herring (*Clupea harengus*) is the most important commercial fish in the region and comprises 63.8 % of total catch for the period from 1929 to 1995. Herring catches were already higher than any other species in the 1870s (Lajus et al. 2013). Absolute catches grew about 23-fold during the next six decades and reached more than 70-fold by the 1990s. This was a greater return than that of all other fisheries in the region (Fig. 3). One reason for increased catches was higher fishing effort due to improved gear and intensified fishing pressure. Herring were mostly fished with gillnets and winter herring seines before World War II, and with fixed nets during spawning season in the 1950s. Bottom trawls first appeared in 1953, but were replaced by pelagic trawl in the 1960s; now pelagic trawls are the most widely used herring gear (Telegin 1955; Popov 2006a). With changing gear, fishing areas expanded and moved from coastal regions to open parts of the Gulf.

Herring, being a marine species, avoid salinity below 2 PSU in the Gulf of Finland (Shirokov et al. 1982). Decrease in salinity reduced herring abundance due to unfavorable conditions for the early stages of ontogenesis, and to a change in the composition of the plankton species they consume (Antonov 2007). At the same time, herring, differently from other marine fishes, do not show high loading on Salinity axis (Fig. 4). It is probably because herring is a rather euryhaline species and may tolerate brackish waters (Svetovidov 1952). Moreover, due to high commercial importance and regulation, herring catches to a large extent depend on social factors determining fishing effort, which was not quantified in this study and may confound the effect of salinity.

Other marine species—sprat (*Sprattus sprattus*), stickleback, cod (*Gadus morhua*), flounder, eelpout (*Zoarces viviparus*)—comprise 15.3 % of total catch (among them, 9.6 % sprat and 5.2 % stickleback). Their catch sizes were highest during periods of higher salinity in the 1970s and early 1980s, resulting in positive loadings of marine species (except stickleback) on Salinity axis (Fig. 4). Increases of salinity in this period were caused by a major inflow of saline waters from the North Sea to Baltic (Alenius et al. 1998). Except for herring, marine species were not listed in commercial catches in earlier periods (Lajus et al. 2013). Only flounder were reported in the Neva River in the early 20th century (Shimansky 1921). This is probably because in early periods, fishing was located in coastal areas, whereas marine fish preferred more open sea. Moreover, it is known that sprat catches were not always separated from herring before WW II (Telegin 1944).

Sticklebacks, represented in catches mostly by the three-spined stickleback (Prokopenko 1983), differed from other marine species in their position in Fig. 4. They are much more euryhaline, thus less dependent on salinity. Stickleback are very tolerant to pollution which makes them a popular bioindicator (Katsiadaki 2007; Sturm et al. 2000). Comparatively high tolerance to pollution may explain their positive association with the Transparency axis (Fig. 4). Sticklebacks were mostly fed to livestock, although during the Leningrad Siege (1941–1944), they played an important role as human food and as a source of oil for medical purposes. In the town of Kronshtadt, on Kotlin Island, this fish was memorized with a small monument on an embankment. With the beginning of the economic crisis in the early 1990s, the market for stickleback crashed, resulting in a drop in catches, i.e. catches of this species, like herring, were regulated by fishing effort rather than natural variables.

Diadromous species comprised 11.0 % of total catch, and 92.7 % of this amount is smelt (*Osmerus eperlanus*). Pattern of smelt catch dynamics is similar with that of herring and do not show dependence on environmental variables, in particular, smelt catches are not associated with the Transparency axis as most of other migrating fish (Fig. 4). Absolute smelt catches from the 1870s to the 1980s increased almost 30-fold, but its proportion of total catch was remarkably constant over more than a century, ranging from 10 to 15 %. Until the 1950s, fishing methods for smelt did not change much—this species was mostly fished with special traps and beach seines in the downstream sector of the Neva River, and catch increased through intensified fishing pressure. Gillnet fishing in the Gulf at that time did not provide higher catches (Popov 2006b). However, the introduction of fixed nets and larger traps in coastal areas resulted in notable increases of catches (Table 1). A maximal number of smelt fixed nets was used in 1974–1975 (Popov et al. 1987). In the 1980s, only about 10 % of the smelt catch came from the Neva River, whereas 20–30 years before this figure was 31 % (Popov 2006b). The evident smelt decline took place in the early 1990s and, in addition to overfishing, was caused by degraded spawning grounds and deteriorated feeding conditions (Sendek and Korolev 2010). Higher abundance and lower commercial value of smelt in comparison with most of other migratory species is a likely explanation of their decline later than other migratory species.

High positive loadings of other diadromous species (except lamprey) on CCA2 (Fig. 4) reflect a decline in their catches due anthropogenic factors, in particular fishing. Salmonides, whitefish (*Coregonus lavaretus*), vimba bream and eel played only a minor role in the 20th century. Catches of vendace (*Coregonus albula*) were quite significant in some years but usually were not large. With the exception of vendace and lamprey, which are still fished in Neva River, other diadromous species continued declines already evident in the early 20th century (Lajus et al. 2013), and by 1995 had completely lost their significance. Trout and whitefish were even moved to regional redlists.

Unlike other diadromous species with distinct local populations, eel form only one population in Europe (Palm et al. 2009; Als et al. 2011). The dynamics of eel catches in the area under study is generally similar to global trends for this species, according to ICES statistics (https://www.ices.dk). Eel catches increased in the Eastern Gulf of Finland and globally during the 1930s, but a decline became evident everywhere after the early 1970s. Now this species is considered critically endangered (http://www.iucnredlist.org/details/full/60344/0). Despite the overall similarity between eel catch trends in the eastern Gulf of Finland and other regions, patterns are somewhat different. In particular, we observed a several-fold decrease in catches in the eastern part of Gulf of Finland after World War II (Table 1), whereas in other areas no such drastic decline took place. This decline was caused either by a decrease in fishing effort or changes in fisheries statistics. Similar patterns were observed for ide (*Leuciscus idus*) perch and vimba bream in our study (Table 1).

Catches of lamprey do not show clear long-term trends and have low loadings on canonical axes (Fig. 4). Neither were trends observed for lamprey in the 19th century (Lajus et al. 2013). We have no statistical reason to associate lamprey catch dynamics with known anthropogenic factors, although some authors assume an association (Kudersky 1999). Abakoumov (1957) links lamprey spawning migration with weather conditions (wind, water level, difference between river and sea temperature). These variables are difficult to directly relate to those we are dealing with, but an association is possible. Vendace show very high variability of catches, it was highly abundant only in the 1870s and in the late 1950s; at other times they did not have large commercial significance, but in general this species showed patterns similar with other diadromous species.

Freshwater fish comprise 9.9 % of total catches for the period of our study. Their catches grew about seven-fold from the 1870s to the 1980s, i.e., less than marine or diadromous fish. Therefore, their contribution to total catches was reduced 4 to 5-fold over the century (Fig. 3). Among freshwater fish, the most important were bream (*Abramis brama*) and pikeperch (*Sander lucioperca*) with ratios of 1.2 and 0.7 % of total catch, respectively. Their catch dynamics show moderate positive association with the Transparency axis (Fig. 4). Hence, we assume that their catch variation is explained primarily by anthropogenic factors, showing some increasing trend during the study period. In the 1870s, pikeperch and bream supported the second and third largest fisheries, respectively, constituting 16.9 and 13.8 % of total catches. Contribution of these species dropped about 10 to 20-fold during the century (Table 1). Interestingly, from the 1870s to the 1930s, absolute catch of pikeperch and bream decreased about a quarter, then catches increased during the next half-century. Expanded fishing area and improved fishing gear caused the increase in pikeperch (Ilienkova 1977), and this was also probably true for bream, reflecting general trends in regional fisheries in this period. It is not clear what caused the catch decrease in the late 19th century and early 20th century. Most likely, natural factors played the greatest role because catches of other species grew during this period, and overfishing is improbable because later catches and fishing pressure were much higher than in that period.

Other freshwater fishes had lower commercial value and supported marginal commercial fisheries. Tiddler, which pooled several small species, made up 69.2 % of freshwater fish catch. A by-product of coastal fisheries for smelt, bream, pikeperch—tiddler was mainly used for animal feed. Other freshwater fish like burbot, ide, pike (*Esox Lucius*) had quite low abundance (0.1 % of total catch or less for each species) and were usually harvested with other species. The same is true for perch which, although comparatively abundant (0.9 %), is not considered valuable in Russia. These species were ordinated closely to zero CCA values (Fig. 4) thus their catch is not clearly regulated by the factors in consideration. This may be because a majority of freshwater species were not directly targeted and catches were quite low (Table 1); thus random and not accounted for factors may play a larger role in determining catch size.

This suggestion is likely confirmed by analysis of residuals from the CCA model (Fig. 6). Departure of residuals in mid-1970 s from trend predicted based on controlled variables shows that there are other factors causing the increase of catches in this period. Although freshwater species do not comprise a significant proportion of total catch, number of their species is rather large, thus they may notably affect the overall picture. According to Ilienkova et al. (1978), an increase of abundance of several freshwater species such as bream, pikeperch, perch, roach, ruffe, and also smelt in mid-1970 s might be due to an increase of water discharge of the Neva River and negative temperature anomalies in the spawning period. Authors suggest that such effects are mostly indirect and explained by availability of forage organisms. They also note that fluctuations of abundance are associated with 11-year cycles of sun activity, which we, however, did not observe in our data. Increase of fishing effort in mid-1970 reported by Popov et al. (1987) for smelt (see above) was likely the case also for other species, for which respective data are not available. This might result in larger catches and thus in departure from the CCA model.

General dynamics of catch composition

Statistical treatment identified several periods in the general dynamics of catch composition: (a) 1944 to the late 1970s, (b) the 1980s, and (c) the first half of the 1990s. In the first period, regional fisheries quickly developed until the mid-1960s, reflecting postwar recovery and eventual rapid fisheries development characterized by expanding fishing area and modernization of gear. By the late 1970s, catches of many species were high, and marine species abundance increased due to high salinity. Great market demand resulted in high collateral catches of species with low commercial value such as tiddler and sticklebacks. Notably, the salinity increase in the early 1960s did not have as strong an effect on catch composition as the peak in late 1970s-early 1980s. Then, continuing intensive fishing of diadromous species resulted in critical declines in their catches (except for lamprey). Eel, vimba bream and whitefish eventually disappeared from fishery statistics. During the second period, we observe a return to a situation similar to the mid-1950s, probably caused by a decrease of salinity. Drastic drop of catches during the third period were driven by:

- The economic crisis that drastically reduced catch of abundant, but cheap species such as tiddler, stickleback, perch;
- The decrease in officially reported catches, particularly for marginal fisheries. Diadromous and freshwater species practically disappeared from fishery statistics

(except lamprey and smelt). This may result from considerable misreporting due to the crash of the Soviet fisheries statistics system (Kudersky et al. 2008), or from drastic population declines caused by overfishing and other human-induced factors;

- The decrease of salinity that adversely affected marine species. Economic changes coincided with regime shifts in the Baltic Sea caused by climate change, in particular, change in atmospheric circulation that took place in the late 1980s (Karaseva et al. 2007).

Conclusions

Earlier interpretations of fish population dynamics in the eastern Gulf of Finland did not employ quantitative data. In our study, we generated a detailed time series of catch for 20 species and species groups and used four environmental variables—summer and winter temperatures, salinity and water transparency. Also, in our interpretations, we used qualitative information on fishing effort and other anthropogenic factors. Overall, trends in fisheries and changes in fish populations that we observed in data from the 15 to 20th centuries (Lajus et al. 2013) continued through the 20th century as well. Fishing areas, fishing gear and target species changed over time in relation to one another, reflecting technological development and commercial demands for fishery products. We found no correlation of fish catches with temperature, which, however, does not deny importance of this factor in general, rather it is explained by absence of pronounced temperature trends in the area during the study period.

Until the 18–19th centuries, fisheries took place mostly in rivers where weirs and set nets targeted sturgeon, salmon and, whitefish. By the end of the 19th century, herring and smelt were the main targets of fixed nets in coastal areas. A century later, the main commercial species, herring, was harvested with pelagic trawls operating offshore in the Gulf. This evolution in fisheries, along with other anthropogenic activities, caused severe declines in diadromous species. Spawning migrations that make them easy to catch and their high market value make diadromous fish the most vulnerable in comparison with other groups. Statistical analysis showed that catches of most diadromous species decreased with increasing transparency, rather reflecting their correlation with fishing pressure and other anthropogenic factors which are inseparable from transparency as all these variables correlate with serial year number. Marine and freshwater fish suffered from anthropogenic pressure, but to a lesser extent probably because of a wider distribution and dispersal, and more capital-intensive fishing methods. Catches of marine species, except herring, considerably increased in the 1970–1980s when salinity was comparatively high.

Acknowledgments This research was supported by a grant from the Russian Foundation for Basic Research 10-04-91005-ANF_a and by a research grant from St. Petersburg State University 1.38.253.2014 for D. L. We thank Gertrud Haidvogl, Didier Pont, Richard Hoffman and Mathias Jungvirth for valuable comments on the manuscript. We are also grateful to Karen Alexander for English editing.

References

Abakoumov VA (1957) Reproductive biology and orientation during spawning migrations of the Baltic lamprey. In: Sbornik rabot studencheskogo nauchnogo obschestva (sektsia ikhtiologii). Moskovskii technicheskii institut rybnoi promyshlennosti i khoziaistva imeni Mikoiana, Moscow, pp 48–59 (in Russian)

Alenius P, Myrberg K, Nekrasov A (1998) The physical oceanography of the Gulf of Finland: a review. Bor Environ Res 3:97–125

Als TD, Hansen MM, Maes GE, Castonguay M, Riemann L, Aarestrup K, Munk P, Sparholt H, Hanel R, Bernatchez L (2011) All roads lead to home: Panmixia of European eel in the Sargasso sea. Mol Ecol 20(7):1333–1346

Antonov AE (2007) Prirodnaya tsikloenergetika. Gidrometeorologicheskoe i rybopromyslovoe prognozirovanie. Gidrometeoizdat, St. Petersburg

Bykova VK (1960) Some data on biology of the Gulf of Finland vendace. Nauchno-tekhnicheskii biulleten' GosNIORKh 10:31–32 (in Russian)

Cabral HN, Costa MJ, Salgado JP (2001) Does the Tagus estuary fish community reflect environmental changes? Clim Res 18:119–126. doi:10.3354/cr018119

Clarke KR, Gorley RN (2006) PRIMER v6: User Manual/Tutorial. PRIMER-E, Plymouth

Davidan IN, Savchuk OP (eds) (1997) Ekosistemnye modeli. Otsenka sovremennogo sostoiania Finskogo zaliva. Problemy issledovania i matematicheskogo modelirovania ekosistemy Baltiiskogo moria. Mezdunarodniy proekt "Baltika" 5. Gidrometeoizdat, St. Petersburg

Eero M, Köster FW, Plikshs M, Thurow F (2007) Eastern Baltic cod (Gadus morhua callarias) stock dynamics: extending the analytical assessment back to the mid-1940s. ICES J Mar Sci 64:1257–1271

Eero M, Köster FW, MacKenzie BR (2008) Reconstructing historical stock development of the eastern Baltic cod (Gadus morhua) before the beginning of intensive exploitation. Can J Fish Aquat Sci 65:2728–2741

Haedrich RL (1983) Estuarine fishes. In: Ketchum BH (ed) Ecosystems of the world. Elsevier Scientific Publishing Company, Oxford, Estuaries and enclosed seas, pp 183–207

Haidvogl G, Lajus D, Pont D, Schmid M, Jungwirth M, Lajus J (2014) Historical sources typology and the reconstruction of long-term historical changes of riverine fish: a case study of the Austrian Danube and northern Russian rivers. Ecol Freshw Fish 23(4):498–515

Hakanson L (2011) Reconstruction of the eutrophication in the Gulf of Finland using a dynamic process-based mass-balance model. In: Friedman AG (ed) Lagoons: biology, management and environmental impact. Nova Science Publishers Inc, Hauppauge, pp 301–332

HELCOM (2009) Eutrophication in the Baltic Sea—an integrated thematic assessment of the effects of nutrient enrichment and eutrophication in the Baltic Sea region. Balt Sea Environ, Proc 115B

HELCOM (2010) Ecosystem Health of the Baltic Sea 2003–2007: HELCOM Initial Holistic Assessment. Balt Sea Environ. Proc, No 122

Heugens EH, Hendriks AJ, Dekker T, van Straalen NM, Admiraal W (2001) A review of the effects of multiple stressors on aquatic organisms and analysis of uncertainty factors for use in risk assessment. Crit Rev Toxicol 31(3):247–284

Holton J (1979) An introduction to dynamic meteorology, 2nd edn. Academic Press, New York

Ilienkova SA (1977) Stock status of pikeperch of the eastern Gulf of Finland. In: Smirnov AN (ed) Biologicheskie i promyslovye resursy Finskogo zaliva (Izvestia GosNIORKh 123). GosNIORKh, Leningrad, pp 97–105 (in Russian)

Ilienkova SA, Popov AN, Turanova AN, Shirokov LV (1978) Fluctuations of abundance of commercial fish of the eastern Gulf of Finland. In: Smirnov AN (ed) Rybokhoziaistvennoe issledovanie vostochnoi chasti Finskogo zaliva (Izvestia GosNIORKh 129), Leningrad, pp 3–9 (in Russian)

Karaseva EM, Nazarov NA, Zezera AS, Feldman VN (2007) Baltic Sea: long-term dynamics of some components of the brakish-water ecosystem in epoche of regime shifts. In: Bolshie morskie ekosistemy Rossii v epokhu globalnykh izmenenii (klimat, resursy, upravlenie). Materialy mezhdunarodnoi nauchnoi konferentsii (Rostov-na-Donu, oktiabr 2007g). IuNTs RAN, Rostov-na-Donu, pp 193–197 (in Russian)

Katsiadaki I (2007) The use of stickleback as a sentinel and model species in ecotoxicology. In: Oslund-Nilsson S, Mayer I, Huntingford FA (eds) Biology of the three-spined stickleback. CRC Press Taylor & Francis Group, Boca Raton, pp 319–351

Khlebovich VV (1969) Aspects of animal evolution related to critical salinity and intertidal zone. Mar Biol 2:338–345

Koliushev AI, Podarueva ZS (1969) [Status of herring resources of the eastern Gulf of Finland and their utilization by the fishery]. In: Bauer ON (ed) Voprosy rybnogo khoziaistva na vnutrennikh vodoemakh SSSR (Izvestia GosNIORKh 69), Leningrad, pp. 343–349 (in Russian)

Kudersky LA (1996) Status of fish resources of Ladoga Lake, the Neva River and the eastern part of Gulf of Finland. In: Alimov AF, Frolov AK (eds) Ekologicheskoe sostoianie vodoemov i vodotokov v basseine reki Nevy. Sankt-Peterburgskii nauchnyi tsentr RAN, St. Petersburg, pp 131–154 (in Russian)

Kudersky LA (1999) The composition and the long-term changes of the fish population in the Neva Bay and the eastern Gulf of Finland. In: Rumiantsev VA, Drabkova VG (eds) Finskii zaliv v usloviakh antropogennogo vosdeistvia. Rossiaskaya academia nauk Institut ozerovedenia, SBMF, St. Petersburg, pp 257–303 (in Russian)

Kudersky LA, Shurukhin AS, Popov AN, Bogdanov DV, Yakovlev AS (2008) Fishes of the Neva River estuary. In: Alimov AF, Golubkov SM (eds) Ekosystema es tuariia reki Nevy: biologicheskoe raznoobrazie i ekologicheskie problemy. Tovarischestvo nauchnykh izdanii KMK, Moscow, pp 223–240 (in Russian)

Lajus J, Kraikovski A, Lajus D (2013) Coastal fisheries in the Eastern Baltic Sea (Gulf of Finland) and its basin from the 15 to the early 20th centuries. PLoS One 8(10):e77059. doi:10.1371/journal.pone.0077059

Lappalainen A, Shurukhin A, Alekseev G, Rinne J (2000) Coastal-Fish Communities along the Northern Coast of the Gulf of Finland, Baltic Sea: responses to Salinity and Eutrophication. Internat. Rev. Hydrobiol. 85(5–6):687–696

Legendre P, Legendre L (2012) Numerical ecology. Elsevier, Amsterdam

Lotze HK, Lenihan HS, Bourque BJ, Bradbury RH, Cooke RG, Kay MC, Kidwell SM, Kirby MX, Peterson CH, Jackson JBC (2006) Depletion, Degradation, and Recovery Potential of Estuaries and Coastal Seas. Science 312(5781):1806–1809

MacKenzie B, Alheit J, Conley DJ et al (2002) Ecological hypotheses for a historical reconstruction of upper trophic level biomass in the Baltic Sea and Skagerrak. Can J Aquat Sci 59:173–190

MacKenzie B, Ojaveer H, Eero M (2011) Historical ecology provides new insights for ecosystem management: eastern Baltic cod case study. Marine Policy 35(2):266–270

Oksanen J, Blanchet FG, Kindt R, Legendre P, Minchin PR, O'Hara RB, Simpson GL, Solymos P, Stevens MHH, Wagner H (2013) Vegan: Community Ecology Package. http://cran.r-project.org/web/packages/vegan/

Palm S, Dannewitz J, Prestegaard T, Wickstrom H (2009) Panmixia in European eel revisited: no genetic difference between maturing adults from southern and northern Europe. Heredity 103:82–89

Popov AN (1983) Population dynamics of the Baltic herring *Clupea harengus membras* L. of the eastern Gulf of Finland and its drivers. In: Fedorova GV (ed) Biologia I promysel ryb v raznotipnykh vodoemakh severo-zapada (Sbornik nauchnykh trudov GosNIORKh 207). Leningrad, Promrybvod, pp 73–83 (in Russian)

Popov AN (2006a) Long-term dynamics of the Batic herring stocks (*Clupea harengus membras* L.) of the eastern Gulf of Finland and its drivers. In: Lavrentieva GM, Susloparova ON (eds) Ekologicheskie aspekty vozdeistvia gidrostroitelstva na biotu vostochnoi chasti Finskogo zaliva (Sbornik nauchnykh trudov FGNU GosNIORKh 331, 2). Saint Petereburg, GosNIORKh, pp 119–139 (in Russian)

Popov AN (2006b) Biology and reproduction of smelt (*Osmerus eperlanus* L.) of the eastern gulf of Finland. In: Lavrentieva GM, Susloparova ON (eds) Ekologicheskie aspekty vozdeistvia gidrostroitelstva na biotu vostochnoi chasti Finskogo zaliva (Sbornik nauchnykh trudov FGNU GosNIORKh 331, 2). Saint Petersburg, GosNIORKh, pp 92–118 (in Russian)

Popov AN, Ruzhin SV, Simkun FV, Prokopenko IA (1982) Stock assessment of commercial fishes of the eastern Gulf of Finland for 1983 and their rational use. GosNIORKh unpublished report, Leningrad (in Russian)

Popov AN, Ruzhin SV, Shirokov LV, Volkov KV, Miasnikova NV, Drozzhina KS (1987) Stock assessment and rational use of fish resources of the eastern Gulf of Finland. GosNIORKh unpublished report, Leningrad (in Russian)

Potter IC, Bird DJ, Claridge PN, Clarke KR, Hyndes GA, Newton LC (2001) Fish fauna of the Severn estuary. Are there long-term changes in abundance and species composition and are the recruitment patterns of the main marine species correlated? J Exp Mar Biol Ecol 258:15–37

Prokopenko IA (1983) Characteristics of the fishery and some biological characteristics of three spine stickleback (Gasterosteus aculeatus L.) from the eastern Gulf of Finland. In: Fedorova GV (ed) Biologia I promysel ryb v raznotipnykh vodoemakh Severo-Zapada (Sbornik nauchnykh trudov GosNIORKh 207). Leningrad, GosNIORKh, pp 84–95 (in Russian)

R Core Team (2014) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. http://www.R-project.org

Schaschaev YuA, Popov AN, Ruzhin SV (1989) Assessment of the status and management of commercial fish stocks in the eastern Gulf of Finland. GosNIORKh unpublished report, Leningrad (in Russian)

Sendek DS, Korolev AE (2010) The reasons for decline of the Neva River smelt population. Voprosy rybolovstva 11(3):514–533 (in Russian)

Shan X, Sun P, Jin X, Li X, Dai F (2013) Long-Term Changes in Fish Assemblage Structure in the Yellow River Estuary Ecosystem,

China. Marine Coastal Fisheries Dynamics Manag Eco Sci 5(1):65–78. doi:10.1080/19425120.2013.768571
Shimansky A (1921) Neva. Rybak Severa 1:9–11 (in Russian)
Shirokov LV, Galkin NP, Il'enkova SA et al (1975) The distribution and abundance of the main commercial fish in the eastern Gulf of Finland (1974) (interim report). GosNIORKh unpublished report, Leningrad (in Russian)
Shirokov LV, Galkin NP, Il'enkova SA et al (1976) The distribution and abundance of the main commercial fish in the eastern Gulf of Finland (report for 1975). GosNIORKh unpublished report, Leningrad (in Russian)
Shirokov LV, Ilenkova SA, Popov AN (1982) Spatial distribution of fish in the eastern Gulf of Finland. In: Shirokov LV (ed) Biologia vodoemov sistemy Ladozhskoe ozero – Nevskaya guba (Sbornik nauchnykh trudov GosNIORKh 192). GosNIORKh, Leningrad, pp 57–59 (in Russian)
Smirnov AN (1972) Growth of whitefish in the gulf of Finland. In: Smirnov AN (ed) Promyslovye resursy Finskogo zaliva (Izvestia GosNIORKh 82). GosNIORKh, Leningrad, pp 3–10 (in Russian)
Smirnov AN (1973) Distribution and abundance of commercial fish in the eastern Gulf of Finland (1969–1973). GosNIORKh unpublished report, Leningrad (in Russian)
Smirnov AN (1977a) Distribution and stock status of the Baltic herring in the eastern gulf of Finland. In: Smirnov AN (ed) Biologicheskie i promyslovye resursy Finskogo zaliva (Izvestia GosNIORKh 123). GosNIORKh, Leningrad, pp 9–27 (in Russian)
Smirnov AN (1977b) Vendace of the gulf of Finland - *Coregonus albula* (L.). In: Smirnov AN (ed) Biologicheskie i promyslovye resursy Finskogo zaliva (Izvestia GosNIORKh 123). Leningrad, GosNIORKh, pp 71–80 (in Russian)
Smirnov AN (1977c) Distribution of some fishes in the eastern gulf of Finland. In: Smirnov AN (ed) Biologicheskie i promyslovye resursy Finskogo zaliva (Izvestia GosNIORKh 123). GosNIORKh, Leningrad, pp 138–157 (in Russian)
Sturm A, Wogram J, Segner H, Liess M (2000) Different sensitivity to organophosphates of acetylcholinesterase and butyrylcholinesterase from three-spined stickleback (Gasterosteus aculeatus): application in biomonitoring. Environ Toxicol Chem 19: 1607–1615
Svetovidov AN (1952) Sel'devye (Clupeidae). Fauna SSSR. Ryby 2(1). Zoologicheskii Institut Akademiya Nauk SSSR.Moscow and Leningrad Clupeidae (in Russian). English translation: Svetovidov AN (1963) Clupeidae (Sel′devye) Translated from Russian by Z. Krauthamer and E. Roifer. Published for the National Science Foundation, Washington, by the Israel Program for Scientific Translations, Jerusalem, [available from the Office of Technical Services, U.S. Dept. of Commerce, Washington]
Telegin KF (1944) Fishing in Soviet waters of the Baltic Sea. GosNIORKh unpublished report, Leningrad (in Russian)
Telegin KF (1946) [The post-war status of fish stocks and fisheries in the Gulf of Finland] GosNIORKh unpublished report. Leningrad (in Russian)
Telegin KF (1955) Puti razvitia tralovogo lova salaki v vostochnoi chasti Finskogo zaliva. Izdatelstvo Lenrybaksoiuza, Leningrad (in Russian)
Telegin KF (1961) The development of the Baltic herring fishery in the eastern Gulf of Finland. Nauchno-tekhnichesky biulleten' GosNIORKh 13–14:83–87 (in Russian)
ter Braak CJF (1986) Canonical correspondence analysis: a new eigenvector technique for multivariate direct gradient analysis. Ecology 67(5):1167–1179
Tiurin PV (1949) Fishing for lamprey in the rivers of the eastern part of the Gulf of Finland and ways of their improving. In: Izvestia Vsesoiuznogo nauchno-issledovatelskogo institute ozernogo I rechnogo rybnogo khoziaistva VNIORKH 29. Ministerstvo rybnoi promyshlennosti SSSR. Leningrad, pp 52–74 (in Russian)
Uiboupin R, Laanemets J (2009) Upwelling characteristics derived from satellite sea surface temperature data in the Gulf of Finland, Baltic Sea. Boreal Environ Res 14:297–304