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RESEARCH PAPER

Chinese mitten crab *Eriocheir sinensis* in the Baltic Sea—a supply-side invader?

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Abstract Although the Chinese mitten crab *Eriocheir sinensis* (H. Milne-Edwards, 1853) (Crustacea, Decapoda, Varunidae) invaded the Baltic Sea about 80 years ago, published information on its present distribution and abundance in this region is lacking. We provide here information on its Baltic-wide distribution and long-term population dynamics. The species has been found all over the coastal Baltic Sea and also in some adjacent rivers and lakes. The Chinese mitten crab appears to have increased in abundance in recent years in the northeastern part of the Baltic Sea (Gulf of Finland, Gulf of Riga, northern Baltic Proper). Higher catch rates were observed in spring (April–June) and autumn (September–November). The size variation of crabs in different samples was low (mean carapace width 6.1–6.3 cm). Despite findings of gravid females, the reproduction of the mitten crab in the central, northern and eastern Baltic region is considered unlikely due to low salinity and the individuals caught are assumed to actively migrate into the region from the species' main European distribution area (southeastern North Sea), certainly over 1500 km migration distance. Thus, the dynamics of the North Sea population is probably regulating, at least in part, the occurrence of the Chinese mitten crab in the Baltic Sea area.

Keywords Baltic Sea basin · Catadromous alien species · Chinese mitten crab · Spatio-temporal distribution · Migration

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Introduction

During the 20th century, over a 100 alien species were recorded in the Baltic Sea (Leppäkoski et al. 2002 and references therein). Many of them have been able to establish self-sustaining populations and several are still expanding their distribution area with increasing abundances. The most impacting invaders include the clam *Mya arenaria* (Linnaeus, 1758), the zebra mussel *Dreissena polymorpha* (Pallas, 1771), the polychaete *Marenzelleria viridis* (Verrill, 1873), the barnacle *Balanus improvisus* (Darwin, 1854) and the predatory cladoceran *Cercopagis pengoi* (Ostroumov, 1892) (Leppäkoski et al. 2002; Zettler et al. 2002; Ojaveer et al. 2004).

A particularly interesting invader in the Baltic Sea is the Chinese mitten crab *Eriocheir sinensis* (H. Milne-Edwards, 1853) (Crustacea, Decapoda, Varunidae). There appear to be few reported cases where an invader's presence in a community relies permanently on its arrival from a distant source; that is, where no reproducing populations occur because of physiological limitations. Here we report on the presence of *E. sinensis* in the Baltic Sea, where it is seasonally common, but where reproduction appears to be impossible.

The origin of *E. sinensis* is Southern China and parts of Korea (Chu et al. 2003). In Europe it was first recorded in the German Aller River in 1912, where it may have been introduced with ships' ballast water discharges (Panning and Peters 1932; Peters et al. 1936; Gollasch 1999). Specimens have been found 900 km upstream the Elbe river (Peters 1933). The crab is well established in western Europe, particularly in the North Sea and its estuaries and adjacent rivers (Peters et al. 1936; Christiansen 1982; Fladung 2000). The species probably spread into the Baltic Sea (i) via the Kiel Canal, (ii) along the Danish coast by passive drift or active migration or (iii) by coastal shipping in, e.g. ballast water tanks, resulting in the first record on the German Baltic coast in 1926 (Boettger 1933; Panning 1938; Herborg et al. 2003). However, it is unlikely that the species is able to attain self-sustaining populations in the central, northern and eastern Baltic Sea. Due to the low salinity the reproduction cycle cannot be completed in these regions (Anger 1991). However, findings of females with eggs in oviducts as well as carrying eggs on pleopods are not unique in the southern Baltic Sea (M. Normant, unpublished data; S. Olenin, personal communications). It is assumed that specimens captured in the Baltic actively migrated into this sea from the North Sea or its rivers (e.g. Peters 1938) or from more haline waters in the western Baltic regions.

Although found in the Baltic Sea for ca. eight decades, comprehensive data on the spatio-temporal distribution of the Chinese mitten crab are scattered. Results of the current study are aimed to fulfil this gap in the basic knowledge by providing information for further assessments for potential ecological impacts of the species in the Baltic Sea and adjacent waterbodies.

Material and methods

Collection of occurrence data

The material has been obtained from different sources. The sources and also methodologies differ by countries and therefore also by sub-basins or parts of the sub-basins of the Baltic Sea.

Historical data on the occurrence of the Chinese mitten crab in the Bothian Sea, Bothnian Bay and along the northern coast of the Gulf of Finland were compiled from the collections of the Finnish Museum of Natural History (FMNH). In addition, recent observations were added by contacting other local museums, fishermen, aquaria and power plants that use cooling water from the sea.

In the Latvian waters of the Baltic Sea (i.e. southern part of the Gulf of Riga and NE part of the Baltic Proper), the Chinese mitten crab findings were obtained from 30 reference fishermen. These are persons who are contracted to the Latvian Fish Resource Agency and have an obligation to submit fishery data. All specimens were caught as by-catch in regular commercial coastal fisheries and summed up by regions (Gulf of Riga and open Baltic) and years.

A special survey of fishermen was conducted by using an illustrated questionnaire/registration form in the eastern Gulf of Finland by Russia in 2003 and 2004. This was aimed at getting information on the distribution but also at the quantification of the catch of the crab.

Qualitative (presence/absence) data on the spatial distribution of the crab were obtained by telephone interviews with commercial fishermen and county-based fishery authorities of the

Ministry of Environment around the whole Estonian coast (southern Gulf of Finland, northeastern Baltic Proper and northern Gulf of Riga). This information was amended with knowledge of fisheries scientists and reference fishermen. The survey was carried out during January–February 2004.

In addition to these original research data, a literature survey was also conducted on the distribution of the species in Lithuanian, Polish and German waters. In addition, the Working Group on Non-indigenous Estuarine and Marine Organisms of the Baltic Marine Biologists (BMB), was contacted for using their knowledge and contacts to national/local specialists to obtain any data available on the Chinese mitten crab. Most of the data (except historical data from Finland) originate from the last decade.

Quantification of the mitten crab findings

The gillnet fishing (net height 1.5–1.8 m, mesh size a = 40–55 mm) was carried out in the shallow coastal area of Muuga Bay at the southern coast of the Gulf of Finland (Fig. 1) since spring 1991. The sampling frequency expressed as the mean number of monthly samplings varied during the whole study period from 8–14 sampling days during the coldest months sampled (March–April, October–December) to 19–22 in the warmest time of the year (June–August).

For each fishing operation that resulted in a catch of *E. sinensis*, the catch-per-unit-effort (CPUE) was calculated according to the formula:

$$\mathrm{CPUE} = C \times L^{-1} \times D^{-1} \tag{1}$$

where CPUE is the catch per unit effort, C the number of crabs in a catch, L the length of the nets (in m) and D is the duration of the catch (in h).

In all years sampling was undertaken from March to December with relatively similar sampling intensity both in terms of number of days fished and number of nets employed. The annual catch index was calculated according to the formula:

$$\mathrm{CI_a} = \sum 10^3 \times \mathrm{CPUE}_i \tag{2}$$

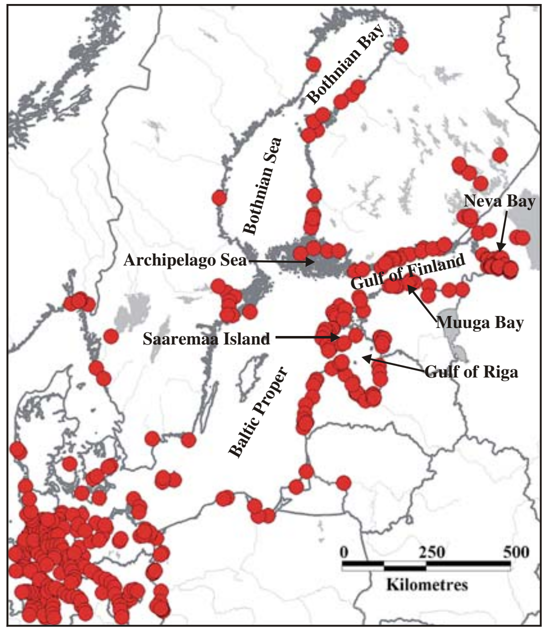

Fig. 1 Spatial distribution (finding locations) of the Chinese mitten crab *Eriocheir sinensis* in the Baltic Sea (dots). In addition to data collected in this study, the following sources were used: Rasmussen (1987), Molin (1995, 1997, and references therein), Jespersen (1998), ICES (1999), Zettler (1999), Jogi (2000), Normant et al. (2000), Tendal (2001), Normant et al. (2002), ICES (2003), Bacevicius (2004), ICES (2004), Czerniejewski and Wawrzyniak (2006), Panov (2006), Ole Secher Tendal (personal communication), and Inger Wallentinus (personal communication)

where $\mathrm{CI_a}$ is the annual catch index and CPUE_i is the monthly total catch per unit effort.

The monthly catch index was calculated as

$$\mathrm{CI_m} = 10^6 \times \mathrm{CPUE}_i \times \mathrm{MN}^{-1} \times \mathrm{MD}^{-1} \tag{3}$$

where $\mathrm{CI_m}$ is the monthly catch index, CPUE_i the monthly total catch per unit effort, MN the monthly mean number of nets used and MD is the monthly mean number of days sampled.

Carapax measurements

The analysed individuals were caught during the period 1933–2004. Carapax width was the only commonly measured parameter in the three regions and is presented for Finnish coastal waters (1933–2004, n = 68), the NE Gulf of Finland

(2003–2004, $n = 22$) and the NE Gulf of Riga (1980–2005, $n = 16$).

Results and discussion

Occurrence in the marine environment

The Chinese mitten crab has been found all over the Baltic Sea (Fig. 1). Based on the available data it can be concluded that the species is less common in north (e.g. the Gulf of Bothnia) than in other parts of the Baltic Sea. The crab is most abundant in the eastern Baltic Proper and the southern Gulf of Riga. This may be explained by the shorter migration distance, which is probably also connected to higher survival of individuals. Also, the colder temperature regime in northern areas may decrease the osmoregulatory capacity of crabs in a low salinity environment, as shown for other decapod species (Charmantier et al. 2001; Lemaire et al. 2002). Correspondingly, the recently recorded higher number of crabs (see temporal dynamics) coincides with positive anomalies both in sea surface and deep water temperatures (Nausch et al. 2003; Feistel et al. 2003), which might reduce the salinity stress experienced in the low-saline Baltic waters.

Information on the quantification of catches is available for several regions and countries of the Baltic Sea for different timeperiods. Since the first record in the northern Gulf of Finland in 1933, altogether 25 crabs were found in the 1930s in an area extending from the Archipelago Sea in the west to Vyborg Bay in the eastern gulf. Since then until the early 2000s, on average 1–2 individuals have been reported annually. However, at least 103 specimens were documented during 2002–2004 with often several individuals caught together. In the Kotka area (northern Gulf of Finland), 32 individuals in 2002 and 22 individuals in 2003 were taken to an aquarium but other individuals delivered by local fishermen were not received (Sari Saukkonen, personal communication). In addition to the counted specimens, there are reports from fishermen in the Quark area of tens locally caught individuals during autumn 2003 but the total number was not documented. Crabs accumulated in the cooling water intakes of power plants, e.g. in the Kotka and Quark areas at clearly higher numbers in 2002–2003 than in previous years. In 2004, the number of records sharply decreased.

Compared to the other parts of the Baltic Sea, the species was relatively recently—first in 1980—recorded in the easternmost Gulf of Finland, close to Neva Bay. The species was found in higher numbers only since 2002 (Panov et al. 2003) with most frequent findings in 2003. In 2004, the number of crabs decreased again. This may, however, have been caused by the decreased fishing effort. In 2003, a total of 58 individuals were found by commercial fishermen, with the majority of records in Neva Bay. Most data originate from two commercial groups of fishermen, one operating inside and the another outside Neva Bay.

In Latvia, systematic reporting on the by-catch of the Chinese mitten crab in commercial fisheries started in 1994. The species occurred mostly (75%) in the gillnet fishery whereas the remaining came from 'fykenet' catches. Since 1995, in total 188 specimens have been reported from different places in coastal waters with most of them found in the Gulf of Riga (136 individuals). Within the basin, the highest abundance was recorded in its southern and western regions. However, the actual by-catch numbers were higher than used in this paper. One reason is that the reporting of some by-caught individuals was not made fully according to the reporting format (e.g. type of fishing gear or fishing location was not shown), and therefore, these data were excluded from the final dataset.

In the region of Saaremaa Island (NE Baltic Proper), the annual crab catch was in the range of 100 individuals in the recent years. The majority of the specimens were caught off the western coast of the island.

According to Swedish reports (ICES 2004), every year single specimens of the crab were caught by Swedish fishermen, but no mass occurrence of the species was reported.

Occurrence in the freshwater environment

The species has been found in several freshwater bodies in the Baltic Sea countries, such as for instance the Saimaa Lake District, Vuoksa River, Odra River, Daugava River, Lielupe River, Lake Ladoga, Lake Vänern and Lake Mälaren (Fig. 1).

Between the first observation in 1932 and 1937 altogether 10 individuals of the species were caught in Latvian freshwater bodies, in the lakes around Liepaja city and lower reaches of the Daugava and Lielupe rivers. In addition, the species has been found more recently in the Bullupe River near Riga and in Engure Lake (Janis Birzaks, personal communication; Maris Vitinsh, personal communication). During the early 1990s, the species was relatively rare in the Daugavgrivas area (Daugava River). However, occurrence of the crab in fishing gear has substantially increased in this area very recently (evidences from 2005) by reaching up to 10 specimens per trapnet per year. Therefore, the Chinese mitten crab is a very frequent guest or even inhabitant in the freswater system near Riga presently.

The first specimen was recorded in Finnish inland waters in 1999 (Valovirta and Eronen 2000). About 10 records have been altogether reported, most of them coinciding with the invasion in coastal waters in the 2000s. All records have been made in the Saimaa Lake District. This lake area, consisting of thousands of lakes and covering 10,640 km^2, is connected to the eastern Gulf of Finland via a 43 km canal that is used for intensive shipping. The fact that there are no records from other lake areas indicates that either shipping or active crab migration via the canal is a likely vector for the crab introductions in Saimaa. The main shipping connections from the inland ports in the Saimaa area are to the Gulf of Finland but also to southern Baltic and North Sea ports (Pienimäki and Leppäkoski 2004).

In the southern and eastern coasts of the Gulf of Finland, the crab was registered only in three areas with altogether four records: small Modriku water reservoir in 2000 (Jogi 2000), Vuoksa River in 1997 and 2003 and Lake Ladoga in 2005 (Panov 2006).

Temporal dynamics

Two independent continuous data series are available and allow for a long-term quantitative estimation of the dynamics of the species. Both data series originate from the NE Baltic Sea: Muuga Bay (Gulf of Finland) and Latvian coastal waters of the Gulf of Riga and Baltic Proper.

In the Gulf of Finland, the catch index was substantially higher in 2002–2004 compared to previous years (1991–2001, Fig. 2a). Since 1995 a gradual increase in the by-catch of the Chinese mitten crab in commercial fishery was reported both in the Baltic Proper and the Gulf of Riga. The increase was highest in shallow waters of the Gulf of Riga (Fig. 2b).

There are additional anecdotal evidences that support the conclusions above. Namely, fishermen near Göteborg (Kattegat area) have claimed that crab records have recently increased (ICES 2004). The same is apparent also from the Finnish records that document substantially more crab findings in 2002–2003 than ever before.

The species displayed a very similar seasonal activity pattern in two regions (Muuga Bay in the Gulf of Finland and Latvian waters). The crabs were most active and caught by fishing gear during spring from March until June and in autumn from September to November. In the eastern Gulf of Finland, the by-catch of the crab strongly

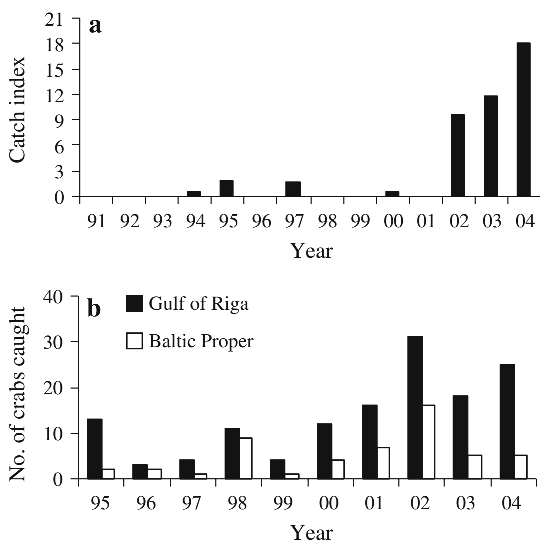

Fig. 2 Annual dynamics of the catch index of the Chinese mitten crab *Eriocheir sinensis* in gillnet fishing in the Gulf of Finland during March–December 1991–2003 (**a**) and the by-catch of the species in commercial fisheries in the Gulf of Riga and NE Baltic Proper during 1995–2004 (**b**)

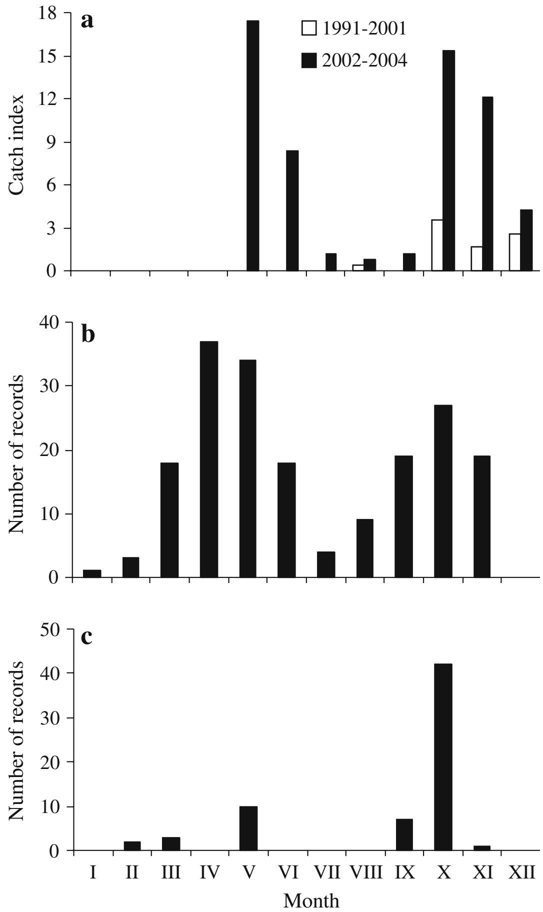

Fig. 3 Monthly dynamics of the catch index of the Chinese mitten crab *Eriocheir sinensis* based on the (**a**) gillnet fishing in the Gulf of Finland during March–December 1991–2003, (**b**) by-catch of the species in commercial fisheries in the Gulf of Riga and NE Baltic Proper during 1995–2004, and (**c**) by-catch of the species in commercial fisheries in the eastern Gulf of Finland in 2003

peaked in October (Fig. 3). The reason why the spring peak occurred earlier in southern regions than in the northern sampling sites is most likely the longer duration of the ice-cover in the latter area, which postpones the fishing season compared to the more southerly regions. As the crab cannot reproduce in the area, this time-lag may also be caused by the longer migration distance from reproduction sites to northern sampling sites.

Both the distribution pattern (small number of records in northern parts) and increasing tendency of occurrence and abundance of *E. sinensis* observed over the last decade might be related to climate variability in the Baltic Sea. This period can be characterised by an increase in the surface water temperature and relatively mild winters (Janas in press; HELCOM 2002). This probably has created more favourable conditions for species preferring warmer water to colonise the northern and eastern Baltic Sea, particularily as higher temperatures are beneficial in regard to osmoregulation ability (Charmantier et al. 2001). For instance, it has been reported that colonisation of cold waters by decapod crustaceans is limited synergistically by low temperature and high haemolymph magnesium concentration (Frederich et al. 2000).

Size distribution and sex ratio

In the Finnish material males and females were represented in almost equal quantities (sex ratio 1.1:1, respectively) with the overall mean carapax width of 6.2 cm (± 0.1 s.e., range 3.8–8.2 cm). Data from the NE Gulf of Riga show a very similar pattern: sex ratio 1:1, carapax width 6.3 ± 0.1, range 5.9–7.4 cm. Crabs investigated in the eastern Gulf of Finland exhibit a substantially different sex ratio than above (males:females 2.4:1), but a very similar size (carapax width 6.1 ± 0.2, range 3.5–7.2 cm).

Migration and reproduction

Most of the Baltic Sea can be considered as a migration area for the species as the crab is unable to reproduce in low salinity conditions (Peters 1938; Anger 1991). The migration distance of the crab from the nearest reproduction ground (Elbe River estuary) via the Kiel Canal to the most distant finding location in the northern Baltic Sea certainly exceeds 1,500 km. This is substantially more than the recorded maximum upstream migration distance of the crab in the Elbe River. Crabs are capable of moving several kilometres daily (Herborg et al. 2003). The crab may potentially also reproduce in the Kattegat/Skagerrak region, which should offer suitable conditions for reproduction and therefore may act as a donor area for crabs found in the central, eastern and northern Baltic Sea. However, there is no substantial number of crab findings from this region. Therefore, based on the current evidence, we assume that the Elbe River estuary is the main source for the Baltic population.

There are three potential scenarios for the Chinese mitten crab in the eastern Baltic Sea: (i) mitten crabs migrate to the SE North Sea to reproduce, (ii) mitten crabs die without reproduction, or (iii) mitten crabs are able to reproduce at lower salinities.

The first hypothesis is based on the laboratory studies, which showed that the tolerance of the larvae of *E. sinensis* from the North Sea toward very low salinity was weak, except in the first zoeal stage and in the Megalopa (Montú et al. 1996). According to Anger (1990), the salt concentration required to the complete larval development is around 20 ppt due to the low osmoregulatory capacity of larval stages (Panning 1952). However, under unfavourable environmental conditions (e.g. combination of low salinity and temperature) extra stages might occur in *E. sinensis*. This phenomenon is unique among brachyuran crabs (Montú et al. 1996). Concerning migration, the breeding grounds are located sometimes more than a thousand kilometres from the place of occurrence, i.e. the energetic cost of such a migration would be high, but other crab species are known to undertake such long migrations. Compared to the migration of adult *E. sinensis* to the southwest, perhaps it is even more important to note the migration of juveniles to the northeast of the Baltic Sea region as far as the northernmost Bothnian Bay, easternmost Gulf of Finland and freshwater habitats in Lake Ladoga.

The second possibility is supported by the fact that eggs may be laid by female *E. sinensis* even at a salinity below 10 ppt indicating that the copulation takes place also in brackish waters (Peters and Panning 1933). This option is reflected in findings of several females with eggs in oviducts as well as carrying eggs in Polish and Lithuanian waters, at salinities of 7–8 ppt (Normant et al. 2002; M. Normant, personal communication; S. Olenin, personal communication). Their presence is a good indicator for reproductive activity as the egg release occurs within 24 h of mating in *E. sinensis* (Herborg et al. 2006). It is well known that egg-carrying females are less mobile (Panning 1938) and therefore it is questionable that they undertake long migrations.

The third option is based on the fact that many organisms are able to adapt to a new environment. Environmental adaptation might be a short-term (e.g. in extreme environments) or a long-term process integrating all aspects of animal biology, such as behaviour, morphology, biochemistry or physiology (Willmer et al. 2000). Studies of different populations of the same crustacean species have shown that within-species differences exist, and that these could allow individuals of such ''physiological races'' to invade a habitat quite different in salinity (or ion) from that of other populations (Harris and Aladin 1997). One of the examples is the shore crab *Carcinus maenas*. The population from the western Baltic Sea (15 ppt) exhibits a higher capacity of hyper-regulation than crabs from the North Sea (30 ppt) (Theede, 1969). Similarly to *E. sinensis*, it is still unknown whether the population of *C. maenas* in the western Baltic Sea is capable of reproduction (Cieluch et al. 2004). It could be assumed that after more than 70 years since the first appearance in the Baltic Sea the larval stages of *E. sinensis* could be able to cope with lower salinities. However, there seems to be no published data on larval stages in zooplankton field studies. To conclude, only detailed studies on crab migration routes, the occurrence of crustacean larval stages, especially in the Baltic Proper, and investigations of the physiology of the mitten crab would help to clarify all the scenarios above.

Ecological significance

The recent increase in crab abundance poses an additional risk of both structural and functional changes in the Baltic Sea ecosystems, especially in its benthic communities. This is especially important in the coastal areas as several other demersal non-indigenous species such as the round goby *Neogobius melanostomus*, the polychaete *Marenzelleria viridis*, the gammarid *Gammarus tigrinus* and the zebra mussel *Dreissena polymorpha* occur in high densities in these areas and have exhibited increased abundance values and expanded distribution areas recently, in the late 1990s–early 2000s (Borowski 2000;

Kotta 2000; Zettler et al. 2002; Antsulevitch et al. 2003; Panov et al. 2003; Kotta et al. 2006).

The Chinese mitten crab is omnivorous and feeds on a wide variety of benthic invertebrates (Panning and Peters 1932; Anger 1990). Prior to the invasion of *E. sinensis* such functional type (large, jawed, mobile, facultative carnivore) was absent in the central and northeastern Baltic Sea. Concurrent with the increase in their density *E. sinensis* may pose a significant predation pressure on the native invertebrate communities. Nevertheless, as we lack quantitative abundance data and information on feeding habits and feeding rates of the crab, it is currently difficult to evaluate the impact of *E. sinensis* on benthic invertebrates. However, a direct positive impact of increased crab abundance on (commercial) fish stocks is unlikely as there are no large predatory fishes currently abundantly present in the northern Baltic Sea.

Another interesting aspect of the Chinese mitten crab in the Baltic Sea is the role that the species plays as a habitat for other invertebrate species. The massive carapax of *E. sinensis* presents a substratum for sessile flora and fauna, such as algae or barnacles. Moreover, the dense patches of hair on the claws might offer a habitat for small organisms belonging to different taxonomic groups, like Nematoda, Bivalvia, Crustacea, Oligochaeta and Gastropoda (Normant et al. in press). As a result, *E. sinensis* is able to transfer both native and non-native species to new habitats.

The rapid increase in the population abundance of *E. sinensis* in the San Francisco Estuary after the invasion in 1992 with associated ecological and economic impacts and the need for better management and control initiated the construction of a conceptual life history model. It appeared that environmental parameters play a strong role in governing both the timing of the life cycle but also of population dynamics of the species (Rudnick et al. 2005). When more detailed information becomes available for the Chinese mitten crab in the Baltic Sea (e.g. age structure) the model may be used as a valuable tool for better understanding (and prediction) of the population dynamics of *E. sinensis* also in the Baltic Sea.

We strongly suggest that there is an urgent need for the development of a systematic monitoring programme of selected non-native species in the entire Baltic Sea. Such monitoring should cover quantitative population characteristics. Our knowledge on 'recent aliens' is often comparatively more advanced (thanks to the existence of comparative pre- and post-invasion datasets) than for 'old aliens'. Basic population characteristics for the 'old aliens', which have been present in the Baltic Sea for decades (like the Chinese mitten crab, the barnacle *Balanus improvisus* and the hydroid *Cordylophora caspia*), are often poorly known. Very often, the 'old aliens' dominate invertebrate communities and therefore they may have essentially changed the abiotic habitat parameters, community structure and biotic interactions in recipient systems, compared to the pre-invasion time (e.g. Olenin and Leppäkoski 1999).

Future challenges

To conclude, four major questions need to be addressed in further studies. First, what is the role of the species in the Baltic ecosystems as a predator, prey, host or some other disturbing agent, in relation to its present abundance? Second, given the currently believed 'supply-side' dynamics of the occurrence of the Chinese mitten crab in the Baltic basin, the question is whether an understanding of the population dynamics of the crab in the North Sea, combined with knowledge of regional oceanographic processes, would permit accurate prediction of the population sizes of the crab in the Baltic Sea? Third, is *E. sinensis* actually able to reproduce at lower salinities than currently known and documented? And fourthly, are the interactions between water temperature, salinity and physiological key processes (osmoregulation) of *E. sinensis* important for its future invasiveness and success within the invaded communities? Resolving some of these issues may need tagging experiments, detailed physiological studies and molecular genetic approaches.

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