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Reproduction range of garfish, *Belone belone* (L.), in the northern Baltic Sea

Lari Veneranta & Lauri Urho

Veneranta, L., Natural resources Institute Finland, Wolffintie 35, FI-65200 Vaasa, corresponding author lari.veneranta@luke.fi
Urho, L., Natural Resources Institute Finland, P.O. Box 2, FI-00791 Helsinki. lauri.urho@luke.fi

The garfish (*Belone belone* (L.)) annually migrates from the North Sea to the Baltic Proper. Before this study, the known reproduction areas were located in the southern Baltic Sea up to the Islands of Gotland, Saaremaa and Hiiumaa. However, the larvae collected with a beach seine in 2005 and further observations of 0+ larvae and juveniles after that indicated successful reproduction in the northern Gulf of Finland and the southern Gulf of Bothnia. These catches of 0+ garfish and several other observations of garfish larvae and juveniles during recent decades demonstrate that today the species is annually also reproducing in the northern Baltic Sea. The salinity limit for garfish reproduction is not precisely known; however, the lowest reported value 5-6 ‰ fits well with our observations. We recorded garfish larvae along shallow sandy shores where the temperature is higher than in adjacent open water areas. We suggest that the longterm increase of surface water temperatures in the Baltic Sea have enabled the reported expansion of garfish reproduction range.

Introduction

The distribution of garfish (*Belone belone* (L.)) includes the eastern Atlantic from Iceland and Norway to northern Africa, the Mediterranean, the Black Sea and the southern Baltic Sea (Ehrenbaum 1904, Demel 1948, Colette and Parin 1970, Fishbase 2019). The garfish annually undergoes spawning migrations into the southern Baltic Sea in April to May (Dorman 1991, Ojaveer & Järv 2003). Literature on garfish is scarce, but the migrations, population composition and fecundity of garfish have been described by Demel (1937), Kompowski (1965) and Draganik & Kuczynski (1983) on the Polish coast and by Dorman (1991) in Swedish waters. The garfish is commercially exploited in the Baltic Proper, where the annual catches are a few hundred tonnes (Eurostat 2020). In the northern part of its distribution range, in Estonia, the annual catches have varied considerably, varying between tens of tons to over a hundred tons annually (Eurostat 2020). Ojaveer & Järv (2003) connected the catch peaks on warm summers that produce strong year-classes.

Von Westernhagen (1974) and Dorman (1991) suggested that garfish in the Baltic Sea constitutes a separate stock with an obvious tolerance to low salinities and cooler water temperatures. Recent changes in global temperatures and especially the increasing trend in the sea surface temperature of the Baltic Sea (Siegel et al. 2006) might be an advantage for garfish by extending the areas suitable for reproduction. The known reproduction range covers the southern Baltic Sea up to northeast Gotland Island and the Väinameri Sea between Muhu, Saarenmaa and Hiiumaa Islands in the east (Otterlind 1985, Dorman 1991, Ojaveer & Järv, 2003) (Fig. 1). The only more northern observation of garfish larvae (66–70 mm long) was made off Helsinki in the northern Gulf of Finland (Segerstråhle 1944). Recently, Numers et al. (2019) reported observations of juvenile garfish in the Northern Baltic, Archipelago Sea. The salinity level (5–6 ‰) in this area is similar to the area of Reda on the coast of Poland, where Demel (1937) observed garfish reproduction. This indicates that garfish might also be able to reproduce in the northern Baltic Sea in favourable conditions, such as sufficient temperatures for reproduction.

Garfish from the southern Baltic Sea exploring northern areas were already reported in the early books on the Finnish fish fauna (Malmgren 1863, Reuter 1893). According to the authors, some garfish individuals were occasionally caught with herring seines on the SW coast of Finland, up to half way into the Gulf of Finland and the Gulf of Bothnia, but no sign of reproduction was observed. Later, during the next century, observations of ripe garfish were also reported in Finnish waters. In recent decades, such catch reports have been annual. The northernmost observations of garfish adults have been in the Bothnian Bay at the latitude of 65 degrees north (Anon. 2019, Fig. 1).

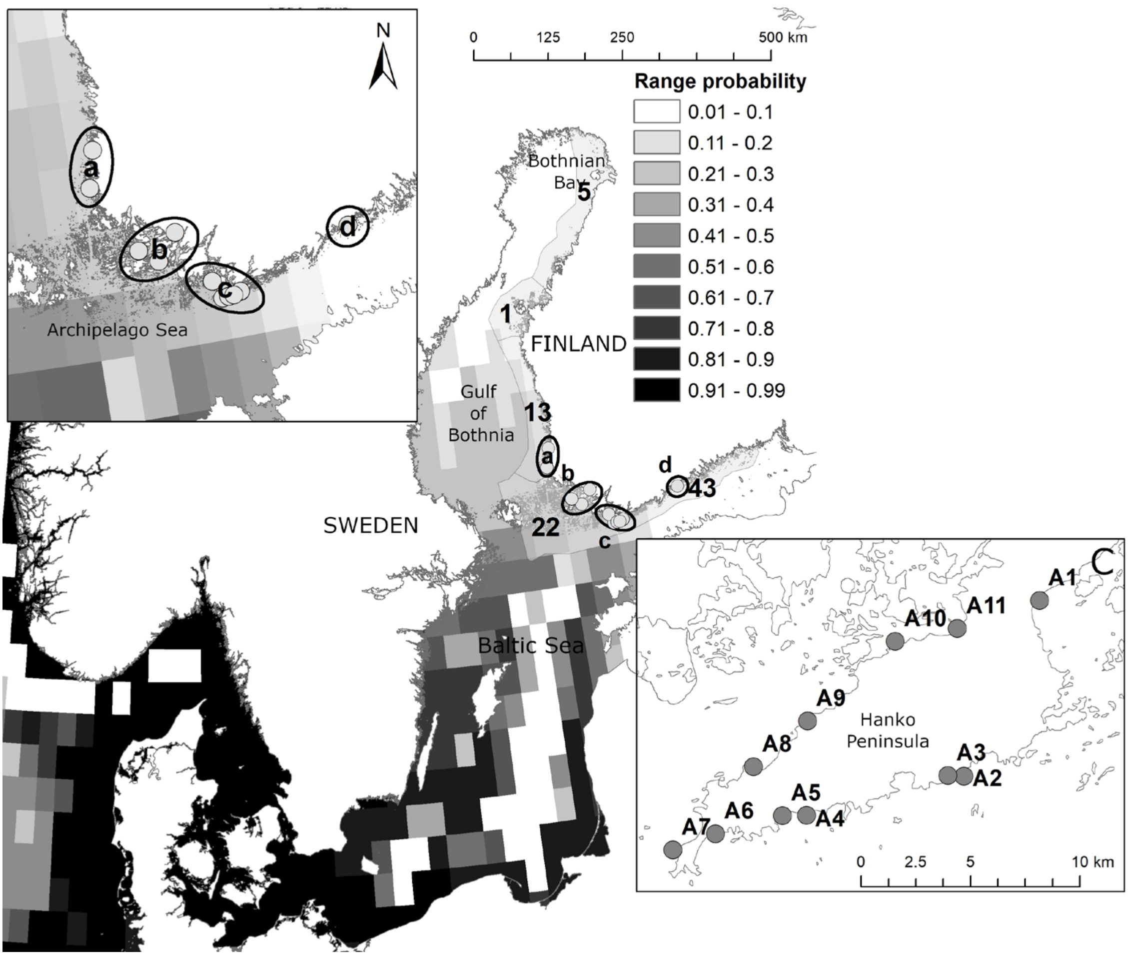


Figure 1. Garfish distribution and larval occurrence in the Baltic Sea. The range probability map is a computer generated native distribution map (Fishbase.org/www.aquamaps version 10/2019). Areas a, b, c and d in SW Finland (inset map) indicate new areas where garfish larvae or juveniles have been reported during the 21st century. In the inset map C are the sampling sites 1-11 where beach seine sampling was conducted in 2005.

Depending on the area, spawning begins in May-June. The favoured spawning temperature of garfish is not well documented, but it apparently seeks out areas warmer than the surroundings (Polte 2004). The eggs are laid on submerged vegetation, most frequently in shallow water (Gasowska 1962), although plants growing at the depth of 12–18 m have also been observed to support garfish eggs (Berg 1949). Garfish spawning on the coast of the North Sea and in the Southern Baltic begins at the end of May and spawning may continue until September (Ehrenbaum 1904, Nikolskij 1954, Polte 2004). In the Wadden Sea, Polte (2004) has observed that garfish prefers shallow seagrass *Zostera noltii* growths on shallow sandy bottoms as a spawning substrate.

Garfish larvae survive at salinities between 7–50 ‰, but the lower salinity limit may be as low as 2–3‰ (Rosenthal & Fonds 1973). Experiments have revealed that garfish embryos are able to develop at salinities exceeding 5.6 ‰ (Von Westernhagen 1974). Fonds et al. (1974) also found the salinity tolerance of garfish embryos to extend below 10 ‰.

Studies on the salinity and temperature tolerance of garfish larvae (Rosenthal & Fonds 1973, Von Westernhagen 1974) have indicated that garfish reproduction in northern Baltic Sea, eg. in Finnish coastal waters may be limited by the low temperature and salinity. Nevertheless, garfish larvae and juveniles have occasionally been observed and reported along the southern coast of Finland in the last thirty years. For example, Sundell (1994), Urho (1999), Vatanen & Haikonen (2006) and Veneranta (2007), Urho & Lehtonen (2008), Urho (2011) have noted species. It has been suggested that garfish larvae may have drifted or swam the 90 km from the known spawning areas in Estonia to the coast of Finland (Urho 1999). Numers et al. (2019) with more recent observations of juveniles suggest that is very unlikely that the currents would bring juveniles to the shallow inner parts of the archipelago of SW Finland or Åland islands. They did not consider the option that already larvae may have drifted there and therefore do not add any additional data supporting spawning in the coastal area of Finland. However, no studies focusing on garfish larvae in the Baltic Sea have been published and occurrence of spawning or larvae in early developmental stages is therefore unknown. In this paper, we present the latest, and unpublished, observations on garfish larvae and juveniles, and describe their surrounding habitats. The possibilities of successful garfish breeding as far north as the northern Gulf of Finland and Archipelago Sea are highlighted. Based on these observations in the marginal area of distribution, we discuss whether the garfish is extending its reproduction range due to environmental change.

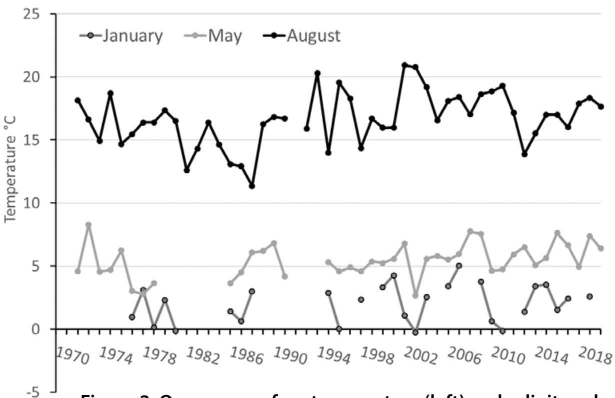
Methods

Sampling of larvae and data

The observations of garfish larvae in area C, around the Hanko Peninsula in SW Finland were done as a part of a more general sampling of juvenile fish. The sampling was carried out from June to September 2005 at 11 shallow sandy beaches (Fig 1). A beach seine having 9-m-long arms with a mesh size of 5 mm and a cod end with 1 mm netting were used to catch larvae and juvenile fish.

The seine covered an area of 375 m^2 with each three replicate hauls at all stations. The total number of hauls was 140 and each site was sampled four to five times. The seine was set in a half-circle by fording out from the shore and returning back with one end of the rope. Once the seine was hauled back to shore, the fish were collected and preserved in 10% formalin. In the laboratory, the total length (TL) of the specimens was measured to the nearest millimetre.

Three additional seine hauls were carried out in 2007 to check the occurrence of larvae. The northern side of the Hanko Peninsula is slightly less exposed to wind due to the vicinity of the mainland and several islands than the south side with a narrower archipelago zone and the vicinity of the open sea. Salinity around the research area usually fluctuates between 5 and 6 ‰ (Fig 2). The sea around the Hanko Peninsula is often covered by ice from November to April, but annual variation is considerable (Jevrejeva et al. 2004). The beach seine sampling stations differed in exposure, steepness, the area of shallow bottom, temperature and turbidity. Vegetation at the study sites was scarce; only the two northernmost sites



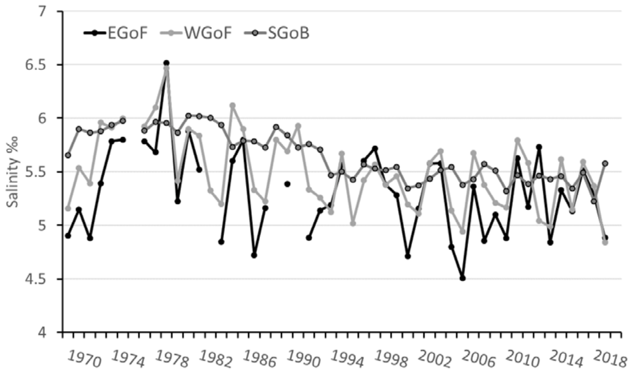


Figure 2. Open sea surface temperature (left) and salinity values (right) in 1970–2020. Salinity measurement areas (time of measurement): EGoF = Eastern Gulf of Finland (May), WGoF = Western Gulf of Finland (May) and SGoB = Southern Gulf of Bothnia (June). Temperatures were measured from the open sea in the Gulf of Finland, off the Hanko Peninsula (Area C). Monthly averages are presented where more than one measurement was taken per month. All values are from the sea surface layer, with temperature or salinity recorded at depths between 0 to 2.5 m. Data from Anon. (2020).

Table 1. Number of caught 0+ garfish at successive samplings and some abiotic features at the different sampling stations in area B in 2005. NS = No sampling. Sampling 1 = 27.–28.6. Sampling 2 = 12.–14.7. Sampling 3 = 26.–28.7. Sampling 4 = 16.–18.8. Sampling 5 = 8.9.

	Sampling					Abiotic features			
Sampling station	1	2	3	4	5	Steepness (%)	Coarseness (index)	Exposure (index)	Shallow area (ha)
1	-	-	7	-	-	0.9	3	13319	41.2
2	-	-	92	2	-	0.2	3	64532	32.6
3	-	1	5	2	NS	0.2	2	22512	19.9
4	-	3	2	-	NS	1.5	3	65507	5.9
5	-	-	6	-	-	0.4	3	64434	21.1
6	-	-	2	-	-	2.7	3	32825	2.7
7	-	-	-	2	-	1.4	4	100719	41.4
8	-	1	-	-	-	2.2	4	9079	4.5
9	-	2	-	-	NS	1	1	13553	36.7
10	-	-	-	-	NS	2.1	1	3557	1.4
11	-	-	-	2	-	2.2	1	4498	4.8
Average length mm (S.D.) below	-	33 (9)	68 (23)	93 (26)	-				
Sampling area, m²	4125	4125	4125	4125	2250				
Number of hauls	33	33	33	33	18				
Total number of 0+ garfish	-	7	114	8	-				

(10 and 11) had a low occurrence of common reed (*Phragmites australis*) at the water's edge and perfoliate pondweed (*Potamogeton perfoliatus*) in deeper water (> 1 m). Separate growths of bladderwrack (*Fucus vesiculosus*) were also found at site seven. The sampling results of this study were pooled into a table 1 together with the results from earlier studies and observations.

Environmental data

At each sampling station the main abiotic characteristics were recorded. The habitat types were identified on the basis of average steepness (0.2–2.7%), the shallow water area connected to sampling site (less than 2 metres in depth, 1.4–41.4 ha), exposure to wind (fetch, Isaeus & Rygg 2005) and bottom coarseness (index value 1–4).

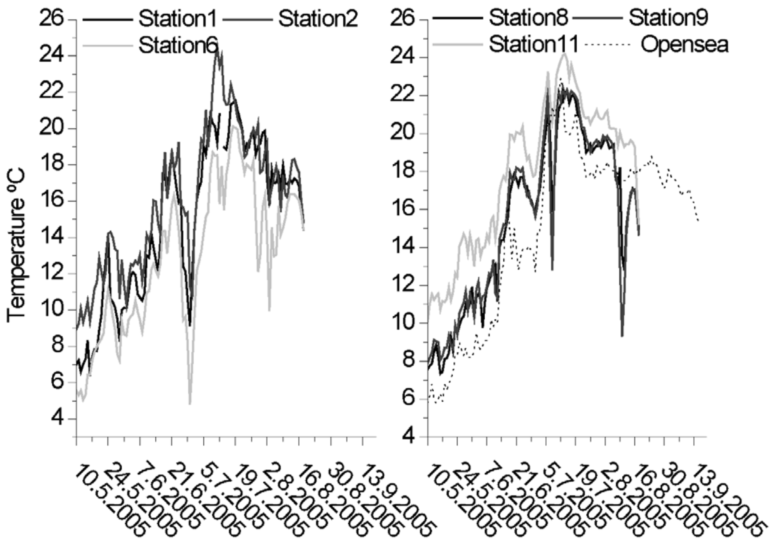


Figure 3. Littoral zone temperatures at a depth of < 1 m at six sampling stations around the Hanko Peninsula: three from the southern side (on the left) and three from the northern side, together with the open sea temperature (on the right).

The cumulative sum of surface water temperatures and turbidity measured at each sampling were also used. A temperature logger (Hobo Water Temp Pro) measuring with an interval of two hours was set at six of the stations at the end of April, immediately after the break-up of the ice.

Salinity and temperature data describing the changes in the northern Baltic Sea at sites close to the sampling stations were obtained from the website merihavainnot.ymparisto.fi (Anon. 2020).

Results

Trends in environmental parameters such as temperature and salinity

Water salinity has had a decreasing trend at all measuring stations located in the Gulf of Finland and southern part of the Gulf of Bothnia since 1980s, with occasional peaks due to saline water pulses (Alenius et al. 1998). At the same time, the temperature has had an increasing trend throughout the year (Fig 2). The temperature trends indicate that the increment was most significant during the summer in May and August, although lack of datapoints distrupts the interpretation in January. The annual fluctuations in temperature are often considerable. According to the temperature logger data collected in this study in 2005, the mean temperature was slightly lower south of the Hanko Peninsula, with monthly means of 9.1 ºC in May, 13.1 ºC in June and 18.7 ºC in July. On the northern side, temperatures were respectively 9.3 ºC in May, 15.4 ºC in June and 20.6 ºC in July. Differences existed between stations. For example, at station 2 the daily mean temperature was 10 ºC in mid-May, 11 ºC at the beginning of June and 15 ºC in mid-June and at the beginning of July. The average temperature in June was 14.7 ºC and the number of monthly day degrees was 440. Around the Hanko Peninsula, winds directed between the south and west can cause upwelling (Haapala 1994). Only the innermost station A11 was not affected by major upwelling occasions, that can decrease the nearshore temperature over 10 °C in a few hours. In mid-August the open sea became warmer than the littoral zone on the south side of the Hanko Peninsula (Fig 3).

Observations of garfish larvae

In area C, garfish larvae were caught at ten of the eleven sandy beaches sampled, both on the northern and the southern side of the Hanko Peninsula. The first observation of garfish larvae was on 13 July 2005 during the second sampling round and the last 0+ were observed on the fourth sampling on 17 August 2005. At the fifth sampling only seven stations were seined and no garfish was observed. Most of the 0+ garfish was caught during the latter half of July. No difference was found in the timing of larval observations between the northern and southern side of the Hanko Peninsula. The abundance of 0+ was highest at station 2 during the third sampling. In other samples the number of larvae was considerably lower (Table 1).

The length of 0+ garfish varied between 23 and 126 mm in 2005 and the length distribution resembled a normal distribution (Fig 4). In 2007, the smallest larva caught was 17 mm in total length and 16 mm in 2009. The larvae having 4 to 5 mm increments to length post hatching indicate the vicinity of the spawning place.

To test the possibility that garfish larvae may have drifted or swam the 90 km from the known spawning areas in the Estonia to the coast of Finland (Urho 1999), we first estimated the most probable hatching and spawning times by combining literature values with our observation and measurements. Higher temperatures shorten the time required for hatching; at 12 ºC it takes 49 days to hatch, at 15 ºC 29 days and at 21 ºC only 17 days. In day degrees the required values are, respectively, 810, 588, 435 and 357 (Fig. 5).

By estimating backwards the mean daily temperatures and day degrees in June and May, spawning was dated for 34 days before hatching. Thus, during the embryo period the average temperature was 14.5 ºC and the number of day degrees was 494. Therefore, spawning was estimated to take place approximately on 28 or 29 May. It may be assumed that the actual spawning happened even earlier, since the temperature logger was situated in shallow, 0.5 m water and the spawning probably occurred in slightly deeper and cooler water. Therefore, it can be presumed that the larvae caught in 2005 had hatched at the end of June or the beginning of July.

In other studies or in known random observations 0+ garfish have been found in the Archipelago Sea as well as the Gulf of Finland (Table 2 and Fig. 1). Based on our observations, the reproduction of garfish has taken place every year, at least from 2003 to 2013 in the Northern Baltic Sea (Table 2). Observations of garfish larvae have become more frequent and at numerous locations on the southwest coast of Finland during the last decades (Table 2), that can be seen also on Numers et al. (2019). Most of the observations have been in the shallow sandy shores of the northern Gulf of Finland.

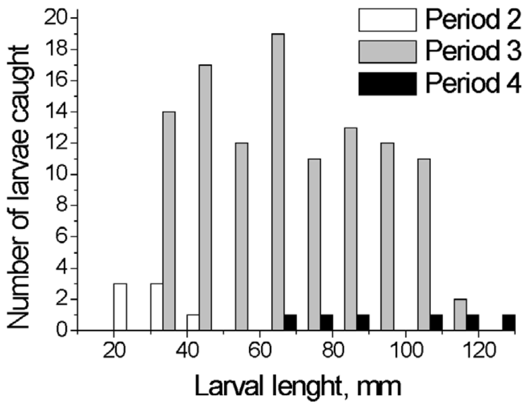


Figure 4. The length distribution of 0+ garfish (larvae and juveniles) in 2005 (Area C).

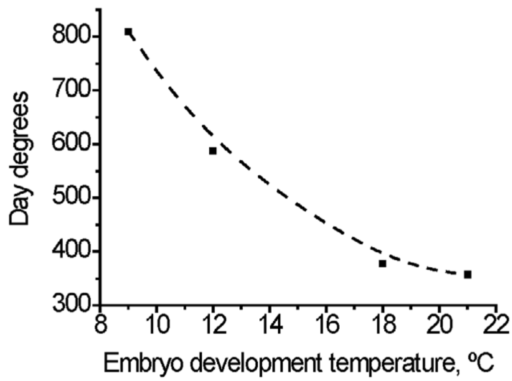


Figure 5. The temperature dependence of garfish embryo hatching time. Drawn from the data of von Westernhagen (1974).

Discussion

Garfish is known to reproduce in the Baltic Proper (Ojaveer & Järv 2003, von Numers et al. 2019). Our larval observations at the northern limit of garfish distribution suggest that the species is extending its reproduction range along with climate change and the increasing water temperatures in the Baltic Sea.

In the 1990s, 0+ garfish were caught with a beach seine in two studies (Table 2). No information about visual observations is available for this period. A decade later, 0+ garfish has frequently been captured by beach seining and visually observed in the northern Gulf of Finland. In our study in 2005, garfish larvae were in several lo-

Table 2. Verified observations of garfish larvae from Finnish coastal areas during the last two decades. (Observations and exact places are documented in (http://kalahavainnot.luke.fi/kartta)

Observation year	Area	Method	Number of hauls in Jul-Aug	Number of garfish larvae / juveniles	Observer/Publication
1990	C	Beach seine	7	2	Urho 1999
1993	C	Beach seine		4	Sundell 1994
2003	C	Beach seine	1	1	Interreg project
2004	B	Visual observation, dip net	-	>10	Nummelin 2004
2005	D	Beach seine	10	3	Vatanen & Haikonen 2006
2005	C	Visual observation, dip net	-	>5	Vähätalo 2005
2005	C	Beach seine	140	129	Veneranta 2005 (this study)
2007	C	Beach seine	3	4	Veneranta 2007 (this study))
2007	C	Beach seine	5	>100	Lehtonen 2007 (this study)
2007	D	Visual observation	-	>5	Mielonen, 2007 (pers. comment)
2008	C	Hand net	-	>3	L. Urho
2009	D	Visual observation	-	>5	A. Lappalainen, 2009 (pers. comment)
2009	C	Hand net	-	>8	L. Urho
2009	A	Visual observation	-	2	A. Saura (pers. comment)
2010	B	Hand net		1	H. Nurmi (pers. comment)
2010	B	Beach seine		3	Marmoni project
2011	B	Hand net		1 (0+/1+)	N. Havia ja P. Nilsson
2011	D	Beach seine		7 (0+& 1+)	Haikonen, 2011
2012	A			3	Tiina Sorjakka & students
2012	A	Beach seine		1	S. Kivinen & R. Oravainen
2012	D	Beach seine		2	Marmoni project
2012	B	Beach seine		1	Marmoni project
2013	A	Visual observation		1	A. Saura (pers. comment)

cations and we were able also to verify the survival and growth. This indicates that garfish reproduction takes place at several sites along the northern Gulf of Finland and seems to be an annual event. Authors have caught spent and feeding garfish (n=4) in the Bothnian Sea and Quark areas 15th June to 22 June, which indicates that spawning likely has occurred earlier in June or end of May, as calculated based on temperatures.

The sea surface temperature has been higher in those years when garfish larvae have been observed, although salinity was rather low compared to the limits indicated in the literature (Fonds et al. 1974). However, it is probably not the higher mean temperature in northern areas, but the longer warm period that enables earlier spawning and a long enough period for larvae to develop and grow during their first summer (eg. Peckan-Hekim et al. 2011). In September when open water temperatures exceeded inshore ones 0+ garfish were not any more caught in the shallow areas.

Garfish embryos or spawning event has not been observed or even searched for in the Northern Baltic Sea In the experiments of Korzelecka-Orkisz et al. (2005), garfish larvae were 12 mm in length at hatching. In our samples the first garfish was caught at a length of 23 mm in 2005, 17 mm in 2007 and 16 mm in 2009. According to Rosenthal & Fonds (1973), growth from hatching to a length of 22 mm takes 13 days at a temperature of 18 ºC. Therefore, it can be presumed that the larvae caught in 2005 had hatched at the end of June or the beginning of July.

According to von Westernhagen (1973), at a temperature of 9 ºC the development of the embryo from fertilization to hatching takes 90 days, but the larvae fail to hatch. Upwelling tends to cause a rapid decrease in the water temperature in the summer that was found to occur more often or was more pronounced on the southern than the northern side of the Hanko Peninsula (Fig. 4). Near the shoreline the temperature was markedly higher than in the open sea area, the average difference between them is 1.24 ºC (S.D. 1.74). Also, according to Fonds et al. (1974), low salinity may prolong the period needed for embryonic development. On the coastline of station 2 the daily mean temperature remained above 10 ºC by mid-June, although after the first week of June the temperature a few times exceeded 12 ºC, the level required for hatching (von Westernhagen 1974).

This only leaves less than two weeks from hatching to the first larvae being caught. During that time the currents in the sea area south of Finland were opposite to the presumed direction of arrival of larvae. Between the hatching period and the first larval observations on the Finnish coast the sea surface currents are weak and directed towards the south, as shown by the sea current information available from the HIROMB model (High Resolution Operational Model for the Baltic Sea by Meteorological and Hydrological Institute of Sweden). This excludes the possibility of larvae drifting from other known spawning regions, such as the west coast of Estonia, to the south-west coast of Finland.

Garfish larvae are known to be able to swim 1–3 body lengths per second at maximum and the estimated cruising speed is about 2.5 to 3.5 km in a day (Rosenthal & Fonds 1973). Based on this assumption, larval progression from the nearest known spawning areas in Estonia should take at least 26 days of active swimming. Therefore, considering the small size of the larvae and the time of their occurrence, their drifting or active swimming to the south-west coast of Finland is improbable.

Apparently, the timing of garfish migration from the Kattegat, North Sea, and the open northeast Atlantic to the Baltic is partly determined by climatic variables, including temperature (MacKenzie et al. 2007). In warm years, garfish migration takes place earlier (Jacobsen 2006). The recent increase in sea surface temperatures of the Baltic Sea not only promotes earlier migration, but also makes spawning and embryonic development possible in more northern areas. As the temperature increases and the thermal regime,thermal area suitable for reproduction, shifts to the north, the limit of garfish distribution will probably follow the northerly shift in the thermal habitat. One factor affecting garfish migration might be the time of ice break-up and subsequent warming of surface waters. Recently, ice break-up in the northern Baltic has occurred 8–20 days earlier than before and the period of ice cover has shortened to a maximum of 44 days in the Archipelago Sea (Jevrejeva et al. 2004).

Precise information on the minimum salinity limit for the development of garfish embryos and larvae is lacking. Studies that have been carried out have not reached a low enough salinity to determine the minimum level for successful embryonic development (Fonds et al. 1979; Rosenthal & Fonds, 1973; Korzelecka-Orkisz et al., 2005), although Fonds et al. (1979) reported that garfish eggs failed to develop at 5‰. On the basis of larval occurrence, the salinity recorded on the southwest coast of Finland and in the Archipelago Sea is high enough. This confirms the finding by Demel (1937) that successful breeding is possible at salinities of 5–6‰. Another possible reason to support successful spawning in low salinity conditions might be stock adaptation. Based on the mean number of vertebrae, von Westernhagen (1974) and Dorman (1991) suggested that a separate garfish stock exists in the Baltic Sea area. However, it is unlikely that the garfish overwinters in the northern Baltic Sea. All observations in Finnish fish observation website (Anon. 2019) are from period May-October, weighting strongly to June-August. Observing the behaviour of adult garpikes in an indoor basin during winter, Rosenthal & Fonds (1973) found that they exhibit panic reactions when the water temperature falls below 6 to 7 ºC.

An interesting issue is how the garfish initially started to spawn in an entirely new location. Most fish species tend to home to spawn in the area where they were born. Urho (2002) suggested larval-juvenile imprinting, so that it is not the spawning place, but more likely the larval and juvenile areas that fish become imprinted to. This provides more flexibility so that a range increment becomes possible as the larval and juvenile areas become larger with increased offspring survival and dispersion.

On the basis of these results, the reproduction of garfish currently takes place as far north as the south-west coast Finland. According to the data presented in this study the reproduction of garfish has taken place at every year at least from 2003 to

2013. More recently, Numers et al. (2019) reported some juvenile observation indicating that garfish reproduction still continues. In recent years, several garfish adults have been caught some hundreds of kilometres north of the larval areas. More observations should be collected to determine the regularity and success of garfish reproduction and the exact minimum salinity and temperature limits. The surface water temperatures, that seem to have risen in the past twenty years, might enable the successive breeding of garfish at the edge of the distribution areas.

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