REPORT

Morphological abnormalities in gonads of the Baltic herring (*Clupea harengus membras*): Description of types and prevalence in the northern Baltic Sea

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Abstract Due to heavy anthropogenic influence and variation of the environmental conditions in the Baltic Sea, reproductive disorders are becoming a major environmental concern. We show here an increasing prevalence of gonadal malformations in the Baltic herring (*Clupea harengus membras*), a key species of the Baltic ecosystem and important in commercial fishery. During 1987–2014, the spawning herring population in the Archipelago Sea (AS) (North Baltic Sea, Finland) was monitored annually and analyzed for gross morphology of the gonads [total number (n) of analyzed fish = 38 284]. Four different types of malformations were repeatedly found and named as asymmetric, rudimentary, segmented, and branched gonads, but also hermaphroditic gonads and miscellaneous (unidentified) disorders were recorded. In 2013, additional samplings (n of fish analyzed = 541) showed similar malformations in herring from the Bothnian Sea. In some gonad types, histological examination revealed disintegration of seminiferous tubules and hyperplasia of the interstitial tissue. In 2014, the overall prevalence of malformations was still relatively low in the AS (frequency = 0–3.4 %; n = 750) and had apparently minimal effect on population recruitment. However, an increasing trend in the time-series (GLM; F = 32.65; p < 0.001) and a significantly higher prevalence in the Bothnian Sea (frequency = 0.7–5.0 %; n = 541; χ^2 = 6.24; p < 0.05) suggest that gonadal malformations may become a new threat for fish in the Baltic Sea. The observed gonad atrophies may be due to environmental endocrine disruption; however, also other explanations may exist and potential explanations are discussed.

Keywords Herring · Gonads · Malformation · Baltic Sea · Reproduction

INTRODUCTION

Successful reproduction is a prerequisite of life in all ecosystems. Production of offspring is a complex process, which proceeds from one stage to another until a new individual is born and reaches sexual maturity. Disturbances can take place at any point in this process, even in natural and pristine conditions, but these are more pronounced in environments that have a high human impact. The Baltic Sea (Fig. 1) is an example of an ecosystem where organisms have an increased risk of reproductive failures, as it is heavily loaded with nutrients that cause eutrophication and oxygen deficiency, is contaminated with various chemical substances (HELCOM 2010), and is polluted even with radioactive emissions (Herrmann et al. 2013). Moreover, the Baltic Sea environment fluctuates according to climatic conditions, which cause changes in water salinity, abundance of species, and ecosystem structure (HELCOM 2007).

Due to its vulnerability to external disturbances, reproduction is a sensitive indicator of the environmental conditions. This is recognized also by the European Union's Marine Strategy Framework Directive (2008/56/EC; MSFD), which aims at achieving a good environmental status in the European marine waters by 2020. This status is determined by several key descriptors, which call for monitoring the state of marine species, including their reproductive success. Reproduction, however, is not monitored in the majority of marine species in the Baltic Sea, although special monitoring programs have been introduced (Lehtonen et al. 2006).

In the Baltic fish, reproductive disorders represent a variety of phenomena with a miscellaneous background (Breitholtz et al. 2001). A high mortality of eggs and

Fig. 1 Sampling areas of the herring in the Archipelago Sea during 1987–2014 and the Bothnian Sea in 2013. A Archipelago Sea (Airisto Inlet); B Bothnian Sea, coast and C Bothnian Sea, open sea. In box A, the locations of the sampled herring trap nets (1–5) in the Airisto Inlet are shown

deformities of larvae and young individuals are the most common problems (Aneer 1987; Westernhagen et al. 1988; Rajasilta et al. 1989; Bengtsson et al. 1999; Gercken et al. 2006), but also a total cessation of reproduction (Pulliainen et al. 1992), hermaphroditism (Bucholtz et al. 2008) and malformation of gonads have been reported (Wiklund et al. 1996). Especially, the latter cases emphasize how reproductive success is dependent on the reproductive health of the parents through processes that damage gonads. However, monitoring of gonad status is a complicated task in any species, because it requires knowledge about the morphology of normal gonads and the ability to detect their structural and functional deviations.

In the Baltic herring (*Clupea harengus membras*), reproductive health is not monitored systematically, although disturbances in its reproduction may affect the whole ecosystem, because of the central position it holds in the food webs. As far as it is known, adult fish are healthy, but they may carry the viral hemorrhagic septicemia virus (VHSV). However, the infection shows no external symptoms and apparently does not harm the fish or affect its reproduction (Gadd et al. 2011). Gonad abnormalities have been reported from herring in the southern Baltic Sea

(Bucholtz et al. 2008), but there is no information on their abundance or variety in the population.

In this study, we describe different gonad malformations found in herring collected from the Archipelago Sea (AS) and the neighboring Bothnian Sea (Fig. 1) with the latter being the main feeding area for the AS herring (Sjöblom 1961; Kääriä et al. 2001). In the AS, the spawning herring population was monitored over 30 years by regular samplings from the spawning grounds (Rajasilta et al. 1999). In the sampling scheme, various routine data for population characteristics were collected, but also the morphology of gonads was recorded when determining the sexual maturity stage of fish. Over the years, gonadal malformations have been found occasionally, but recently they have become more frequent in the samples and also new types of malformations have been found. As some of them indicate serious disturbances in the reproductive system, our aim was to provide baseline information for their further monitoring, to promote studies on finding out the reasons for malformations, and to draw attention to the problem in general as it may be more common than is thought also in other fish species and aquatic ecosystems.

Table 1 Number of herring (*n*) examined annually in 1987–2014 in the Airisto Inlet (trap net samples) and the Bothnian Sea (trawl and gill net samples). ND = no data

	Year	<i>n</i>	Year	<i>n</i>
Airisto Inlet				
Trap net	1987	3647	2001	1782
	1988	1346	2002	749
	1989	792	2003	897
	1990	1942	2004	596
	1991	1925	2005	449
	1992	61	2006	298
	1993	149	2007	149
	1994	2347	2008	ND
	1995	ND	2009	1410
	1996	819	2010	1050
	1997	4668	2011	840
	1998	7737	2012	516
	1999	1198	2013	1268
	2000	899	2014	750
Bothnian Sea				
Trawl	2013	100		
Gill net	2013	441		

MATERIALS AND METHODS

Sampling and studies of fish

During 1987–2014, spawning herring were collected annually from commercial trap nets in the Airisto Inlet, which is one of the most important spawning areas of herring in the AS (Fig. 1; for the description, see Rajasilta et al. 1999). Random samples containing about 150–200 fish were taken from the catch over the spawning season (May–July) and kept at -20°C until further treatment. In the laboratory, fish were thawed and their total length (mm) and total weight (accuracy 0.1 g) were measured. Gonads were removed from the body cavity to determine the sex, stage of sexual maturity (Kesteven's classification; Bagenal and Braum 1971), and gonad weight (accuracy 0.01 g), and otoliths were removed for age reading. If abnormal gonads were found, their external appearance was described in the data form (1987–2014), and they were photographed (2012–2014). In the Bothnian Sea, samples were taken in 2013 from the catches of commercial trawlers operating in the open sea and from gill nets catching spawning herring on the coast (Fig. 1). The total number of fish examined was 38 284 in the Airisto Inlet (1987–2014) and 541 in the Bothnian Sea (2013) with a varying sample size during different years (Table 1). In June 2014, also samples of fresh fish were collected from the trap net catch

in the Airisto Inlet, and abnormal gonads found were preserved in 10 % buffered formalin for histological scrutiny.

Description of gonad types and histological studies

During the study, the gonad types were described by visual inspection of the gross morphology of gonads in all fish collected. In addition, the fine structure of the gonad tissue was examined histologically in some of the gonad types (number of fish examined 1–5/gonad type). Fresh tissue samples from fully mature gonads that were fixed in 10 % neutral-buffered formalin were dehydrated and cleared in xylene, embedded in paraffin, cut, and analyzed both in the horizontal and longitudinal sections (3–6 μm) from several levels of each gonad in order to properly cover the putative tissue changes. The slides stained with hematoxylin–eosin were examined by an optical light microscope.

Statistical analysis

The annual trend of the gonadal malformations in fish collected from the Airisto Inlet in 1987–2014 was studied using logistic regression modeling (Generalized Linear Models, GLIMMIX procedure). Year was used as a continuous variable, and the total number of herring and number of malformations as the response variables. Distribution of the dataset was defined as a binomial distribution, and its linearizing link function was logit function. Differences in prevalence of gonadal malformations between the AS and the Gulf of Bothnia were examined using χ^2 test. All statistical analyses were conducted with the statistical software SAS 9.3 and SPSS.

RESULTS

Gonad types and their prevalence

The gonad types found were divided into seven different categories by gross morphological characteristics with type 1 being the normal gonad (Fig. 2). From the early study years, it was not possible to identify the type of the malformation exactly, as some of them were recorded only as “abnormal gonads.” On the other hand, malformations were rare in the samples and almost all were represented by *asymmetry* (Fig. 2; type 2), which was clearly documented as “one gonad,” so that their occurrence in the samples could be calculated exactly. In this gonad type, fish had one normal gonad, but sometimes it seemed to be formed as a fusion of the two gonads into one. Another example of asymmetry, triplicate gonads (Fig. 2), was found in male fish in 2013. Asymmetry with one gonad was found in both

Fig. 2 Morphological gonad types found in the Baltic herring collected from the Archipelago Sea and the Bothnian Sea. The numbers refer to the gonad types as follows: 1 normal gonads (*left ovary; right testis*), 2 asymmetric gonads (testis with three strands from one fish), 3 rudimentary gonads (*left testis; right ovary*), 4 segmented (constricted) gonads (testis), 5 branched gonads (testis), 6 hermaphrodite, 7 miscellaneous disorder (ovary). For further explanations, see text

Fig. 3 Prevalence (F %) of gonad abnormalities in the Baltic herring collected from the spawning grounds in the Airsto Inlet during 1987–2014. **a** Asymmetric gonads and **b** all abnormal gonad types. *Nd* no data; number of fish examined is shown in Table 1

Fig. 4 **a** Structure of healthy mature testis of the Baltic herring. The lumen of seminiferous tubules is filled by darkly stained mature sperm cells (*open arrows*). The tubule wall is occupied by differentiating spermatogenic cells (*asterisks*). Narrow interstitial tissue (*solid arrows*) delineates the tubules; **b** a higher magnification of (**a**); **c** structure of a partly atrophic testis. Sperm cells are found in some tubules (*open arrow*), whereas tubules on the *left-hand side* are atrophic; and **d** segmented testis. Tubules are filled by mature sperm (*open arrow*); interstitial tissue is hypertrophied (*solid arrows*). Bar lengths: **a**, **d** 100 μ m; **b**, **c** 50 μ m

sexes and at an almost equal ratio (female: male ratio = 1.3:1) in the time-series. Their frequency in the samples was always low ($F < 0.5$ %) in the Airisto Inlet, and they showed no trend over time (Fig. 3a).

Rudimentary gonads (Fig. 2; type 3) were defined separately from asymmetry, as in this morphological type, the other gonad often looked macroscopically and microscopically normal (Fig. 4), while the other one had not developed fully and was small in size. Sometimes also both gonads were altered, and some of them were partly atrophied and showed disintegration of seminiferous tubules (Fig. 4c). In the data from the Airisto Inlet, they were found occasionally from 1987 onwards in both sexes.

Instead, *segmented (or constricted) gonads* (Fig. 2; type 4) were found only in male herring. Fish usually had both testes, but they were segmented into separate “compartments” of variable size, and the gonad morphology was severely altered. Sometimes, only one testis was left and the other one was just a rudiment, which usually had dark color indicating a breakdown of the tissues. Histologically,

compared to normal testes (Fig. 4a, b), the segmented testes showed hyperplasia of the interstitial tissue (Fig. 4d). Nevertheless, spermatogenesis seemed to proceed normally in the segmented testes.

Branched gonads (Fig. 2; type 5) were also found only in male herring. The testis tissue formed branches that were attached to the main body of the testis with a narrow “neck.” No major histological changes could be found in the branched testes. In addition to these gonad types, *hermaphroditism* (Fig. 2; type 6) was found, but only in one specimen in 2012 from the Airisto Inlet. Moreover, in 2013, tumor-like or necrotic tissue in the ovaries was found in one individual collected from the Bothnian Sea. As this condition deviated clearly from the other gonad malformations, it was classified as *miscellaneous abnormalities* (Fig. 2; Type 7).

In fish collected during 2012–2014, asymmetric and rudimentary gonads were found in both sexes, but segmented and branched gonads only in males (Fig. 5). Of the cases, 62 % were males and 38 % females. In the total data, the frequency of males having gonad malformations was

Fig. 5 Proportion (% of total, $n = 38$) of different gonadal malformations found in male and female herrings during 2012–2014 in the Archipelago Sea and the Bothnian Sea (Type 6 = hermaphrodite)

also somewhat higher than that of females (55.3 and 44.7 %, respectively).

During the study period, when all different types were considered, gonad abnormalities increased significantly in the Airisto Inlet ($F = 32.65$; $p < 0.001$; $df = 1$; Fig. 3b). The trend was due to their higher number in the spawning population in 2013–2014, during which time the prevalence of malformations almost doubled from the previous years. There was some variation between the sampling dates and locations, but no consistent pattern was observed, except a slight increase of the frequencies in June from 2013 to 2014 (Table 2). In the Bothnian Sea, abnormal gonads were significantly more frequent than in the Airisto Inlet in 2013 ($\chi^2 = 6.24$; $df = 1$; $p < 0.05$), with the average prevalence being 2.8 % in the samples (number of fish examined = 541). In some samples of this area, even 4–5 % of the fish had abnormal gonads (Table 2).

Abnormal gonads were found in fish of different lengths (range 13–26 cm) and ages (range 3–7 years). Fish having them did not deviate by external appearance from those having normal gonads, but in 2014, a high rate of infections by parasitic worms (*Acanthocephala*) was observed in the AS herring population (11 % of total number of fish examined). Parasites were present in the body cavity of the fish, but they were mostly found in fish with normal gonads.

DISCUSSION

General methodical sources of error

Comparison of the results from different studies is difficult, mainly because of the inconsistency in terminology and study methods used (Hecker et al. 2006). In our study, descriptions made on the basis of visual inspection of

Table 2 Prevalence (F %) of morphological abnormalities in the gonads of the Baltic herring collected from the Airisto Inlet (A) and the Bothnian Sea (B = coast; C = open sea) in different locations and at different dates in 2013 and 2014. Sample type: S = spawning fish (collected from the spawning grounds); and PS = fish at pre-spawning stage (collected from the open sea prior to spawning). The locations of the trap nets sampled in area A (1–5) are shown in Fig. 1

Area (location)	Date	Sample type	Tot n examined	Type of gonad abnormality	F %
2013					
A					
(4)	May 23	S	187	2	0.5
(1)	May 25	S	104	3	1.0
(2)	May 28	S	105	5	1.0
(4)	June 2	S	185	2	0.5
(3)	June 5	S	104	4	1.9
(5)	June 10	S	119	2, 3	3.4
(4)	June 13	S	95	5	1.1
(3)	July 3	S	187	3	0.5
(5)	July 3	S	164	3	0.6
B	July 2	S	152	4	0.7
	July 6	S	85	3, 4, 7	4.7
	July 12	S	165	2, 3, 4	3.6
C	May 29	PS	69	2	1.5
	May 31	PS	40	2, 3	5.0
	June 3	PS	30	2	3.3
2014					
A					
(1)	May 30	S	194	3, 4	1.0
(5)	June 5	S	149	4, 5	1.3
(4)	June 19	S	225	2, 3	1.8
(2)	July 7	S	180	–	0

gonads are inevitably subjective, but on the other hand the results were obtained from the same population and using the same study methods and classification criteria, so that they probably contain less of this type of error.

The herring samples from the Airisto Inlet indicated an increasing number of gonad abnormalities in recent years, but as the material was collected during a long time period and was analyzed by different people over the years, potential differences in the assessment have to be considered. In the first study years, when abnormalities were found only occasionally, their description was less exact than in the recent years, when more different cases appeared in the samples. Observations on one gonad were recorded exactly, but sometimes the gonads were described as “abnormal,” which gave no information about the gonad type. In spite of this, it is most likely that all deviations from the normal gonads were noticed even in the first study years, as the gonads were always removed from the body cavity and examined individually for the determination of

the maturity stage. Thus, the overall prevalence of abnormalities is probably quite correct in our time-series, but the prevalence of different types remains open with exception of the years 2012–2014.

The frequency of abnormalities in the AS herring was low until 2013, although there was some variation between the years. During some years (e.g., 1992 and 1993), the sample size was probably too small to detect any malformations that had a low prevalence in the population, but in most years the sample sizes were reasonably large and the sampling covered the whole spawning season, thus revealing the possible seasonal trends. In 2013, a slight increase of malformations was observed in June in the AS samples, but this may be only an occasional finding. However, the variation among the samples collected from the same area, and during the same year, demonstrates the importance of frequent sampling over the whole spawning season, and this depends on a long reproduction period in the species monitored for gonad abnormalities.

The types of gonad malformations

The gonad abnormalities observed in the Baltic herring resemble those of the European whitefish (*Coregonus lavaretus*) from Lake Thun, Switzerland, which also showed a high variety of morphological types (Bernet et al. 2004, 2008). The two species shared some similarities in the gross morphology of gonads, but there were also differences between them. For instance, adhesion of the gonad tissue to the peritoneal wall, frequently found in the lake whitefish, was not observed in the herring at all, whereas segmented gonads and hermaphroditism were found in both species.

In the AS herring, the most common gonad type deviating from normal was asymmetry, which was found during the whole study period at variable but low frequencies. In most cases addressed as asymmetries, fish had only one well-developed gonad strand, but also the development of three strands can occur as shown by one case found in 2013 (Fig. 2). In principle, asymmetric gonads can develop in different ways, but most likely the reproductive system with three gonads is determined early at the embryonic stage when the primordial gonads and gonoducts are formed (DeFalco and Capel 2009). The same applies to the development of one single strand only, although this condition can also have a normal start at embryonic phase but end up to a situation where the other gonad degenerates or fuses together with the remaining gonad later. Ideally, asymmetric gonads may be just mild modifications of the normal condition and do not prevent the fish from reproducing normally. The same concerns with the other malformations, as even males with segmented gonads may be able to reproduce, although apparently with reduced

capacity, as part of the testis is disturbed. However, finding out the total effect of gonad malformations on the reproductive success of herring requires not only further studies on their anatomy and histology, but also experimental work testing the fertilization rate and development of the embryos using germ cells from altered gonads.

Possible causes of gonad malformations

Depending on the taxonomical status of the species, Teleostean fish exhibit some diversity in gonad forms (Parenti and Grier 2004; Henderson et al. 2014; Wootton and Smith 2015). It is not known if the number of gonads is fully conserved at a genetic level in fish (DeFalco and Capel 2009), but the basic pattern is a pair of ovaries and testes in the majority of species. In the Baltic fish, anomalies in gonad morphology seem to be rare in general, based on the low number of studies reported (Wiklund et al. 1996; Bucholtz et al. 2008). However, they may also remain unnoticed, if for instance the sexual maturity is determined without taking the entire gonad out so that its morphology can be seen properly. Beside the lake whitefish (Bernet et al. 2004, 2008), gonad anomalies have been found also in some tropical fish (Omotosho 1987), and especially frogs and reptiles suffer from this condition (e.g., Guillette et al. 2000; Hecker et al. 2006). In many cases, the anomalies are causally linked with the chronic exposure to herbicides (Coady et al. 2005) or other environmental contaminants disturbing the endocrine system of an animal. In our study, the reason for the increase in abnormalities remains open, but some alternatives can be suggested or ruled out as less probable.

Dioxins, their relative compounds, and PCBs are widely distributed in the Baltic biota (HELCOM 2004) and known for their disrupting effects on animal reproduction and embryonic development (Colborn et al. 1993). Also the Baltic herring has suffered from a high concentration of these environmental contaminants especially in the northern sea areas, where our study material originates. The dioxin concentrations were high in the late 1980s and the early 1990s, but a recent study shows that they have significantly decreased thereafter, being relatively low at present (Airaksinen et al. 2014). This opposite trend of the dioxin concentration and gonad malformations of the herring thus suggests that dioxins may not be a root cause. In the Baltic herring, the time-series on dioxins is based on the analyses of whole fish (Airaksinen et al. 2014), which leaves a possibility that their concentration is higher in gonads. This is improbable, however, as lipophilic substances like dioxins are deposited with lipids in the muscle tissue, which is the main lipid storage of the herring (Marmon et al. 2009). The fat content of the ovaries is low (1–2 % of the wet weight of the ovary; Laine 2003), and

therefore their dioxin concentrations are obviously much lower than in fish.

The infections of parasitic worms, which may disturb the immune defense and hormonal systems of the fish, are also a less apparent cause, as they were not connected with the prevalence of gonad malformations and were found only in 2014. The possible effects of micro-organisms were not investigated here, but for instance the microsporidian parasite *Pleistophora mirandellae*, which caused gonad malformations in the Baltic roach, affected mainly females (Wiklund et al. 1996), while in the herring males suffered from anomalies even more than females. In all, malformations were found in fish of different sizes and ages, suggesting that the problem concerns the whole population and is not, for instance, a consequence of fish aging.

According to the assessment report of HELCOM (2010), the entire Baltic Sea is an area with a high contamination by hazardous substances, which include a large variety of different chemicals from heavy metals to pharmaceuticals and natural hormones and even radionuclides. It is therefore probable that the gonad anomalies of the Baltic herring have a complex background and with several different origins. As the spawning areas of the herring are situated on the coast, its early life phases from embryonic and larval development to metamorphosis take place in the environments, where human impact is highest and the endocrine disrupting chemicals (EDCs) concentrate. Hermaphroditism (intersexuality) is a typical condition related to the EDCs (Arukwe and Goksøyr 2003; Hecker et al. 2006 and the references therein), but in the herring it was not common. However, spawning fish with well-developed gonads do not necessarily indicate the real prevalence of hermaphroditism or any other gonad malformations in the population if the development of gonads stops at early phases, and fish do not migrate to the spawning grounds at all. Moreover, examination of gonads by visual inspection is not a sufficient method either, as for instance some types of hermaphroditism cannot be seen without histological cross sections of the gonad tissue (Sadovy and Shapiro 1987). During 2013, in the Bothnian Sea, fish were studied also at a pre-spawning stage, but the actual situation can be found out only by examination of fish at different ages and developmental stages, such as at metamorphosis and the early onset of the maturation cycle and using appropriate methods.

It is possible that various chemicals of municipal, industrial, or agricultural origin are involved in the formation of gonad abnormalities in the Baltic herring, and some of them could be related to the changes of the Baltic ecosystem and develop in one way or another as a response to declining salinity that has taken place during the past 30 years (Hänninen et al. 2000; Hänninen and Vuorinen 2015). Salinity may affect the hormonal system and

reproduction of fish (Billard et al. 1981), but most likely a euryhaline species like the Baltic herring is able to adjust to variation of salinity, which is a typical feature of the Baltic Sea. During the salinity decline, herring's growth decreased (e.g., Rönkkönen et al. 2004; Möllmann et al. 2005) apparently as a life-history strategy to ensure the reproduction in variable environmental conditions (Rajasilta et al. 2015). In spite of the reduction of fish body size, the herring stock of the Bothnian Sea has shown good recruitment and an increase of the spawning stock during the past 20 years (Lindegren et al. 2011). An increased population density may also act as a stressor that influences the nutritional status and hormonal system of the fish (Barton and Iwama 1991), but, as a response to overcrowding, herring are supposed to respond firstly by a decrease of their gonad weight (van Damme et al. 2009), which has not been observed (Rajasilta et al. 2015). Disturbances in the gonad structure are less likely in this situation, but at high population densities the risk of various infections inevitably increases (Reno 1998). Thus, if some of the gonadal malformations are caused by infections, their prevalence may increase at increasing population densities.

CONCLUSIONS

Our study revealed a new type of reproductive disorders in the Baltic herring, but clearly further studies are needed that focus on their anatomy and histology to understand the reasons behind this condition. At a population level, gonad abnormalities may have minimal influence on the reproductive capacity of the Baltic herring at present, but monitoring of gonad health is necessary in herring and presumably also in other fish species. Future scenarios predicting the development of the Baltic Sea suggest an increase of rainfall and fresh water input into the Baltic (Vuorinen et al. 2015), which would increase the air-borne fall of pollutants and discharges of nutrients, biocides, and other environmental contaminants from the catchment area. Especially, in commercially exploited species, also the reproductive health of the parental stock should be examined and monitored, so as to find out the reasons for the reduced recruitment and stock size, if such emerge.

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