Rapid Communication

First record of the parasitic copepod (*Mytilicola orientalis* Mori, 1935) in blue mussels (*Mytilus* spp.) of the Baltic Sea

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Abstract

The parasitic copepod *Mytilicola orientalis* infesting mussels and oysters was so far only described in saline waters – such as the North Sea. In April 2018, it was recorded for the first time at a low salinity location in the Kiel Bight, Baltic Sea. Two mature females of *M. orientalis* were found in two separate individuals of Baltic blue mussels (*Mytilus* spp.). Prevalence of parasites in the whole sample was low (3.6%), and no males or eggs were detected. In a second sample from October 2018, another adult female was found indicating spread over larger areas and longer time periods. The findings of this study further indicated that larvae from introduced *M. orientalis* adults can hatch under low saline conditions of Kiel Fjord and are able to infest and to develop within tissues of Baltic blue mussels. It therefore may just be a matter of time before the establishment of the full life cycle of *M. orientalis* in the Baltic Sea.

Key words: *Mytilicola* disease, invasive parasite, oyster, red worm, salinity tolerance, parasite spillover

Introduction

The blue mussel is an active suspension feeder, filtering phytoplankton and suspended particles from the water column. In addition to these food items, mussels also ingest parasite larvae. As a consequence, wild and farmed bivalves are subject to various diseases caused by macro- and microparasites such as copepods, trematodes, nematodes, polychaetes, and protozoans (e.g. Katkansky and Warner 1968; Montes 1990; Motes and De Paola 1996; Aguirre-Macedo and Kennedy 1999; Brenner et al. 2014). Two of these parasites, the intestinal mytilicolid copepods *Mytilicola orientalis* Mori, 1935 and *M. intestinalis* Steuer, 1902, are introduced species in the North Sea (Pogoda et al. 2012): *M. intestinalis* was initially introduced via *Mytilus galloprovincialis* Lamarck, 1819 from the Mediterranean into the North Sea in the 1930s and is nowadays an established parasite of the indigenous blue mussel *Mytilus edulis* L. in this region (e.g. Dethlefsen 1975; Lauckner 1983; Davey 1989; Thieltges et al. 2008). In contrast, *M. orientalis* was

co-introduced with Pacific oysters (*Crassostrea gigas* Thunberg, 1793) to France in the 1970s and in the southern North Sea in the early 1990s (Goedknegt et al. 2016). Its main host, the Pacific Oyster, has massively invaded the Wadden Sea (Reise et al. 2017), and most populations are infected by *M. orientalis* (Elsner et al. 2011, Goedknegt et al. 2016).

The native range of *M. orientalis* is in Japanese waters. It has a direct life cycle with a free-living larval dispersal stage, after which it resides in the intestines of molluscs (Mori 1935). After its introduction to Europe, the parasite spread via its principle host to various mollusc species (Goedknegt et al. 2016). In particular, native blue mussels (*Mytilus edulis*) are increasingly serving as new hosts for *M. orientalis*, with infection prevalences being similar to or even exceeding those in Pacific oysters in some areas (Pogoda et al. 2012; Goedknegt et al. 2016).

Due to their bright red colour, Mytilicolidae became infamous as the "red worm disease", and especially *M. intestinalis* was blamed to be the cause of mass mortalities of blue mussels in the North Sea in the 1950s and 60s (Korringa 1968; Blateau et al. 1992). However, until today, evidence of severe health impairments of bivalves as a direct effect of infestations with Mytilicolidae species are lacking (Bernard 1969; De Grave et al. 1995) making it questionable whether mass mortalities were really caused by the parasites (Demann and Wegner 2019).

Most of the common parasites species of blue mussels are restricted to environments with higher salinities. Baltic blue mussels, such as *Mytilus trossulus* Gould, 1850 and the hybrid population of *M. edulis* and *M. trossulus,* as it is found in Kiel Fjord and Kiel Bay (Stuckas et al. 2017), are less burdened with parasites. In particular, both *Mytilicola* species were thought to be totally absent in the Baltic Sea (Feis et al. 2016; CABI 2018).

Materials and methods

Baltic mussels intended to be used for an exposure study in Kiel Bight (not described here) were obtained from a mussel farm (Kieler Meeresfarm, N54°22′31.80″; E10°9′48.60″) within Kiel Fjord situated next to the watergate of Kiel Channel connecting German North Sea with the German Baltic Sea coast (Figure 1). The Kieler Meeresfarm produces mussels using a floating longline system with vertically suspended ropes as artificial settlement substrate for free swimming veliger larvae. Settled mussel larvae remain at the ropes until market size is reached. Mussels were sorted and lengths of shells were measured. 320 mussels of a size class between 4 and 6 cm shell length (mean 4.73 cm ± 0.33 cm, n = 320) were distributed in 4 labelled nylon bags (each filled with 80 mussels). In early October 2017, mussels were transferred to Kolberger Heide (N54°27′21.60″; E10°20′13.80″), where bags were attached by divers to four steel moorings in approximately 12 m depth (Figure 1). After 6 months of exposure, mussels were retrieved at 11 April

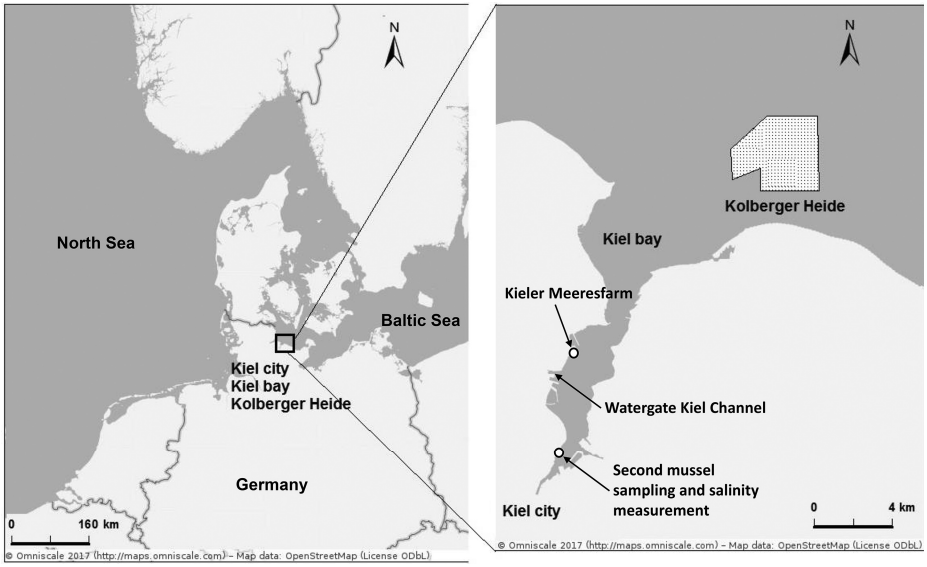

Figure 1. Map of the city of Kiel with surrounding marine areas, showing the mussel farm (Kieler Meeresfarm), the area where salinity measurements were taken, the area where the second sampling in October 2018 was conducted, and the area of mussel exposure in Kiel Bay/Kolberger Heide (map modified after Strehse et al. 2017, using geo data provided by EGEOS GmbH; with kind permission of Elsevier).

2018 from the moorings and transported in aerated ambient water to the lab in Bremerhaven using cooling boxes. In the lab, mussels were dissected and prepared for various biomarker analysis. While dissecting the exposed mussels, a large specimen of *Mytilicola* was discovered. Therefore, the remaining 55 mussel not intended to be used for the biomarker analysis were inspected for the presence of macro parasites (Meyer 1951; Korringa 1950). Although *M. intestinalis* showed some tolerance towards lower salinities (Korringa 1968), neither of the two species has so far been reported from the Baltic Sea. To further exclude any influence of the farming background of these mussels, an additional sample of naturally settled mussels was taken on 04 October 2018 from a swimming dock further towards the end of the fjord (N54°19′52.95″; E10°9′3.96″). Fifty-two mussels with an average size of 4.03 ± 0.08 cm were dissected using the same procedures targeting *Mytilicola* as described for the first sampling.

Analysis of macro parasites

First, the length of each mussel was measured to the nearest 0.1 mm using vernier calipers. Mussels were then opened, drained, and the soft body was removed and placed on the bottom of a glass compressorium. Mantle, gills, food, adductor muscle and other tissues were dissected carefully and dispersed. The digestive gland was gently pulled apart using tweezers. Distributed tissues were than squeezed using the cover glass of the compressorium. The preparations were examined under a stereo magnifying glass (10–50-fold magnification) with transmitting light for the presence of macro parasites. Individuals were identified according to descriptions from the literature (e.g. Dethlefsen 1970, 1972; Lauckner 1983; Watermann et al.

Table 1. Monthly means of salinities at [a] Kiel Fjord (ca. 1 m depth) in front of Geomar West Shore Campus and [b] at the bottom of Kolberger Heide/Kiel Bay (ca. 12 m depth) for the time period between January 2017 and April 2018 ([a] data were kindly provided by Kiel Marine Organism Culture Centre (KIMOCC), Geomar, Kiel, Germany and [b] by the Leibniz Institute for Baltic Sea Research (IOW), Warnemünde (IOW), Germany).

	Kiel Fjord [a]	Kolberger Heide [b]
	psu	psu
Jan 17	–	20.71
Feb 17	–	19.04
Mar 17	–	17.60
Apr 17	15.95	17.08
May 17	14.98	16.98
Jun 17	16.16	16.77
Jul 17	15.96	18.65
Aug 17	16.01	18.66
Sep 17	16.51	–
Okt 17	15.82	–
Nov 17	17.59	–
Dec 17	18.11	19.19
Jan 18	16.90	18.41
Feb 18	14.09	16.79
Mar 18	12.57	14.17
Apr 18	11.81	13.14

1998). In a final step, all shells of the analysed mussels were inspected for the presence of shellboring polychaetes using the stereo magnifying glass.

Salinity regime in Kiel Fjord and Kiel Bight

The Baltic Sea is characterised by a decreasing salinity gradient (25–5 psu) from west to east. According to Bendtsen et al. (2007), the area around Kiel Bight has an average bottom salinity between 11–18 psu. Kiel Fjord, where the Kieler Meeresfarm is situated, has even lower average salinity due to the freshwater inflow of the river Schwentine. The data show the seasonal variation in salinity for the years 2017/18 at: [a] 1 m depth from a pontoon in front of Geomar West Shore Campus (N54°19′48.78″; E10°8′59.44″) in the immediate vicinity of the second mussel sampling site, and [b] at the bottom of Kolberger Heide in approximately 12 m depth, which were kindly provided by Kiel Marine Organism Culture Centre (KIMOCC), Geomar, Kiel, Germany and by the Leibniz Institute for Baltic Sea Research (IOW), Warnemünde, Germany, respectively (Table 1).

Salinity tolerance of larval hatching

To investigate the possibility of infection under the low salinity conditions of the Baltic Sea and to deduce further invasion potential, a salinity tolerance experiment was performed to investigate the salinity tolerance of eggs and early larvae. To do so, egg sacs from adult female *M. orientalis* and *M. intestinalis* were collected from a mixed oyster and mussel bed in the Northern Wadden Sea off the island of Sylt (Germany, N55°02′17″; E08°26′32″). Egg sacs were cleaned and incubated singly in 24 well plates. Each egg sac was randomly assigned to one out of four salinity treatments that included

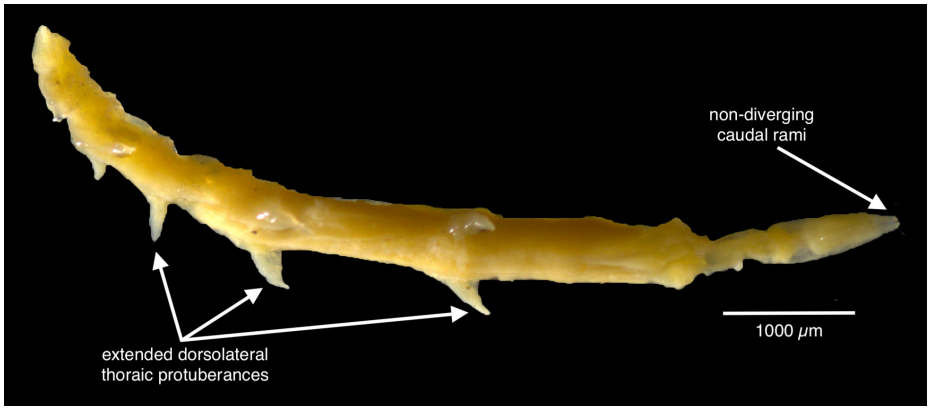

Figure 2. Photograph of one specimen of *M. orientalis* discovered in Baltic blue mussels. The size characterizes this specimen as an adult female and the morphological features indicated by arrows clearly identifies it as *M. orientalis* (Goedknegt et al. 2018).

salinities of 0.01 psu (fresh water), 9.6 psu (1:2 seawater:fresh water mix), 18 psu (2:1 mix), and 28 psu (sea water). Both fresh and sea water were filtered at 0.45 µm. In total, 44 egg sacs of *M. intestinalis* and 20 egg sacs of *M. orientalis* were incubated, and hatching of nauplii was monitored over a period of 14 days. Cumulative hatching was analysed by a Poisson distributed generalized linear mixed model (GLMM) as a function of species affiliation, salinity and their interaction as main effects. Additionally, the model included replicate and day as random intercept effects to account for non-independence of the data. The R statistical environment was used to calculate statistics (R Development Core Team).

Results

In total, 55 mussels were examined for the presence of macro parasites. During the 6 months of exposure at the moorings at Kolberger Heide, average size of mussels increased slightly to 4.90 cm ± 0.35 cm (n = 55). In 2 out of 55 mussels, adult individuals of *Mytilcola* were found (prevalence = 3.6%). No other parasite species could be detected in tissues nor the shells of investigated mussels. In 52 dissected mussels of the second sample from the inner fjord, one *Mytilicola* specimen was found (prevalence = 1.92%).

All parasite specimens were cleaned and stored in 70% ethanol. The morphology of the three specimens clearly identified them as mature females of *M. orientalis.* The identification was based on the extended dorsolateral thoracic protuberances and the non-diverging caudal rami (Figure 2) that represent the best morphological markers and allow species assignment for females with high certainty (Goedknegt et al. 2018). At lengths of 6.77 and 7.69 mm, both females in the first sample as well as the specimen found in the second sample were adults and could potentially reproduce, but carried no egg sacs.

Cumulative larval hatching was significantly higher in *M. orientalis* than in *M. intestinalis* (Estimate = 4.963 ± 0.096, z = 51.59, $p < 0.001$) and increased significantly with salinity (Estimate = 0.165 ± 0.003, z = 47.80,

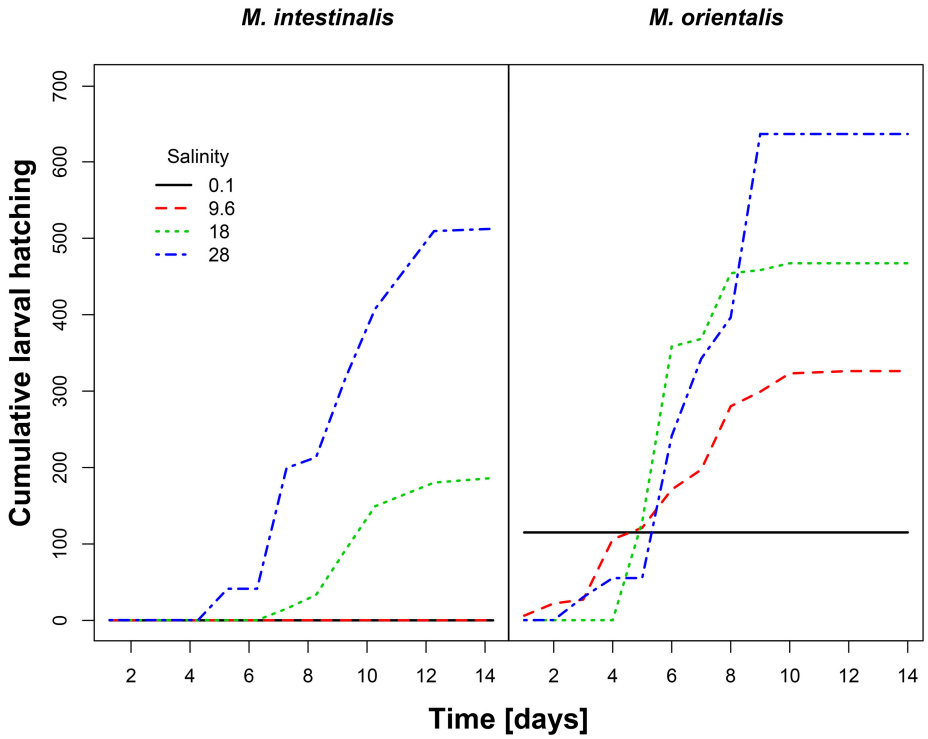

Figure 3. Cumulative hatching of 44 *M. intestinalis* and 20 *M. orientalis* egg sacs incubated at different salinities. Colours show the different salinity treatments. Hatching of *M. orientalis* at salinity 0.1 represents a single egg sac from which 115 larvae hatched on day 1, but none of them were able to moult into the infective copepodite I stage.

$p < 0.001$). However, both species reacted differently to salinity (interaction species × salinity, Estimate = −0.133 ± 0.004, z = −37.07, $p < 0.001$). This difference becomes most obvious with the complete failure of *M. intestinalis* to hatch at salinity 9.6 psu and lower, whereas *M. orientalis* still showed considerable hatching success at 9.6 psu. Even at salinity 0.1 psu, 115 larvae hatched from a single egg sac on day 1 (Figure 3). Larval survival was additionally impaired by low salinities. While nauplii of both species showed 100% survival at a salinity of 28 psu, salinity at 18 psu reduced nauplii survival in *M. intestinalis* to 55% while it did not harm *M. orientalis* (nauplii survival at 18 psu was 100%). However, all *M. orientalis* hatchlings at 9.6 psu failed to moult into copepodite I and died shortly after hatching.

Discussion

The size and stage of the discovered specimen suggest that the first occurrence of *M. orientalis* in the Baltic Sea was a result of an infection in the waters of the Baltic Sea. Due to the cultivation method used at Kieler Meeresfarm, only wild free swimming blue mussel larvae are able to reach and subsequently attach themselves to the artificial substrate of the longline cultivation system. For the transplantation experiment, mussels were brushed from the substrate, measured, and directly put in nylon bags before transferred to Kolberger Heide. Due to the described handling, an infection outside of Baltic waters can definitely be excluded. It only

remains unclear whether the two mussels got infected with *M. orientalis* at the Meeresfarm in Kiel Fjord or later during the exposure study a few miles east in Kiel Bight. Comparing both sites, the mussel farm in Kiel Fjord is the ideal place for any potential transfer of mussel parasites from waters of the North Sea into the Baltic. This is because it is situated close to the Watergate of Kiel Channel where ships using the shortcut between the North and Baltic Seas need about one day to pass the channel. Travel time is short enough for infested North Sea mussels to survive when attached to the hulls of ships, and then release their larvae after the channel passage.

The second sample was collected in the inner Kiel Fjord, which is situated further east from Kiel Channel. While this reduces the absolute number of ships passing, it also shows that infections can occur independent of the aquaculture setting and proximity to major ship traffic.

Only the first copepodite stage is infectious for the mussel during the short and direct development of larvae (Jensen 2010). The time to develop from larvae to mature adults of *M. intestinalis* may take up to several months and is dependent of temperature and food availability at the actual position in the host (Gee and Davey 1986). Since *M. orientalis* develops faster than *M. intestinalis* (Feis et al. 2016), it might be also possible that the infection found in the first sample actually occurred during the exposure experiment at Kolberger Heide (Kiel Bight). Furthermore, the different sizes might suggest that the infection occurred at different time points suggesting that infected mussels are repeatedly introduced into the Kiel Fjord via ship hull fouling.

In Kiel Fjord, larvae of *M. orientalis* are confronted with about half of the salinity range (ca. 15 psu, Casties et al. 2015) of the North Sea. However, the hatching experiment performed here suggests that larvae of *M. orientalis* seem to be more flexible than *M. intestinalis* and can withstand these salinity changes much better (Figure 3). Therefore, it may not be surprising that *M. intestinalis* did not manage to successfully travel through the channel and spawn in Kiel Fjord despite its longer lasting establishment in the North Sea. In contrast, *M. orientalis* only became common in the North Sea in recent decades and could infect *M. edulis* after the introduction of its principle host, *C. gigas*, in the 1990s (Goedknegt et al. 2018). Its broad environmental tolerance probably enabled it to spread to the Baltic Sea in the last 20–30 years.

M. orientalis is sexually dimorphic and with obligatory sexual reproduction (Bolster 1954). This means that both sexes must meet in one host for successful reproduction. Thus, the detection of two mature females without eggs in different mussel individuals only shows that the species is able to survive and to develop under the conditions encountered in the Baltic Sea. It is not a proof that *M. orientalis* has already successfully established as an invasive species in the Baltic Sea. For this, all life stages

including mature males and eggs need to be present to complete the life cycle. However, the increasing prevalence of *M. orientalis* in North Sea mussels (Pogoda et al. 2012; Elsner et al. 2011; KM Wegner, *personal observation*) will certainly increase the number of "ship-travelling" infected mussels in Kiel Channel and will consequently also increase the infestation risk of Baltic blue mussels (*Mytilus* spp.).

Baltic *Mytilus* spp. are hybrids between *M. trossulus* and *M. edulis* to varying degrees (Stuckas et al. 2017). This genetic difference to the *M. edulis* population in the North Sea might impose an invasion barrier, but previous studies have already demonstrated that mussels from the Kiel Fjord are suitable hosts with infection rates reaching up to 50% in controlled infection experiments (Feis et al. 2016). While these experiments were carried out at high salinities, the successful growth to maturity in different areas of the fjord and at different times of the year together with the larval hatching results presented here strongly indicate that the completion of the life cycle should be possible in the Kiel Fjord and might even extend to regions of lower salinity further east in the Baltic Sea.

Future studies using a broader seasonal and geographic sampling design can help to answer the question of whether *M. orientalis* is already reproducing and has thus successfully invaded the western Baltic Sea. Additional experiments investigating the sensitivity of all life stages and life history traits (e.g. egg production) to low salinity could further clarify which life stage transitions and energetic constraints will limit its eastward spread. Yet already the successful hatching and moulting in the laboratory together with infection and growth to adulthood from natural infection in the field shown here clearly demonstrates that the conditions for a successful bio-invasion are met and it is probably only a matter of time when the complete life cycle can be observed in the wild.

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