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Invasive species in the Baltic Sea and their impact on commercial fish stocks

European Maritime, Aquaculture and Fisheries Fund (EMFAF)

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Invasive species in the Baltic Sea and their impact on commercial fish stocks

Final Report

CINEA/EMFAF/2021/3.1.4/Lot1/03/SC12

Implementing FWC EASME/EMFF/2018/1.3.2.3/011-Lot1

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LIST OF ABBREVIATIONS

Term	Description
BSAP	Baltic Sea Action Plan
CFP	Common Fisheries Policy
CINEA	European Climate, Infrastructure and Environment Executive Agency
CMO	Common Market Organisation
CPL	Consortium Project Leader
EC	European Commission
eDNA	Environmental DNA
EMFAF	European Maritime, Fisheries and Aquaculture Fund
HELCOM	The Baltic Marine Environment Protection Commission (Helsinki Commission)
ICES	International Council for the Exploration of the Sea
MSFD	Marine Strategy Framework Directive
NIS	Non-indigenous species
OSPAR	The Convention for the Protection of the Marine Environment of the North-East Atlantic (Oslo Paris Commission)
PSU	Practical Salinity Unit
SC	Specific Contract
SCL	Specific Contract Leader

ABSTRACT

The brackish, semi-enclosed Baltic Sea is especially vulnerable to the possible negative impacts of invasive species. Here, we examine the effects on commercial fish stocks of four species established in the larger areas of the Baltic Sea. The round goby, established in all major basins of the Baltic Sea, has become an important prey for many predatory fish and birds, but it can also compete successfully with native fish for prey. Records of round goby feeding directly on commercial fish species are rare. The sea walnut, a ctenophore jellyfish, has invaded the southern part of the Baltic Sea, where it preys heavily on zooplankton, thereby potentially outcompeting planktivorous fish such as herring and sprat. Initial concerns that the sea walnut may prey on fish egg and larvae were put to rest after studies showed no such effects. The mud crab has become a stable component of benthic communities in most of the Baltic Sea. No negative effects of this invader have been reported; however, mud crabs have become an important prey for benthic fish in many areas. The fishhook water flea, a small planktonic crustacean, has invaded the Central Baltic Sea, and its role has become double-edged, in that it contributes significantly to the diet of herring, sprat and smelt in the Baltic Sea, while also competing with these other fish species for zooplankton as prey.

ABSTRAKT

Słonawe, półzamknięte Morze Bałtyckie jest szczególnie podatne na możliwe negatywne oddziaływanie gatunków inwazyjnych. W tym raporcie zbadano wpływ jaki na stada ryb eksploatowanych komercyjnie mają cztery gatunki inwazyjne, zamieszkujące większe obszary Morza Bałtyckiego. Babka krągła, występująca we wszystkich głównych basenach Morza Bałtyckiego, stała się ważną ofiarą wielu drapieżnych ryb i ptaków, ale może również skutecznie konkurować o pokarm z rodzimymi rybami. Wzmianki o żerowaniu babki krągłej bezpośrednio na komercyjnych gatunkach ryb są nieliczne. Orzech morski, reprezentujący Ctenophora, dokonał inwazji w południowej części Morza Bałtyckiego, gdzie intensywnie żeruje na zooplanktonie, potencjalnie konkurując z rybami planktonożernymi, takimi jak śledź i szprot. Początkowe obawy, że orzech morski może żerować na ikrze i larwach ryb, zostały rozwiane, gdyż badania nie wykazały takich skutków. Krabik amerykański stał się stałym składnikiem zbiorowisk bentosowych w większości obszaru Morza Bałtyckiego. Nie odnotowano żadnych negatywnych skutków oddziaływania tego gatunku; jednakże krabik amerykański stał się ważnym składnikiem pokarmu ryb demersalnych na wielu obszarach. Wioślarka kaspijska, mały skorupiak planktonowy, dokonała inwazji na środkowym Bałtyku, a jej rola stała się niejednoznaczna, ponieważ w znacznym stopniu stała się składnikiem diety śledzia, szprota i stynki w Morzu Bałtyckim, jednocześnie konkurując z innymi gatunkami zooplanktonu, które są pokarmem ryb.

EXECUTIVE SUMMARY

The brackish semi-enclosed Baltic Sea is especially vulnerable to the negative impacts of invasive non-indigenous species (NIS). Biodiversity, number of species and levels of ecological niches are generally low, making alterations in any part of the ecosystem particularly disruptive. Climate change is altering living conditions in the Baltic Sea, which is warming at a rate of 0.6°C per decade. This warming gives invasive species from lower latitudes a physiological advantage over native species. Moreover, the Baltic Sea is surrounded by nine industrialised countries. All these pressures increase the vulnerability of the Baltic Sea, making it particularly prone to invasions by NIS.

A total of 615 separate invasion events of 225 NIS and cryptogenic[1] species has been recorded since the 1800s in the Baltic Sea. This report focusses on four of the main NIS in the Baltic Sea: the round goby, the sea walnut (a ctenophore jellyfish), the mud crab and the fishhook water flea (a planktonic crustacean).

Round goby

The round goby (*Neogobius melanostomus*)

Biology: Round goby (*Neogobius melanostomus*) is a bottom-dwelling fish native to the Ponto-Caspian region. It is an invasive species in the North American Great Lakes, several European inland waterbodies and throughout the Baltic Sea. Normal length 10-25 cm.

Ecosystem effects: Round goby has both positive and negative ecological impacts on ecosystems. The species is an important prey for predatory fish and birds but can also compete with native fish species. Where it exists in high numbers, the round goby may change the dynamics of the ecosystem.

Invasion: Round goby was first detected in the Baltic Sea in 1990 in the Bay of Gdańsk in Poland. Since then, it has become abundant in most coastal areas around the Baltic Sea, with the exceptions of the northern parts of the Bothnian Sea and in the more saline areas of Kattegat and Skagerrak, where round goby is more scarcely distributed. The main vector of introduction is most probably ship traffic. Round goby larvae, which are pelagic, can easily be transported in ballast water of vessels. Ballast water is pumped

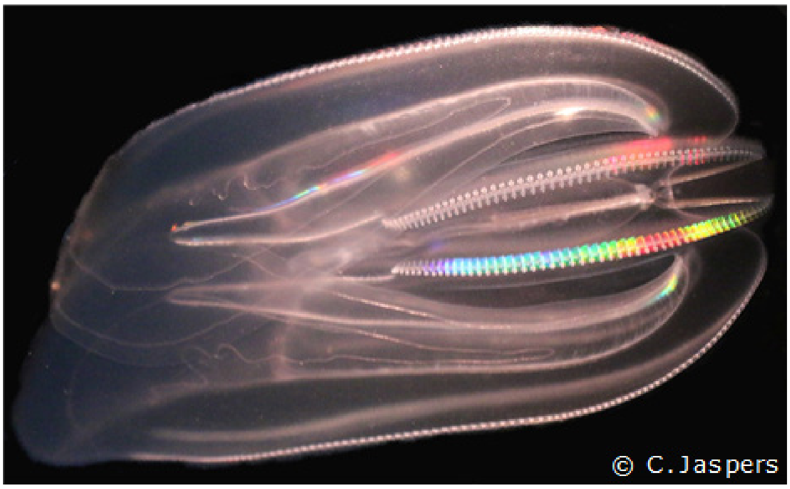
[1] A cryptogenic species may be either a native species or an introduced species, clear evidence for either origin being absent

into empty cargo tanks when not used to increase stability and manoeuvrability, and it is then emptied into the environment when new cargo is taken aboard.

Effects on commercial fish stocks: Although records of round goby feeding directly on adult commercial fish species are rare, it has been observed to feed on the eggs of herring (*Clupea harengus*) and the larvae of flounder, cod, pike, pikeperch, perch, sprat and salmonid species. Some evidence suggests that round goby also has indirect effects on stocks of turbot and flounder along the Latvian coast; due to a significant overlap in diets of the three species, it is suggested that round goby may compete with these native species for prey.

Recommendations: Regular monitoring to estimate round goby abundance is necessary to assess its region-specific impacts. We therefore recommend the development and establishment of regular monitoring programmes for round goby, taking into account seasonal migration patterns into deeper waters. Eradication of round goby in the Baltic Sea is not possible. Rather, a strategy to bring the population below levels of significant ecosystem impacts should be devised. Round goby is fished commercially (mostly in Latvia); such fishery could form part of such a strategy.

The sea walnut



Sea walnut (*Mnemiopsis leidyi*)

Biology: The sea walnut (*Mnemiopsis leidyi)* is a ctenophore jellyfish native to the east coast of the Americas. It is characterised by high growth rates and a large reproductive capacity feeding primarily on zooplankton, such as copepods. It is omnivorous, feeding on both macroalgae and small bottom-living invertebrates. Normal length up to 10 cm.

Invasion: The sea walnut was first sighted in the early 1980s in the Black Sea and has subsequently spread throughout Southwestern Eurasia. In Northern Europe, the sea walnut was first officially confirmed in 2005 from different regions around the extended North Sea area where it was introduced, probably via ballast water from the coast of the Northeast United States. In the Baltic Sea, the sea walnut is distributed from the Danish straits to the Bornholm Basin. It is confined to this area since reproduction ceases at low salinities, and its presence depends to a certain extent on the influx of new larvae from the North Sea.

Effects on commercial fish stocks: Since the sea walnut is a planktonic filter feeder, and due to its significant abundance, concern was raised early on that it may be able to prey significantly on eggs or larvae of cod, herring or sprat. However, lab studies showed no such predation; in addition, due to spatial and temporal mismatch of the main peaks of abundance of sea walnuts and eggs or larvae of both cod, herring and sprat, there is probably little predation on the eggs or larvae of these fishes by the jellyfish. However, in areas where the sea walnut is very abundant, heavy predation control on the zooplankton has been documented. The sea walnut may therefore constitute an important competitor for zooplankton prey to planktivorous larvae of cod, and both larval, juvenile and adult herring and sprat.

Recommendations: So far, regular monitoring to estimate its abundances is limited to the BITS survey and local research projects. We therefore recommend the development and establishment of a regular monitoring programme, taking into account seasonal distribution patterns and the confinement of the distribution range to the Southern Baltic Sea. If possible, this programme should be synchronised with any monitoring in the Kattegat/Skagerrak, since these waters are the origin of the influx of the species. We also suggest monitoring for larvae in the remainder of the Baltic Sea to be able to detect possible further spread northwards. Because it is a planktonic species, control, much less eradication, of the sea walnut population is not possible by any means.

The mud crab

Mud crab (*Rhithropanopeus harrisii*)

Biology: The Harris mud crab (*Rhithropanopeus harrisii)* (Gould, 1841) (Crustacea: Brachyura: Xanthidae) is native to the Atlantic coast of North America. The species is omnivorous, able to tolerate a wide range of temperatures and salinities and very opportunistic in terms of choice of habitat. Harris mud crab has a high reproductive capacity and a long planktonic larval period. These abilities have likely facilitated its spread to two oceans, over 28 countries, 10 seas and 10 freshwater inland reservoirs. Length up to 25 mm.

Invasion: After the invasion of the mud crab into the Baltic Sea in 1936, its distribution was limited to the southern and southeastern area. The most recent introductions of the mud crab in the Baltic Sea occurred in Finland (2009), Estonia (2011) and Sweden (2014) probably through ship ballast water transport of larvae. Mud crab is found throughout the Baltic Sea, but larval hatching is not possible in salinities below 5 PSU (practical salinity unit, somewhat equivalent to promille), and its reproduction in the Baltic Sea is constrained by salinities below 4 PSU. Thus, mud crab is found only in the southern and central parts of the Baltic Sea, where it is recorded at depths from 0 to 20 m.

Effects on commercial fish stocks: The mud crab influences the food web, and it has direct effects on local fish as a new source of prey for these fish. It can exert high grazing pressures on eelgrass and macroalgae such as bladderwrack and thus may affect bottom communities in areas where it exists in high numbers. Most importantly, it may change nearshore nursery grounds for many fish species by decreasing the abundances of important invertebrate fish prey such as amphipods.

Recommendations: Routine biological monitoring in the Baltic Sea does not include monitoring coastal mobile fauna. The most commonly used method to collect mud crabs is with habitat collectors, i.e. cages filled with bivalve or oyster shells or ornamental stones, in which the crabs may enter and leave the trap during the deployment period. This method is presently used in HELCOM/OSPAR port surveys, and habitat collectors have also been included in new method guidelines in the HELCOM NIS monitoring programme. We recommend developing this method for all applicable regions. Eradication of the mud crab in invaded areas is impossible. It may be possible to lessen the ecological impact of the crab in specific local (enclosed) areas by physical removal, but this method is labour intensive.

The fishhook water flea

Fishhook water flea (*Cercopagis pengoi*)

Biology: The fishhook water flea (*Cercopagis pengoi*) is a planktonic crustacean (cladoceran) native to the Ponto-Aralo-Caspian basin. It is a generalist predator capable of feeding on a variety of prey such as planktonic copepods and cladocerans, but it is also an important prey itself for planktivorous fish and predatory zooplankton such as mysids. The species' length varies from 1 to 3 mm without tails and from 6 to 13 mm with tails. The fishhook water flea reproduces asexually during the summer and sexually during undesirable conditions. Sexual reproduction can lead to production of over-wintering or resting eggs that are resistant to freezing, ingestion by predators and desiccation.

Invasion: The fishhook water flea most probably arrived in the Baltic Sea with ships from its native area, the Ponto-Caspian region. Since it first invaded the Baltic Sea in the 1990s, it has become a prominent member of the zooplankton community in the Baltic proper and Gulf of Finland. It is present from July to October, but most abundant in August and September, which is the same time of year as the period when biomasses of other zooplankton naturally decline.

Effects on commercial fish stocks: The fishhook water flea contributes significantly to the diet of herring, sprat and smelt in the Baltic Sea. At the same time, since it depends on the same zooplankton prey as planktivorous fish, it can be an important competitor for prey to herring, sprat and smelt. Thus, abundances of the copepod *Eurytemora affinis*, an important prey for herring, sprat and smelt, have declined by 90% since the invasion. These changes were particularly conspicuous at higher temperature (>15 °C), which may indicate that the effects of the fishhook water flea on the prey of herring, sprat and smelt may be accentuated in a future world afflicted by climate change. By way of its special morphology (its long hook) the fishhook water flea can also influence the efficiency of fisheries when thousands of individuals become entangled and thus forming a paste like substance which gets caught on fishing lines and in nets. This is estimated to infer significant economic loss to fish farms and fishers.

Recommendations: Since 1979, the HELCOM monitoring programme has included mesozooplankton sampling. Mesozooplankton sampling is conducted between two and twelve times a year, depending on the sub-basin and country, and summertime is included in the sampling scheme in the whole Baltic Sea. The fishhook water flea is included in this monitoring, and we conclude that fishhook water flea monitoring is currently well conducted in all of the Baltic Sea. The fishhook water flea cannot be eradicated in the Baltic Sea, and there are no means for minimising its population size or impact.

STRESZCZENIE WYKONAWCZE

Słonawe, półzamknięte Morze Bałtyckie jest szczególnie narażona na negatywne skutki inwazyjnych gatunków obce / nierodzimych (IGO). Różnorodność biologiczna, liczba gatunków i poziom nisz ekologicznych są generalnie niskie, co sprawia, że zmiany w dowolnej części ekosystemu są szczególnie niszczące. Zmiana klimatu modyfikuje warunki życia w Morzu Bałtyckim, które ociepla się w tempie 0,6°C na dekadę. To ocieplenie daje gatunkom inwazyjnym z niższych szerokości geograficznych przewagę fizjologiczną nad gatunkami rodzimymi. Ponadto Morze Bałtyckie otoczone jest przez dziewięć uprzemysłowionych krajów. Wszystkie te presje zwiększają wrażliwość Morza Bałtyckiego, czyniąc je szczególnie podatnym na inwazje IGO.

Łącznie odnotowano 615 niezależnych przypadków inwazji 225 gatunków IGO i gatunków kryptycznych[1] w Morzu Bałtyckim od lat 1800. Ten raport skupia się na czterech głównych IGO w Morzu Bałtyckim: babka krągła, orzech morski (reprezentujący Ctenophora), krabik amerykański i wioślarka kaspijska (skorupiak planktonowy).

Babka krągła

Babka krągła (*Neogobius melanostomus*)

Biologia: Babka krągła (*Neogobius melanostomus*) jest rybą przydenną pochodzącą z rejonu Ponto-Kaspijskiego. Jest to gatunek inwazyjny w Wielkich Jeziorach Ameryki Północnej, w kilku przypadkach w wodach śródlądowych Europy oraz w Morzu Bałtyckim. Normalna długość to 10-25 cm.

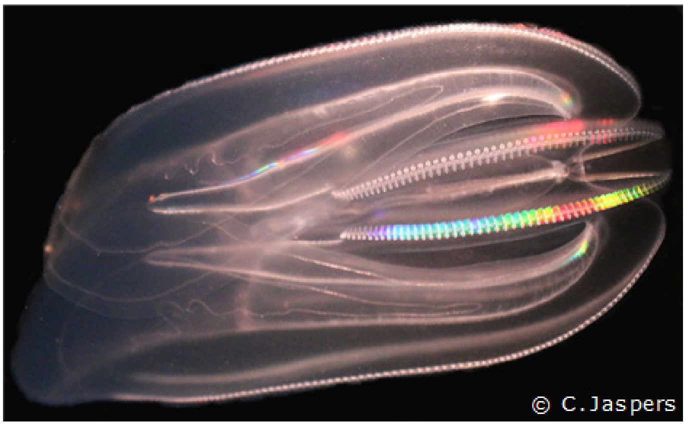
Wpływ na ekosystem: Babka kragła ma zarówno pozytywny jak i negatywny ekologiczny wpływ na ecosystem. Ten gatunek jest ważną ofiarą dla drapieżnych ryb i ptaków, ale może również konkurować z rodzimymi gatunkami ryb. W rejonach gdzie występuje licznie, babka krągła może zmienić dynamikę ekosystemu.

Inwazja: Babka krągła została po raz pierwszy zaobserwowana w Morzu Bałtyckim w 1990r w Zatoce Gdańskiej w Polsce. Od tego czasu stała się powszechna w większości przybrzeżnych rejonów wokół Morza Bałtyckiego, z wyjątkiem północnych części Morza Botnickiego oraz bardziej zasolonych rejonów Kattegat i Skagerrak, gdzie babka krągła jest słabiej rozpowszechniona. Głównym wektorem dystrybucji jest najprawdopodobniej przemieszczanie się statków. Larwy babki krągłej, które są pelagiczne, mogą być w łatwy sposób transportowane wraz z wodami balastowymi statków. Wody balastowe są wpompowywane do pustych zbiorników ładowni, gdy nie jest ona wykorzystywana, w celu zwiększenia stabilności i zwrotności, a następnie wody są wypompowywane do środowiska gdy ładunek jest zabierany na statek.

Wpływ na stada ryb eksploatowanych komercyjnie: Pomimo, że przypadki żerowania babki krągłej bezpośrednio na dorosłych osobnikach ryb istotnych komercyjnie są nieliczne, obserwowano odżywianie się ikrą śledzia (*Clupea harengus*) oraz larwami storni, dorsza, szczupaka, sandacza, okonia, szprota i ryb łososiowatych. Niektóre doniesienia dowodzą, że babka krągła ma również pośredni wpływ na stada turbota i storni wzdłuż łotewskiego wybrzeża; w związku ze znaczącym pokrywaniem się preferencji pokarmowych tych trzech gatunków, co sugeruje, że babka krągła może konkurować z tymi gatunkami rodzimymi o pokarm.

Rekomendacje: Regularny monitoring występowania babki krągłej jest konieczny w celu określenia jej wpływu, specyficznego dla danego rejonu. Zatem zalecamy stworzenie i ustanowienie programu regularnego monitoringu babki krągłej, który uwzględniałby sezonową migrację do głębszych wód. Likwidacja babki krągłej w Morzu Bałtyckim nie jest możliwa. Należy raczej opracować strategię mającą na celu sprowadzenie populacji poniżej poziomu znaczącego wpływu na ecosystem. Babka krągła jest poławiana komercyjnie (głównie na Łotwie); tego typu rybołówstwo mogłoby stanowić część wspomnianej strategii.

Orzech morski



Orzech morski (*Mnemiopsis leidyi*)

Biologia: orzech morski (*Mnemiopsis leidyi)* to przedstawiciel Ctenophora rodzimy dla wschodnich wybrzeży Ameryki. Charakteryzuje się dużym tempem wzrostu i dużymi zdolnościami reprodukcyjnymi, odżywia się głównie zooplanktonem, takim jak widłonogi. Jest wszystkożerny, żywi się zarówno makroglonami, jak i małymi bezkręgowcami żyjącymi na dnie. Normalna długość do 10 cm.

Inwazja: Orzech morski został po raz pierwszy zaobserwowany na początku lat 80. XX wieku w Morzu Czarnym, a następnie rozprzestrzenił się w południowo-zachodniej Eurazji. W Europie Północnej orzech morski został po raz pierwszy oficjalnie potwierdzony w 2005 r. w różnych regionach obszaru Morza Północnego, dokąd został wprowadzony, prawdopodobnie poprzez wody balastowe z wybrzeży północno-wschodnich Stanów Zjednoczonych. W Morzu Bałtyckim orzech morski rozprzestrzeniał się od Cieśnin Duńskich do Basenu Bornholmskiego. Jest on ograniczony do tego obszaru, gdyż rozmnażanie nie jest możliwe przy niskim zasoleniu, a jego obecność jest w pewnym stopniu uzależniona od napływu nowych larw z Morza Północnego.

Wpływ na stada ryb eksploatowanych komercyjnie: Ponieważ orzech morski jest filtratorem planktonożercą i występował w znaczących ilościach, początkowo obawiano się, że może być zdolny w znaczącym stopniu żerować na ikrze i larwach dorsza, śledzia i szprota. Jednakże badania laboratoryjne nie potwierdziły takiego drapieżnictwa; dodatkowo w związku z brakiem regularności czasowej i przestrzennej w pojawianiu się szczytów występowania orzecha morskiego względem występowania ikry i larw dorszy, śledzi i szprotów, prawdopodobnie żerowanie na ikrze i larwach tych gatunków ryb odbywa się w niewielkim stopniu. Niemniej jednak w rejonach, gdzie orzech morski występuje licznie, udokumentowano intensywną kontrolę zooplanktonu przez tego drapieżnika. Orzech morski może zatem być istotnym konkurentem w kwestii żerowania na zooplanktonie dla planktonożernych larw dorsza oraz larwalnych, młodocianych i dorosłych stadiów śledzi i szprotów.

Rekomendacje: Dotychczas regularny monitoring w celu oszacowania jego liczebności ograniczał się do rejsów BITS i lokalnych projektów badawczych. Zatem zalecamy stworzenie i ustanowienie programu regularnego monitoring, uwzględniającego sezonowe rozmieszczenie oraz ograniczenie zasięgu występowania do południowego Morza Bałtyckiego. O ile to możliwe, program ten powinien być zsynchronizowany z każdym monitoringiem prowadzonym w Kattegat/Skagerrak, ponieważ wody te są źródłem napływu tego gatunku. Sugerujemy również monitorowanie występowania larw w pozostałej części Morza Bałtyckiego, co umożliwiłoby wykrycie ewentualnego dalszego rozprzestrzeniania się gatunku w kierunku północnym. Z uwagi na fakt, że jest to gatunek planktonowy, kontrola, a tym bardziej redukcja populacji orzecha morskiego nie jest w żaden sposób możliwa.

Krabik amerykański

Krabik amerykański *(Rhithropanopeus harrisii*)

Biologia: krabik amerykański (*Rhithropanopeus harrisii)* (Gould, 1841) (Crustacea: Brachyura: Xanthidae) jest gatunkiem rodzimym atlantyckich wybrzeży Ameryki Północnej. Ten gatunek jest wszystkożerny, zdolny do tolerancji szerokich zakresów temperatur i zasolenia oraz oportunistyczny pod względem wyboru habitatu. Krabik amerykański ma wysoką zdolność reprodukcyjną, a planktonowa larwa utrzymuje się przez długi czas. Te zdolności prawdopodobnie przyczyniły się do jego rozprzestrzenienia się w dwóch oceanach, ponad 28 krajach, 10 mórzach i 10 śródlądowych zbiornikach słodkowodnych. Długość do 25 mm.

Inwazja: Po inwazji krabika amerykańskiego w Morzu Bałtyckim w 1936r, jego występowanie ograniczało się do południowego i południowo-wschodniego rejonu. Ostatnie introdukcje krabika amerykańkiego w Bałtyku miały miejsce w Finlandii (2009), Estonii (2011) i Szwecji (2014), prawdopodobnie na skutek transportu larw z wodami balastowymi statków. Obecnie krabik amerykański jest znajdowany w różnych rejonach Bałtyku, ale wykluwanie się larw nie jest możliwe w zasoleniu poniżej 5 PSU (praktyczna jednostka zasolenia, której ekwiwalentem jest promil), a jego reprodukcja w Bałtyku jest ograniczona przez zasolenie poniżej 4 PSU. Zatem krabik amerykański jest notowany wyłącznie w południowych i centralnych rejonach Bałtyku, gdzie występuje na głębokościach od 0 do 20 m.

Wpływ na stada ryb eksploatowanych komercyjnie: Krabik amerykański wpływa na sieć troficzną i w sposób bezpośredni na lokalne ryby jako nowe źródło pokarmu. Może wywierać duży wpływ na trawę morską Zostera czy makroalgi (takie jak morszczyn pęcherzykowy) i w ten sposób może wpływać na zbiorowiska przydenne na obszarach, gdzie występuje w dużych ilościach. Co najważniejsze, może zmieniać przybrzeżne miejsca rozwoju młodocianych form ryb wielu gatunków, poprzez zmniejszenie liczebności istotnych składników pokarmu ryb – bezkręgowców takich jak Amphipoda.

Rekomendacje: Rutynowy monitoring biologiczny Morza Bałtyckiego nie uwzględnia monitoring przybrzeżnej fauny mobilnej. Najczęściej używaną metodą zbioru krabika amerykańskiego jest zbiór w pułapki habitatowe, np. klatki wypełnione muszlami małży lub ostryg albo kamieniami ozdobnymi, do których kraby mogą wchodzić i wychodzić z pułapki w okresie rozstawiania. Ta metoda jest obecnie stosowana w projekcie badania portów HELCOM/OSPAR i pułapki habitatowe zostały również uwzględnione w wytycznych do programu monitorowania IGO wg HELCOM. Zalecamy opracowanie tej metody dla wszystkich rejonów. Pozbycie się krabika amerykanskiego z rejonów objętych inwazją nie jest możliwe. Zmniejszenie wpływu tego kraba na środowisko na określonych lokalnych (zamkniętych) obszarach może odbywać się poprzez fizyczne usunięcie go, ale metoda ta jest pracochłonna.

Wioślarka kaspijska

Wioślarka kaspijska (*Cercopagis pengoi*)

Biologia: Wioślarka kaspijska (*Cercopagis pengoi*) to planktonowy skorupiak (Cladocera) rodzimy dla basenu Ponto-Aralo-Kaspijskiego. Jest drapieżnikiem, zdolnym żerować na różnych ofiarach, takich jak widłonogi planktonowe i wioślarki, ale sam w sobie jest także ważną ofiarą dla ryb planktonożernych i drapieżnego zooplanktonu, takiego jak Mysidae. Długość przedstawicieli tego gatunku waha się między 1 a 3 mm bez ogona i 6 do 13 mm z ogonem. Wioślarka kaspijska rozmnaża się bezpłciowo latem i płciowo w niesprzyjających warunkach. Rozmnażanie płciowe może prowadzić do produkcji jaj zimujących lub odpoczywających, które są odporne na zamarzanie, połknięcie przez drapieżniki i wysuszenie.

Inwazja: Wioślarka kaspijska prawdopodobnie dotarła do Morza Bałtyckiego statkami z rejonów rodzimego występowania, rejonu Ponto-Kaspijskiego. Od czasu pierwszej inwazji w latach 1990tych stała się obiecującym składnikiem zbiorowisk zooplanktonu w Bałtyku właściwym i Zatoce Fińskiej. Występuje od lipca do października, ale najliczniejsza jest w sierpniu i wrześniu, tzn w czasie gdy biomasa innych przedstawicieli zooplanktonu naturalnie maleje.

Wpływ na stada ryb eksploatowanych komercyjnie: Wioślarka kaspijska jest znaczącym elementem diety śledzia, szprota i stynki w Morzu Bałtyckim. Jednocześnie, z uwagi na fakt że jej występowanie zależy od tego samego zooplanktonu co planktonożernych ryb, może być istotnym konkurentem o pokarm dla śledzia, szprota i stynki. Zatem liczebność widłonoga *Eurytemora affinis*, ważnego składnika pokarmu śledzia, szprota i stynki, zmniejszyła się o 90% od początku inwazji. Zmiany te były szczególnie widoczne w wyższej temperaturze (>15°C), co może wskazywać, że wpływ wioślarki kaspijskiej na pokarm śledzia, szprota i stynki może się uwydatnić w przyszłości w świecie dotkniętym zmianami klimatycznymi. Dzięki swojej szczególnej morfologii (długi haczyk) wioślarka kaspijska może również wpływać na efektywność połowów, gdy tysiące osobników zostają zaplątane, tworząc w ten sposób papkowatą warstwę, która zostaje złapana na żyłkach i sieciach. Szacuje się, że powoduje to znaczne straty ekonomiczne dla gospodarstw rybackich i rybaków.

Rekomendacje: Od 1979, program monitoringowy HELCOMu uwzględnia zbiór prób mezozooplanktonu. Zbiór prób mezozooplanktonu odbywa się między dwa a dwanaście razy w roku, zależnie od podobszaru i kraju, a w czasie letnim jest uwzględniony w schemacie sampling dla całego Bałtyku. Wioślarka kaspijska jest włączona w ten monitoring, zatem należy podsumować, że monitoring tego gatunku jest obecnie odpowiednio prowadzony w rejonie całego Bałtyku. Wioślarki kaspijskiej nie można pozbyć się w Morzu Bałtyckim i nie ma środków pozwalających zminimalizować wielkość jej populacji lub jej wpływu.

1. INTRODUCTION

1.1 Background

Invasions of non-indigenous species (NIS) pose a serious threat to global biodiversity and ecosystem function worldwide. In addition, NIS may be a major social problem due to economic losses (Warziniack et al., 2021, Haubrock et al., 2022), affecting for example tourism and fisheries (Galil et al., 2015). The brackish, semi-enclosed Baltic Sea is especially vulnerable to any negative impacts of invasive species. Biodiversity, number of species and levels of ecological niches are generally low, making alterations in any part of the ecosystem particularly disruptive (Paavola et al., 2005). Moreover, climate change is altering the living conditions in the Baltic Sea. It is warming at a rate of 0.6°C per decade (Viktorsson et al., 2020), and this warming gives invasive species from lower latitudes a physiological advantage over native Baltic species. Moreover, the Baltic Sea is surrounded by nine industrialised countries affecting the ecosystem. In combination with climate change, anthropogenic pressures further increase the vulnerability of the Baltic Sea (Reusch et al., 2018) making it prone to invasions by NIS (Ojaveer et al., 2017), with an increasing rate of new NIS sightings over the past 100 years, as documented for Danish waters (Jensen et al., 2023).

Most species living at present in the Baltic Sea are post-glacial immigrants that have extended their native range from adjacent marine or freshwater regions. Consider these species as native to the Baltic Sea is commonly accepted (Olenin et al., 2017). However, there is a continuous net immigration of species into the Baltic Sea through both natural dispersal and human-mediated introduction of species, and that is why scientists sometimes call the Baltic Sea 'a sea of invaders' (Leppäkoski et al., 2002). The rate of new arrivals has greatly increased in recent decades due to the intensification of global trade, human mobility and removal of former custom barriers (data in AquaNIS editorial board 2015).

The information system for non-indigenous species lists a total of 615 separate invasion events of 225 NIS and cryptogenic[2] species for the Baltic Sea since the 1800s (AquaNIS editorial board 2015). To be considered invasive, the NIS must adapt to the new area and alter the ecosystem. However, the level of 'alteration' remains unclear. The MSFD (Marine Strategy Framework Directive) considers something to be in good environmental status when 'non-indigenous species introduced by human activities are at levels that do not adversely alter the ecosystem' (Annex I of the MSFD) and proposes an inventory of the temporal occurrence, abundance and spatial distribution of all NIS. Several NIS have been responsible for large-scale habitat transformations and changes in food web structure and increasing competition (Olenin et al., 1999, Jormalainen et al., 2016, Tiselius & Møller, 2017, Riisgård et al., 2012). However, ecological impacts have not been well documented for all identified NIS; in addition, when studies are available, they focus on more general ecological perspectives (e.g., Ojaveer et al., 2021).

Of the 220 NIS and cryptogenic species, 72 are currently established in the Baltic Sea, and about one-third of these are spread in larger areas of the Baltic Sea (AquaNIS editorial board 2015). However, data on the general impact are either lacking or very incomplete for 60% of the widespread NIS (Ojaveer et al*.,* 2021). Ojaveer et al., (2021) ranked the NIS in the Baltic according to their potential ecological impact as follows: the ctenophore *Mnemiopsis leidyi* at the top followed by the cladoceran *Cercopagis pengoi,* the bivalve *Dreissena polymorpha*, the shrimp *Palaemon elegans*, the round goby *Neogobius melanostomus*, the bivalve *Mya arenaria*, the polychaete *Marenzelleria* spp*.*, the mud crab *Rhithropanopeus harrisii*, the amphipod *Gammarus tigrinus* and, finally, the barnacle *Amphibalanus improvisus*. The effect of these widespread NIS on commercial fish stocks is poorly understood, partly because relationships between ecological impacts and changes in fish stocks are difficult to quantify since effects may be both direct and indirect. However,

[2] A cryptogenic species may be either a native species or an introduced species, clear evidence for either origin being absent.

it can be assumed that the presence of NIS might have negative (yet potentially also positive) implications for certain native commercially used fish species. In this study, we aim at improving the basic scientific knowledge on the possible effects of invasive species on Baltic Sea commercial fish stocks and fisheries. The present report describes the findings.

1.2 Work plan

Four of the most important NIS in the Baltic Sea were chosen as case study species in this study. These species were chosen based on the impact on the Baltic Sea ecosystem as a whole and on the amount of information available on their impact on commercial fish stocks. The work was divided into the seven specific subjects described in the seven chapters of the report:

1. A general introduction to the extent and importance of NIS in the Baltic Sea.
2. A review of scientific and grey literature to identify the geographic extent of the impact and the possible vectors for the spreading to and within the Baltic Sea.
3. Another literature review and an online survey to quantify the impact of the four species on commercially and recreationally important fish stocks and fisheries.
4. A treatise on the gaps in the knowledge on the effects of invasive species in the Baltic Sea. This was based on the literature surveys in Chapters 2 and 3.
5. An investigation of the most probable future evolution of current invasions.
6. An investigation of possible future invasion scenarios.
7. Formulation of recommendations to monitor and, if needed, to combat the presence of invasive species or to minimise their negative impacts. This includes recommendations on the most promising tools or solutions to put into practice and advice on the possibility to transform any of the four species into target species for local fisheries.

2 MAIN INVASIVE SPECIES

2.1 Main invasive species with impacts on fisheries

For a review of the available knowledge on the four case study species, the Web of Science was used to identify published articles that investigated the presence of invasive species in the Baltic Sea. To keep the search terms very broad, 'Baltic Sea invasive species' was used in the search criteria 'TOPIC', which resulted in 376 (English-language) papers. These papers were screened to find four NIS with well documented impacts in the Baltic Sea. For the literature review and for the online survey, commercial and recreational fish stocks were defined based on the species listed in the 'ICES Fisheries Overviews, Baltic Sea ecoregion' (version 2: 06.02.23) (ICES 2022).

After screening, the species considered as invasive in the Baltic Sea were classified in different groups (Table 1). The relevant papers for each group were then studied more closely to identify the dominant and widespread invasive species for which ecological impacts on the Baltic Sea ecosystem are documented (Table 1). This list of main invasive species corresponds well with the results of Ojaveer et al., (2021). However, the three species *Palaemon elegans, Mya arenaria* and *Amphibalanus improvisus* identified by Ojaveer et al., (2021) were excluded from this study following the refined baseline inventories of NIS provided by Tsiamis et al., (2019, 2021). These species are considered cryptogenic (i.e., species that cannot be classified as non-indigenous or native in a particular region, Carlton 1996) in the Baltic Sea by Sweden, Denmark, Germany, Finland, Estonia, Latvia, Lithuania and Poland (Tsiamis et al., 2019, 2021). Among the seven identified invasive species, there were more records regarding the effects of round goby (*Neogobius melanostomus)*, sea walnut (*Mnemiopsis leidyi)*, mud crab *(Rhithropanopeus harrisii)*, and fishhook water flea (*Cercopagis pengoi)* on fisheries. Thus, after initial evaluation by the project experts, round goby, sea walnut, mud crab and fishhook water flea were selected as case studies for deeper analysis.

Table 1: Groups and main invasive species identified by literature review

Taxonomic group (most documented species)	Most important species
Fish (round goby, other gobies)	Round goby, *Neogobius melanostomus**
Jellyfish (sea walnut, other jellyfish species)	Sea walnut, *Mnemiopsis leidyi**
Crabs (mud crab, brush-clawed shore crab, Asian shore crab, Chinese mitten crab, invasive blue crab)	Mud crab *Rhithropanopeus harrisii**
Planktonic crustaceans (fishhook water flea)	Fishhook water flea, *Cercopagis pengoi**
Polychaetes (*Marenzelleria* spp., other Polychaeta species)	*Marenzelleria* spp.
Amphipods (*Gammarus tigrinus*, other amphipods)	*Gammarus tigrinus*
Bivalves (Dreissenidae, wedge clam, other bivalves)	*Dreissena polymorpha*
Copepods	*Eurytemora* sp.
Phytoplankton	*Prorocentrum minimum*
Crayfish	
Other species	

* *Selected species with more documented impacts on fisheries for case studies*

2.1.1 Round goby (Neogobius melanostomus)

Photo 1: Round goby (*Neogobius melanostomus*)

Round goby (*Neogobius melanostomus*) (Photo 1), a bottom-dwelling fish native to the Ponto-Caspian region, is an invasive species in the North American Great Lakes and several European inland waterbodies, as well as throughout the Baltic Sea (Kornis et al., 2012, Behrens et al., 2022). The maximum life span of round goby is six years, and individuals found in the Southern Baltic Sea (maximum adult length 25 cm) are among the largest round gobies recorded in coastal waters worldwide (Sokołowska and Fey 2011). Round goby has all the traits to be a successful invader. It has a high reproductive turnover rate (repeated spawning during whole summer, eggs guarded from predation by males, reproduces in both fresh and salt water, relatively early age at maturation (2-3 years)) and high tolerance to various environmental factors (eurythermic and euryhaline) (Corkum et al., 2004; Kornis et al., 2012; Behrens et al., 2017; Christensen et al., 2021). Round goby is also a strong competitor because it is larger and more aggressive than most fish species with the same lifestyle (e.g., black goby *Gobius niger*, sand goby P*omatoschistus minutus*, eelpout *Zoarces viviparus* or bullhead *Cottus gobio*) in the invaded areas (Kornis et al., 2012). It has flexible feeding habits and can switch among prey according to availability (Borcherding et al., 2013; Nurkse et al., 2016).

Round goby has both positive and negative ecological impacts on ecosystems. The species is an important prey species for predatory fish and birds (Kornis et al., 2012, Rakauskas et al., 2013, Liversage et al., 2017, Happel et al., 2017) but can also compete with native fish species (Balshine et al., 2005) such as flounder (*Platichthys flesus*) in the Baltic Sea (Karlson et al., 2007, Ustups et al., 2016) and bullhead (*Cottus perifretum*) in some rivers in the Netherlands (Verreycken, 2013). Round goby has been shown to potentially disturb the spawning of native fish species (Janssen and Jude, 2001) or to consume native fish species' roe and larvae (French and Jude, 2001; Roseman et al., 2006; Wiegleb et al., 2018). Direct predation by round goby on macroinvertebrate communities can lead to a reduction in abundance of certain prey species (e.g., Lederer et al., 2006, Naddafi and Rudstam 2014, Henseler et al., 2021, Van Deurs et al., 2021), resulting in cascading food web alterations in invaded ecosystems (Skabeikis et al., 2019).

2.1.2 Sea walnut (*Mnemiopsis leidyi*)

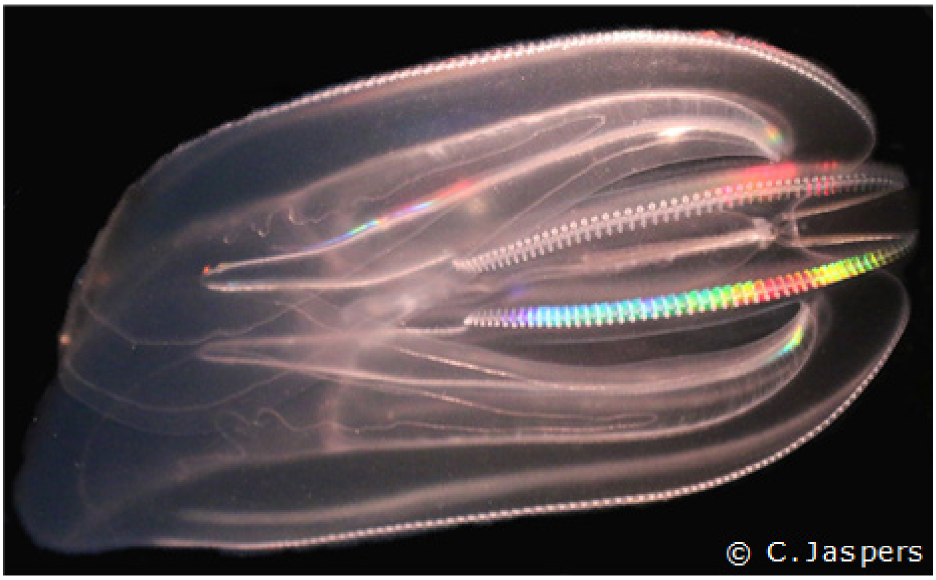


Photo 2: Sea walnut (*Mnemiopsis leidyi*)

The sea walnut (*Mnemiopsis leidyi)* (Photo 2) is a lobate ctenophore native to the east coast of the Americas with a maximum recorded size of 170 mm in the North Sea (Baiandina et al., 2022). Animals go through a metamorphosis with eggs hatching into heart-shaped cydippid larvae that develop lobes and auricles during the transitional stage, while during the adult stage, tentacles are reduced, and the feeding mode changes. As adults, the sea walnut entrains large volumes of water due to current generation by the auricle (Colin et al., 2010), while larvae depend on a passive encounter of prey via fanned-out tentacles (Sullivan and Gifford 2004). It is a successful non-indigenous species which has been present in European waters since the 1980s (Purcell et al., 2001; Faasse and Bayha, 2006; Costello et al., 2012, Jaspers et al., 2018). The sea walnut is characterised by high growth rates and a large reproductive capacity (Jaspers et al., 2015). Due to the change in morphology, larvae and adult sea walnut have different prey preferences. While adults primarily prey on larger zooplankton, such as copepods (Colin et al., 2010), larvae feed on microzooplankton <100 µm (Sullivan et al., 2004). Reproduction rates are high; in the Kattegat, it has been shown that one animal can produce up to 11,000 eggs per day (Jaspers et al., 2014). It is striking that this simultaneous hermaphrodite, which has a high hatching success (65–90%) during self-fertilisation, keeps reproducing under starvation and channels energy from the body into gonadal tissue (Jaspers et al., 2015). In fact, large-sized animals have been documented to keep reproducing for twelve days without food while shrinking in body size (Jaspers et al., 2015). Thus, at times when the prey field is disadvantageous to adults (prey too small), even to the extent of adult starvation, the sea walnut can still produce new offspring, which can then take advantage of the smaller prey, which likely explains the fast population increase, especially in eutrophic areas (Riisgård et al., 2007, Jaspers et al., 2018).

In areas where the sea walnut is very abundant, predation on the zooplankton to the extent that zooplankton abundances get heavily reduced, has been documented, such as in the Limfjord (Petersen et al., 2020, Riisgård et al., 2007) or in the Skagerrak. In the Skagerrak, this predation drives variations in zooplankton population size, which in extension creates changes in the phytoplankton concentration of nearshore water (Tiselius and Møller 2017). Thus, nearshore waters become murkier during periods with high numbers of sea walnuts in the Skagerrak.

2.1.3 Mud crab (*Rhithropanopeus harrisii*)

Photo 3: Mud crab (*Rhithropanopeus harrisii*)

The Harris mud crab (*Rhithropanopeus harrisii)* (Gould, 1841) (Crustacea: Brachyura: Xanthidae) (Photo 3) is native to the Atlantic coast of North America (Williams 1984, Projecto-Garcia et al., 2009) and has many characteristics of a successful invader. The species is omnivorous, euryhaline, eurytherm and an opportunistic habitat utiliser, moreover, the Harris mud crab has high reproductive capacity and a long planktonic larval period (Costlow et al., 1966, Turoboyski 1973, Roche et al., 2007, Forward 2009, Fowler et al., 2013). These abilities have likely facilitated its spread to two oceans, over twenty-eight countries, ten seas and ten freshwater inland reservoirs (Roche et al., 2007, Kotta and Ojaveer 2012; Fowler et al., 2013). In both its native and non-native range, the mud crab is found in a variety of different habitats that support different kinds of shelter in sandy, muddy, and rocky bottoms (Ryan et al., 1956, Turoboyski 1973, Williams 1984, Petersen 2006, Fowler et al., 2013). Females can begin to spawn at a size (carapace width) of 4.8 mm in the native range and at a size of 8 mm in invaded regions (Ryan et al., 1956, Turoboyski 1973). The maximum size of *R. harrisii* is reported to be higher in invaded regions (26 mm) than the native range (15.5 mm) (Ryan et al., 1956, Turoboyski 1973, Fowler et al., 2013).

The mud crab detects its prey by chemical cues (Kidawa et al., 2004) and is a significant predator on benthic invertebrates (Nurkse et al., 2016, 2018) in the Baltic Sea. The invasion of mud crab reduced abundance, richness and diversity of bladderwrack-associated native invertebrate species on a rocky littoral shore in the inner Archipelago Sea of coastal Finland (Jormalainen et al., 2016, see also Forsström et al., 2015). This predation pressure enforced a major shift in the community dominated previously by herbivorous and periphyton-grazing gastropods and crustaceans to a mussel-dominated community with overall low abundances of herbivores in the area (Jormalainen et al., 2016). The mud crab has been shown to affect fish populations in the Baltic Sea (see Task 2).

2.1.4 Fishhook water flea (*Cercopagis pengoi*)

Photo 4: Fishhook water flea (*Cercopagis pengoi*)

The fishhook water flea (*Cercopagis pengoi*) (Photo 4), native to the Ponto-Aralo-Caspian basin, is a generalist predator capable of feeding on a variety of prey species of different sizes (Pichlová-Ptáčníková and Vanderploeg, 2009). As many other successful invaders, the fishhook water flea is eurytherm and euryhaline, having a high tolerance to variations in both temperature and salinity (Gorokhova et al., 2000). The species' length varies from 1 to 3 mm without tails and from 6 to 13 mm with tails (Benson et al., 2018). The fishhook water flea reproduces asexually during the summer and sexually during undesirable condition (Benson et al., 2018). Sexual reproduction can lead to production of over-wintering or resting eggs that are resistant to freeze-drying, desiccation and ingestion by predators (Benson et al., 2018).

Since it first invaded the Baltic Sea in the 1990s, the fishhook water flea has become a prominent member of the zooplankton community in the Baltic proper and Gulf of Finland (ICES areas SD27, SD28, SD29, SD32). It is present in the northern Baltic proper from July to October but is most abundant in August and September, which is the same time of year as when biomasses of other zooplankton naturally decline (Gorokhova et al., 2004). The initial phase of the invasion lasted at least until 2004. Accordingly, studies show that abiotic environmental variables did not explain the inter-annual variability in the seasonal cycles of *C. pengoi* during 1991-2004 in Estonian coastal waters (SD28, SD29, SD32) indicating that the species was at its initial phase of invasion during this period (Kotta et al., 2006).

The fishhook water flea preys on copepods and cladocerans, but is also an important prey itself for planktivorous fish and predatory zooplankton such as mysids. In essence, the cladoceran adds another trophic level between zooplankton and planktivores to the Baltic Sea planktonic food web (Kotta et al., 2006). Accordingly, stable isotope analysis has shown a shift of trophic level from 2.6 to 3.4 in young-of-the-year herring (Gorokhova et al., 2005). Ecological communities consist of organisms organised in food webs in which organisms on the higher trophic level feed on those on the trophic level below. Thus, primary producers such as algae inhabit trophic levels 1, whereas the herbivores feeding on these algae inhabit trophic level 2. Accordingly, young-of-the-year herring have shifted from feeding on a combination of herbivores (level 2) and primary carnivores (level 3) to strictly carnivores. Young herring have therefore become dependent on other species than previously.

A long-term study of the zooplankton community in the Gulf of Riga (SD28) showed a significant correlation between phytoplankton and zooplankton densities until 1990 (Kotta et al., 2004). After the invasion of the fishhook water flea in 1991, the zooplankton community was more strongly regulated by this invasive species rather than phytoplankton dynamics. In this period, abundances of other cladoceran species were negatively correlated to fishhook water flea abundance (Kotta et al., 2004, Ojaveer et al., 2004), whereas copepods were positively correlated to fishhook water flea abundance (Kotta et al., 2004). In addition, the seasonality of zooplankton abundances is influenced by *C. pengoi*. The peak of abundances of *Bosmina* and *Acartia* occurred earlier in the summer possibly due to fishhook water flea predation during late summer (Ojaveer et al., 2004).

Using an impact index, which measures the predation pressure of the fishhook water flea on the zooplankton community, Naumenko and Telesh (2019) showed that, in the Vistula Lagoon (SD26), the impact of the fishhook water flea was low immediately after the invasion into the lagoon in 1999 (1999-2003). The impact increased significantly during the following years (2004-2008) but has decreased again subsequently (2009-2013). During 2014-2016, the abundance of the fishhook water flea was very low, consequentially having very low impact (Naumenko & Telesh, 2019). The foremost effects of the invasion in the lagoon included a significant decrease in the production of the copepod *Eurytemora affinis*.

In our judgement, the introduction of the fishhook water flea has invoked a regime shift in the pelagic community in the Central Baltic Sea and Gulf of Finland. This shift is most clearly identified by the de-coupling of zooplankton and phytoplankton densities. The balance between the two different directions of trophic interactions seems to have shifted from a predominately bottom-up to a more top-down scenario. The changing seasonality may also infer important changes in the workings of the food web.

2.2 Areas in the Baltic Sea where impacts of non-indigenous invasive species occur

Information on the wider geographic distribution, environmental range, and habitat choice of the four species was obtained from the literature review (see 2.1) were used to create maps identifying the areas in the Baltic where impacts of selected NIS occur. The maps in this task were created by ArcGIS Pro v.3.1.

The information to provide distribution maps was collected from published reports, scientific literature, and national databases (see below). Only presence data (1990-2022) were collected for round goby, whereas both presence and absence data (2005-2022) were available for sea walnut. Information about the occurrence and relative abundance of the fishhook water flea was achieved from Olenin et al., (2017). The data were not available to provide a distribution map for mud crab in the Baltic Sea. When the data availability allows (e.g., for round goby and sea walnut), the presence of the invasive species is showed in the map adjacent to our study area (e.g., in Kattegat and Swedish west coast) (see Figures 1 and 3). However, we report the impact of the invasive species on commercial fish stocks only in our study area (i.e., Baltic Sea) (see Figures 2, 4, 5, 7).

2.2.1 Round goby (*Neogobius melanostomus*)

Round goby was first detected in the Baltic Sea in 1990 in the Bay of Gdańsk in Poland (Skóra and Stolarski 1993). Since then, it has spread to most coastal areas around the Baltic Sea (Azour et al., 2015; Kotta et al., 2016; ICES 2022) with the exception of the northern parts of the Bothnian Sea and in the more saline areas of Kattegat and Skagerrak.

Water temperature and salinity, depth, propagule pressure (shipping) and wave exposure are factors suggested to affect round goby distribution in the Baltic Sea (Kotta et al., 2015, 2016, Behrens et al., 2017, Florin et al., 2017, Holmes et al., 2019; Christensen et al., 2021; Behrens et al., 2022). A modelling study suggests that the probability of occurrence of round goby in the Baltic Sea area becomes higher with increasing water temperature, chlorophyll *a* concentration, shipping density and bottom current velocity and lower with increasing depth, and exposure to waves (Holmes et al., 2019). Regarding temperature, the preference for warmer waters has been supported in a recent pan-Baltic study investigating seasonal migration and thermal experience of round goby based on catch data (Behrens et al., 2022). Moreover, the species prefers rocky habitats, although it may also colonise soft substrate (Kornis et al., 2012; Ustups et al., 2016; Sapota and Skóora, 2005). Round goby mainly occur in shallow coastal areas, yet they migrate to deeper and offshore areas during autumn and winter (Behrens et al., 2022). The round goby can tolerate salinity from 0 to 40.5 PSU and temperatures from −1 to + 30°C (Vassilev et al., 2012). However, its dispersal may be limited by salinity (Azour et al., 2015; Green et al., 2021). No populations are established in purely marine (> 30 PSU) conditions. The colder water in the northern parts of the Bothnian Sea might also be a limiting factor (Christensen et al., 2021; Behrens et al., 2022).

Recent data (1990-2022) showed that round goby are present in most coastal areas of the Baltic Sea (Figure 1). Our literature review identified the areas in the Baltic Sea (at an ICES subdivision scale), for which an impact of round goby on commercial fish stocks has been reported (Figure 2).

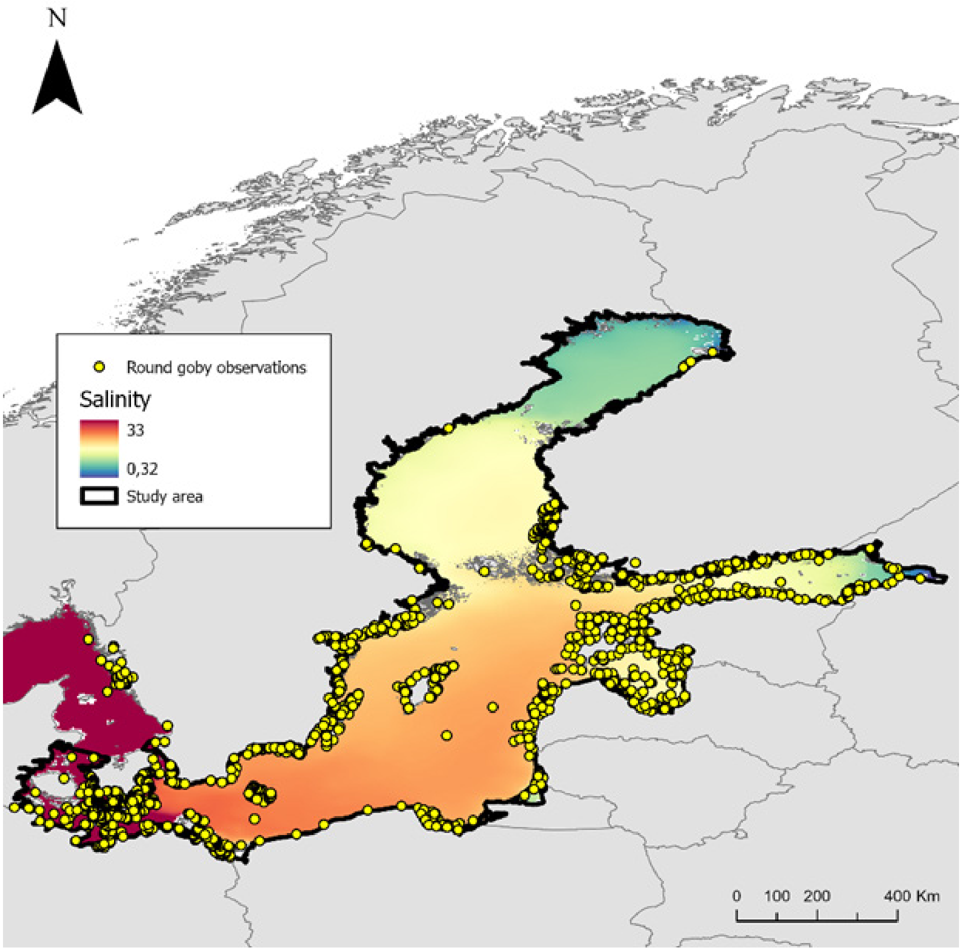


Figure 1: Reported round goby observations (1990-2022) in the Baltic Sea (ICES 2022a, Analysportalen).

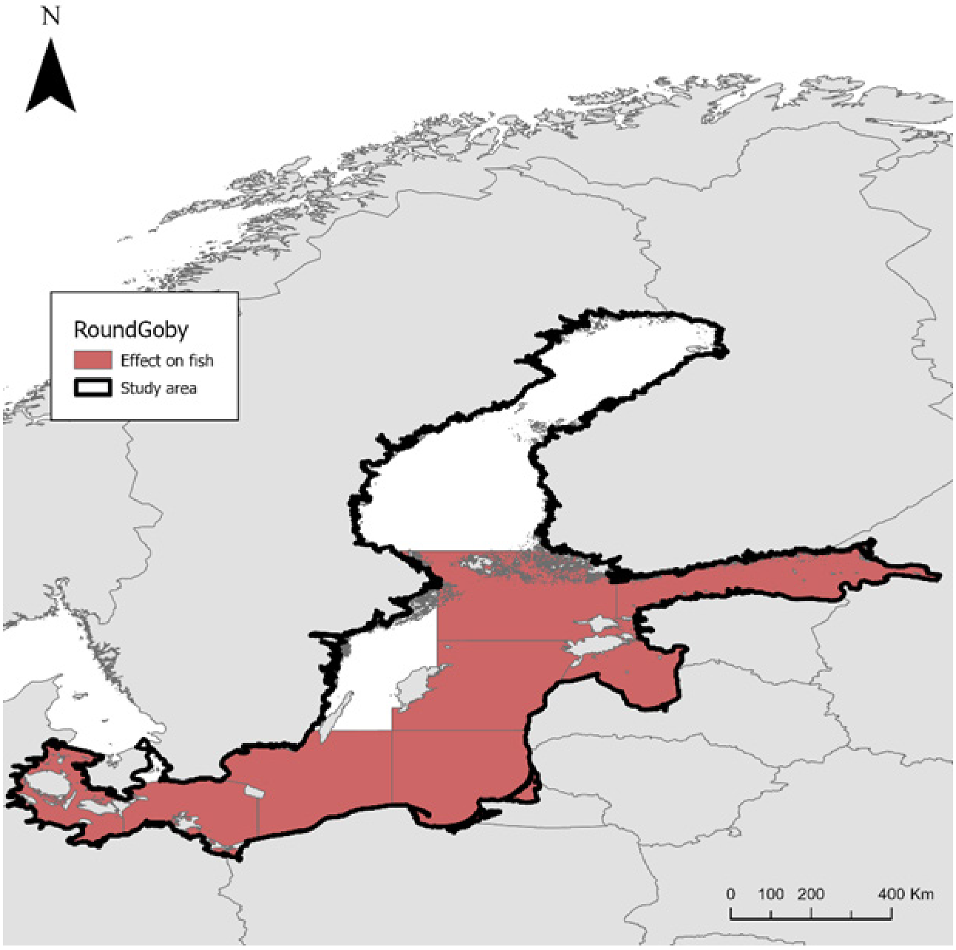


Figure 2: ICES subdivisions in the Baltic Sea, for which an impact of round goby on commercial fish stocks has been reported based on the second literature review (in red).

2.2.2 Sea walnut (*Mnemiopsis leidyi*)

The sea walnut was first sighted in the early 1980s in the Black Sea and has subsequently spread throughout Southwestern Eurasia, including the Caspian Sea, Sea of Azov, the Eastern Mediterranean Sea, and has most lately expanded into the Northwestern Mediterranean Sea (Jaspers et al., 2018). In Northern Europe, the sea walnut was first officially confirmed in 2005 in different regions around the extended North Sea area: the coast of the Netherlands during July (Faasse et al., 2006); the Nissum Fjord in Denmark during August (Tendal et al., 2007); Le Havre, the French part of the English Channel, during September (Antajan et al., 2014); and the Oslo Fjord, Southeast Norway, during October (Oliveira et al., 2007). By 2007, the sea walnut was confirmed in all Danish waters, including the Bornholm Basin (Jaspers et al., 2018).

Even though the sea walnut has a high tolerance towards environmental stressors, such as temperature and oxygen conditions (Jaspers et al., 2021), salinity drastically affects reproduction rates, and reproduction ceases at low salinities (Jaspers et al., 2011). This phenomenon likely explains why the sea walnut has not spread further into the Baltic Sea's low saline waters than the Bornholm Basin (Haraldsson et al., 2013). Furthermore, a short cold winter period (January–March) during the early 2010s led to the disappearance of the sea walnut from large areas of Northwestern Europe, including the Baltic Sea, Belt Sea, Skagerrak/Kattegat and Norwegian coastline from summer 2011 until spring 2014 (Jaspers et al., 2018). However, one warm winter (January–March) with high current velocities during 2014 was sufficient for re-colonising the entire distribution range occupied before 2011.

Furthermore, no population structure was observed in the entire Northwestern European distribution range in 2014. This lack of a population structure indicates that the North Sea, where the sea walnut has been observed since its first recordings in 2005, acts as a refuge to swiftly re-seed animals over all Danish waters (Jaspers et al., 2018). The sea walnut shows a strong seasonality, which has the highest abundance during summer and autumn (Haraldsson et al., 2013).

Presence/absence data (2005-2022, Jaspers et al., 2018, Jensen et al., 2023, Analyseportalen) have shown that low salinity is a limiting factor for the sea walnut occurrence in major parts of the Baltic Sea (Figure 3). The literature review identified the areas in the Baltic Sea (at an ICES subdivision scale), for which an impact of the sea walnut on commercial fish stocks has been reported (Figure 4).

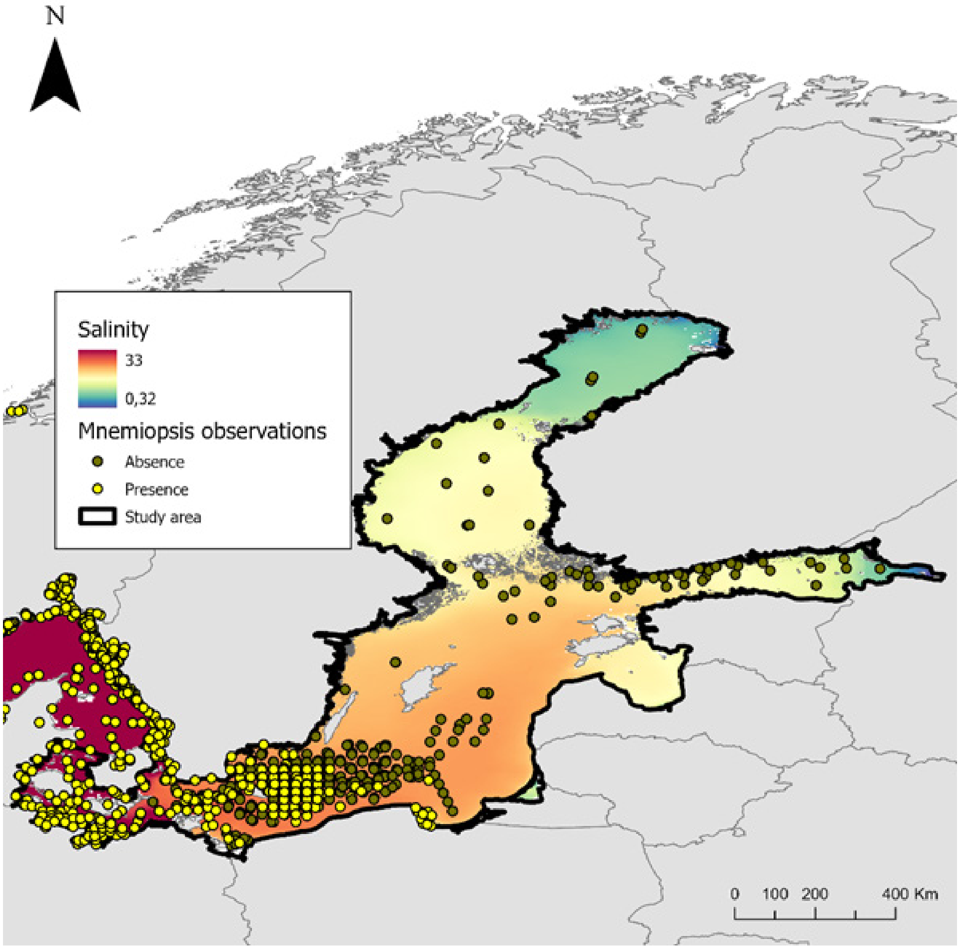


Figure 3: *Mnemiopsis leidyi* presence/absence locations (2005-2022) in the Baltic Sea (Jaspers et al., 2018, Jensen et al., 2023, Analyseportalen).

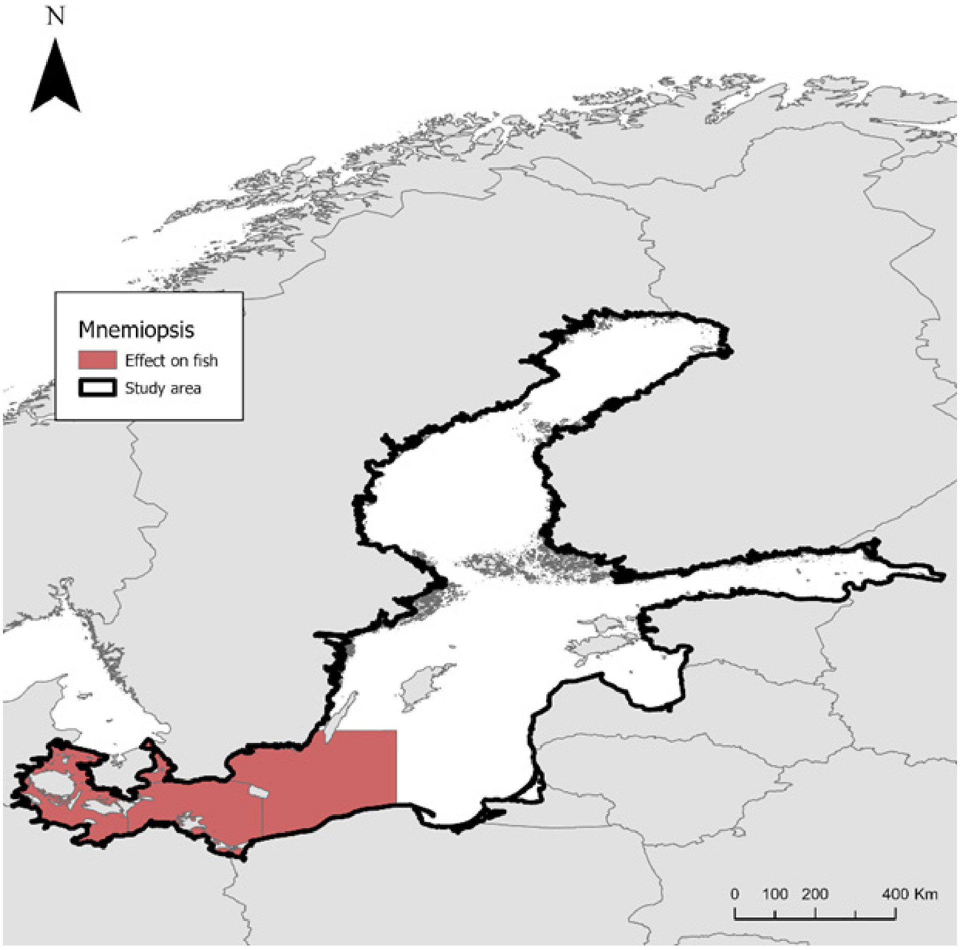


Figure 4: ICES subdivisions in the Baltic Sea, for which an impact of the sea walnut on commercial fish stocks has been reported based on the literature review from Chapter 2.1 (in red).

2.2.3 Mud crab (*Rhithropanopeus harrisii*)

After the invasion of the mud crab into the Baltic Sea in 1936 (Nurkse et al., 2015), its distribution was limited to the southern and southeastern area (Kotta and Ojaveer, 2012). The most recent introductions of the mud crab in the Baltic Sea occurred in Finland (2009) and Estonia (2011) (Kotta and Ojaveer, 2012), as well as in Sweden (2014) (AquaNIS). *R. harrisii* are able to tolerate a wide range of salinity between 2.5–40 PSU (Boyle et al., 2010, Fowler et al., 2013) and can survive low temperatures in the Baltic Sea (Turoboyski 1973) and temperatures as high as 30 C in the Gulf of Mexico (Costlow et al., 1966). However, larval hatching is not possible in salinities below 5 PSU (Costlow et al., 1966) and the crab reproduction in the Baltic Sea is constrained by salinities below 4 PSU (Holopainen et al., 2018). In the Southern Baltic Sea (the Gulf of Gdańsk), the species was recorded at depths from 0 to 20 m (Hegele-Drywa and Normant 2014). The availability of suitable habitats and food availability can also influence the abundance of the species in the invaded area (Nurkse et al., 2015). An outdoor mesocosm experiment conducted on the northern shore of the Gulf of Riga, the Northeastern Baltic Sea, showed that the mud crab preferred to occupy vegetated boulders (covered with the brown macroalga *Fucus vesiculosus*) compared to unvegetated boulders or sandy habitats (Nurkse et al., 2015; see also Riipinen et al., 2017).

At present, the available data are not enough to provide a mud crab distribution map in the Baltic Sea. The literature review in Chapter 2.1 identified the areas in the Baltic Sea (at an ICES subdivision scale), for which an impact of the mud crab on commercial fish stocks has been reported (Figure 5).

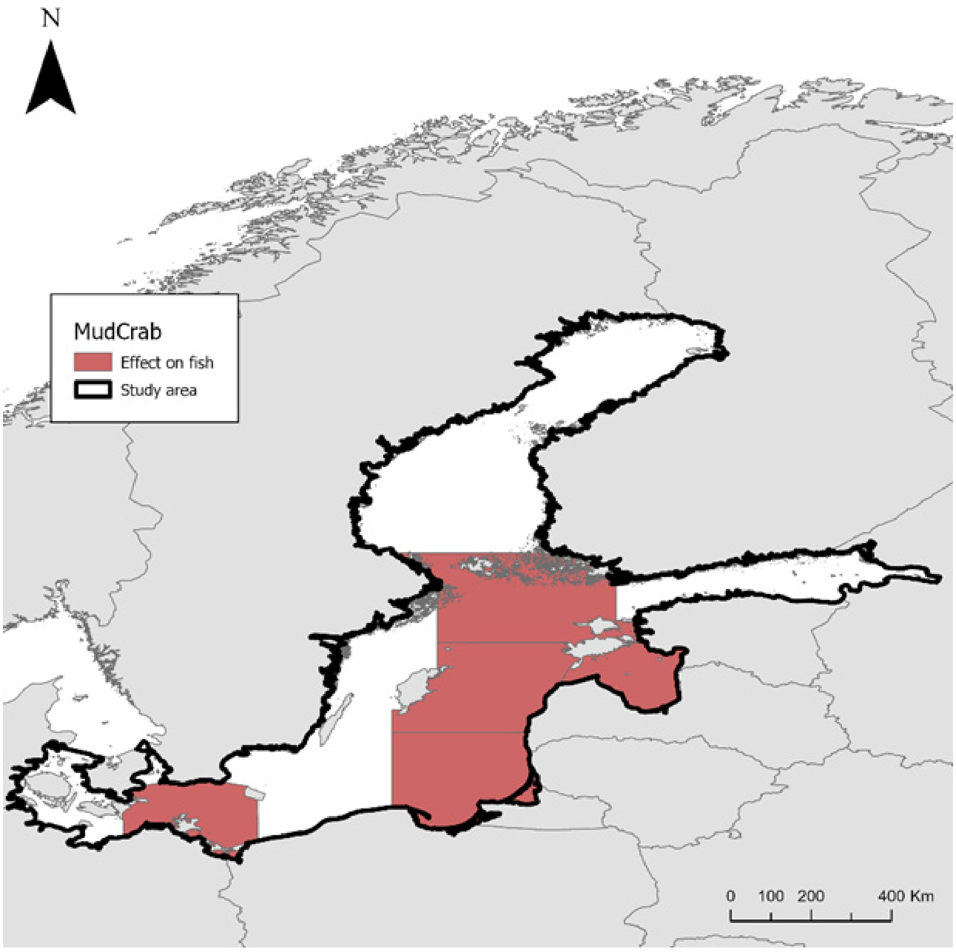


Figure 5: ICES subdivisions in the Baltic Sea, for which an impact of the mud crab on commercial fish stocks has been reported based on the literature review from Task 2 (in red).

2.2.4 Fishhook water flea (*Cercopagis pengoi*)

The fishhook water flea was first found in 1992 in the Gulfs of Finland and Riga. It spread rapidly to the Baltic proper, and by 2002 this cladoceran reached the Gulf of Bothnia, including the Bothnian Bay in the north and by 2004 also the German coast in the south (Olenin et al., 2017). It is now present in the major part of the Baltic Sea proper, with highest abundances in the Gulf of Finland and Gulf of Riga (Figure 6). Being a planktonic organism, it cannot choose its habitat, and it occupies most of the pelagic on the invaded areas, but it is most often restrained to the photic zone as all other zooplankton. Although the fishhook water flea can tolerate very low salinities and temperature (Gorokhova et al., 2000), it has only been observed infrequently in the Bothnian Bay. For some reason, it has been restrained from entering the bay, possibly due to low concentrations of zooplankton prey.

The literature review in Chapter 2.1 identified the areas in the Baltic Sea (at an ICES subdivision scale), for which an impact of the fishhook water flea on commercial fish stocks has been reported (Figure 7).

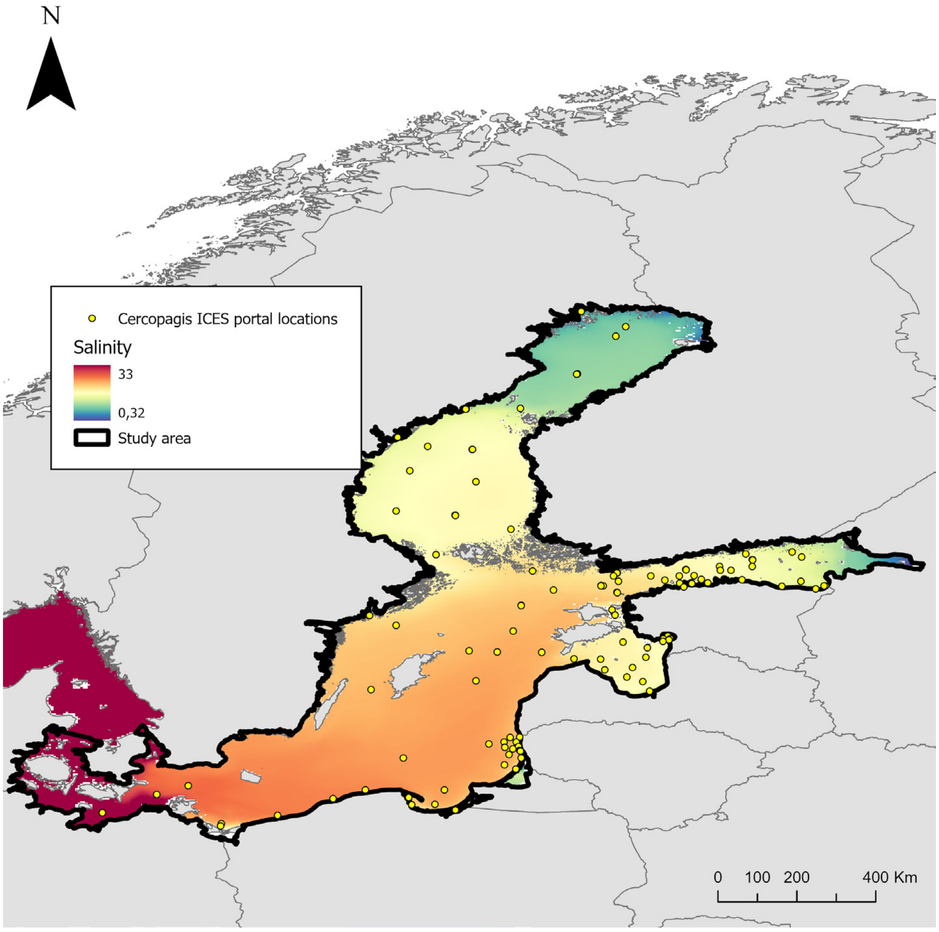


Figure 6: Observations of fishhook water flea for the Baltic Sea (ICES portal).

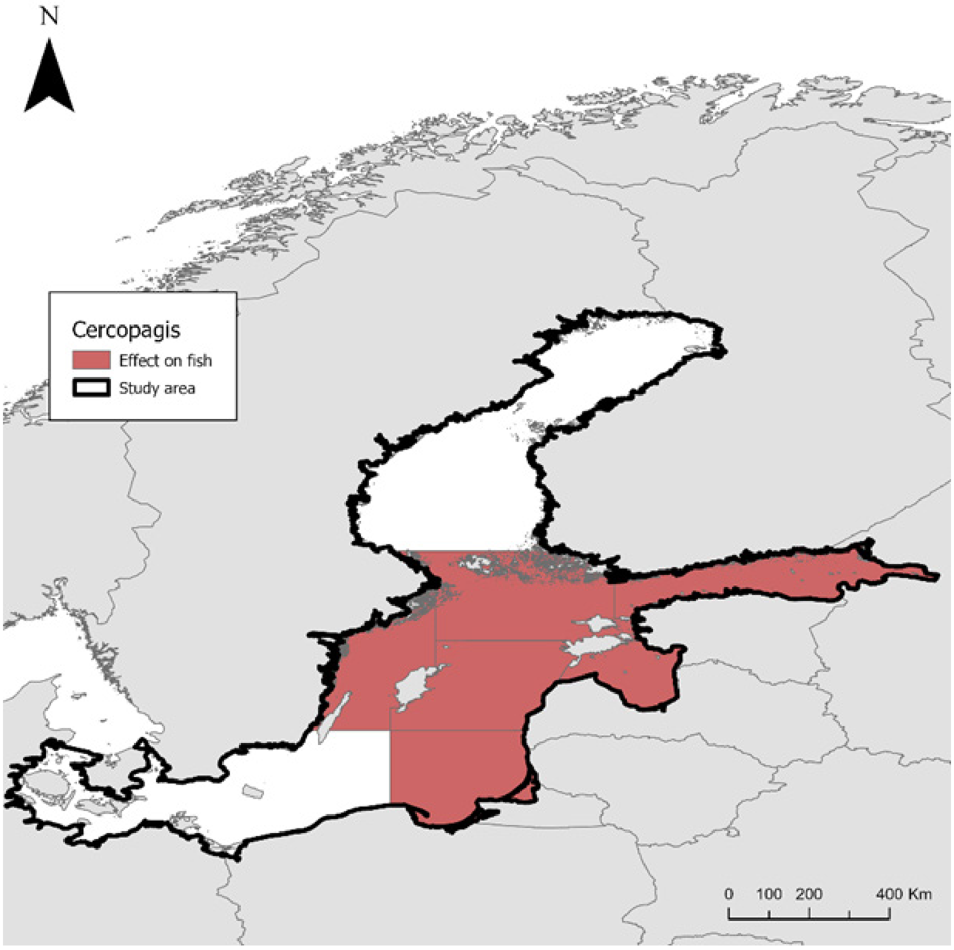


Figure 7: ICES subdivisions in the Baltic Sea, for which an impact of the fishhook water flea on commercial fish stocks has been reported based on the literature review from Task 2 (in red).

2.3 Vectors of spreading of invasive species

Shipping is deemed to be an important vector for half of aquatic NIS in Europe both through biofouling (Accumulation of aquatic microorganisms on vessel hulls and submerged surfaces) and ballast discharges (release of ballast water into the port of discharge, which is mainly used to provide stability and manoeuvrability of ships during a trip) (Korpinen et al., 2019, Zenetos et al., 2022). It has also been shown that shipping has a strong impact on aquatic NIS incidence in the Baltic Sea (Gren et al., 2022).

Following the terminology of the CBD (Convention on Biological Diversity) classification of 2014 and utilising the opinions of national experts, Tsiamisa et al., (2019, 2021) suggested different pathways for the introduction of round goby, sea walnut, mud crab and fishhook water flea in the Baltic Sea (Table 2). Multiple vectors have been involved in the introduction of each of these four species in the respective invaded areas (Table 2). Here, we also elaborate on the vectors for each species mentioned in the available resources.

2.3.1 Round goby (*Neogobius melanostomus*)

The main vector of introduction of the round goby from native areas to both the Baltic Sea and the Great Lakes in North America is most likely ship traffic (Corkum et al., 2004, Kornis et al., 2012, Kotta et al., 2016, Florin et al., 2018). Round goby larvae, which are pelagic and nocturnal, can easily be transported through ballast water (Hensler and Jude, 2007; Kornis et al., 2012). However, it cannot be ruled out that the round goby is also transported by ship hulls (e.g., Zaiko et al., 2011). Potential vectors are angling (baitfish) or transport by recreational boats (as baitfish and/or through biofouling) upstream rivers.

Table 2: Pathways of introduction of NIS in different parts of the Baltic Sea determined by NIS national experts

Source: Tsiamis et al., (2019, 2021). Pathway A: TRANSPORT- STOWAWAY: Hitchhikers on ship/boat (excluding ballast water and hull fouling); Pathway B: TRANSPORT- STOWAWAY: Ship/boat ballast water; Pathway C: TRANSPORT- STOWAWAY: Ship/boat hull fouling; Pathway D: CORRIDOR: Interconnected waterways/basins/ seas; Pathway E: Secondarily dispersed through natural expansion within that area; P_HIGH: Pathways with high certainty; P_MEDIUM: Pathways with medium certainty; P_LOW: Pathways with low certainty; P_: Pathways with unknown certainty

NIS	Country	Date of first observation	Pathway A	Pathway B	Pathway C	Pathway D	Pathway E
Round goby	Germany	1999		P_MEDIUM			P_HIGH
	Denmark	2008	P_			P_	
	Sweden	2008		P_LOW			P_LOW
	Estonia	2002		P_LOW			P_LOW
	Finland	2005		P_MEDIUM			P_LOW
	Latvia	2002		P_HIGH			
	Lithuania	2002		P_MEDIUM			P_HIGH
	Poland	1990		P_MEDIUM	P_MEDIUM	P_LOW	P_MEDIUM
Sea walnut	Germany	2006		P_HIGH			P_HIGH
	Denmark	2007	P_				
	Sweden	2006		P_LOW			P_LOW
	Poland	2007		P_MEDIUM			P_MEDIUM
Mud crab	Germany	1948-1950					
	Denmark	1936					
	Sweden	2014		P_			P_
	Finland	2009		P_MEDIUM			
	Latvia	2001	P_MEDIUM			P_MEDIUM	
	Lithuania	2013		p			p
	Poland	1951		P_MEDIUM	P_MEDIUM		
Fishhook water flea	Germany	2004					P_
	Sweden	1995					P_HIGH
	Estonia	1992		P_MEDIUM			
	Finland	1992		P_MEDIUM			
	Latvia	1999				P_HIGH	
	Lithuania	1992		P_LOW			P_HIGH
	Poland	1999		P_MEDIUM			P_LOW

2.3.2 Sea walnut (*Mnemiopsis leidyi*)

The sea walnut enters the Baltic Sea from the North Sea through the Danish straits. It does not reproduce well in the Baltic Sea (see 2.2.2) so its presence in the Baltic Sea is a result of continued influx from the North Sea. The sea walnut was introduced into the North Sea probably via ballast water from NE USA coast (Jaspers et al.., 2021). In fact, whole genome data have revealed that the animals are recurrently re-seeded into the North Sea area (Jaspers et al., 2021). High connectivity from the Southwestern North Sea throughout Northwestern Europe has a high and documented ability to swiftly re-seed animals over large distances, also following local extinctions (Jaspers et al., 2018).

2.3.3 Mud crab (*Rhithropanopeus harrisii*)

Little is known about the vectors of introduction of the mud crab into Baltic Sea (Spiridonov and Zalota 2017). A previous study indicated that the Harris mud crab has probably been introduced once or repeatedly to Europe by different invasion mechanisms (e.g., hull fouling, ballast water, as hitchhikers in the oyster aquaculture trade) (Projecto-Garcia et al., 2010). However, several studies have suggested that shipping (mostly through the ballast waters of ships) is supposed to be the main vector of mud crab around the globe including the Baltic Sea (Rodriguez & Suarez 2001, Roche and Torchin 2007, Kotta and Ojaveer 2012, Fowler et al., 2013, Hegele-Drywa and Normant 2014, Aarnio et al., 2015, Spiridonov and Zalota 2017).

2.3.4 Fishhook water flea (*Cercopagis pengoi*)

The first records of the fishhook water flea in the Baltic Sea are from the Gulf of Finland and the Gulf of Riga in 1992 (Kotta et al., 2006). Most probably, it arrived in the Baltic Sea with ships from its native area, the Ponto-Caspian region. By 2004, it had expanded to the whole Baltic proper, the Pomeranian Bay and the northern parts of the Gulf of Bothnia. Since the fishhook water flea is a pelagic species, the secondary spread is by advective transport of all life stages. There are also indications that resting eggs may survive passage through predators' guts and spreading may be facilitated by e.g. migrating planktivorous fish (Antsulevich and Välipakka 2000).

3 IMPACTS ON COMMERCIAL FISH STOCKS

Information regarding the impacts of the four case study species on commercially and recreationally used fish stocks and fisheries were gathered and evaluated. In a systematic literature review comprising both grey and peer-reviewed literature, information on the impact of the case study species were extracted and summarised. To obtain additional information, an online survey was conducted, which can serve to fill the knowledge gaps detected during the literature review. As survey participants, both scientists and fishers working on/around the Baltic Sea were targeted.

3.1 Literature review

For the literature review and for the online survey, commercial and recreational fish stocks were defined based on the species listed in the 'ICES Fisheries Overviews, Baltic Sea ecoregion' (version 2: 06.02.23) (ICES 2022).

The search for grey literature was conducted by checking local databases, as well as ResearchGate and Google Scholar. References were inserted in systematic review protocols (see below) and information on the impacts of invasive species on commercial fish species and fisheries filled in (exemplary review protocols can be found in the attachments). To search for and retrieve information from peer-reviewed literature, a systematic literature review was conducted similar to the PRISMA approach (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (O'Dea et al., 2021). One literature review was conducted for each case study species (round goby, *Neogobius melanostomus*; sea walnut, *Mnemiopsis leidyi*; mud crab, *Rhithropanopeus harrisii*; fishhook water flea, *Cercopagis pengoi*). The search for peer-reviewed literature was conducted in Scopus[3] and Web of Science[4], separately for the four case study species using all combinations of the following keywords (Table 3) using the 'AND' operator, e.g., 'Baltic AND round gob* AND impact'; 'Baltic AND round gob* AND effect'.

Table 3: Keywords used in the systematic literature review

Region	Invasive species	Specific question
Baltic	Round goby*	impact*
	Neogobius melanostomus	effect*
	Comb jelly	affect*
	Mnemiopsis leidyi	influenc*
	(Harris) mud crab	competition
	Rhithropanopeus harrisii	predation
	fishhook water flea	food web*
	Cercopagis pengoi	interacti*

In Scopus, the keywords were entered into the field 'Article title, Abstract, Keywords', while the field 'all fields' was used for Web of Science. The search for each species was conducted by one person. Duplicate records of references were removed using an R script and the remaining references were inserted into the final systematic review protocol. The reading of papers and information extraction were conducted by different people by assigning a certain number of papers to each project participant. Papers were first screened regarding their relevance for the questions to be answered using specific in/exclusion criteria (Table 4).

[3] https://www.scopus.com/search/form.uri?display=basic#basic
[4] https://www.webofscience.com/wos/woscc/basic-search

Table 4: Criteria and coding used to decide whether papers were included in the literature review or whether they were excluded i.e., not relevant.

In/Exclusion Coding	In/Exclusion Reasoning	Explanation
yes	none of the below	The study fits the search criteria.
no_A	not dealing with/mentioning impact of case study species on commercial fish/fisheries	The study does not deal with/mention the impact of the respective case study species on commercial fish stocks/fisheries.
no_B	outside geographic scope	The study does not focus on the Baltic Sea.
no_other	other reason for excluding the paper	

When papers were judged to be relevant (Table 5), the content was read, and the information filled into the review protocol. Based on the information within the protocols, the impact of the respective invasive species on commercial fish was summarised.

Table 5: Number of papers found during the systematic literature review and those considered relevant.

Case study species	Papers found	Relevant papers
Round goby (*Neogobius melanostomus*)	91	27
Sea walnut (*Mnemiopsis leidyi*)	56	10
Mud crab (*Rhithropanopeus harrisii*)	37	8
Fishhook water flea (*Cercopagis pengoi*)	61	12

The results of the systematic literature review of commercial and recreational fish stocks affected by the four case study species are shown in Tables 6-9.

Table 6: List of commercial and recreational fish stocks affected by round goby and corresponding references

Evidence/ Assumption	Commercial/ recreational fish species (Common name)	Commercial/recreational fish species (Scientific name)	References describing the impact
evidence	eel	*Anguilla anguilla*	Bzoma & Stempniewicz 2001
assumption	herring	*Clupea harengus*	Wiegleb et al., 2018, Henseler et al., 2020, Wallin et al., 2023
assumption	pike	*Esox lucius*	Florin et al., 2018, Wallin et al., 2023, Herlevi et al., 2023
assumption	cod	*Gadus morhua*	Almqvist et al., 2010, Järv et al., 2018, Rakauskas et al., 2020, Więcaszek et al., 2020, Funk et al., 2021, Wallin et al., 2023, Herlevi et al., 2023
assumption	perch	*Perca fluviatilis*	Almqvist et al., 2010, Järv et al., 2011, Oesterwind et al., 2017, Liversage et al., 2017, Rakauskas et al., 2020, Więcaszek et al., 2020, Wallin et al., 2023, Herlevi et al., 2023
assumption	flounder	*Platichthys flesus*	Corkum et al., 2004, Karlson et al., 2007, Järv et al., 2011, 2015, Schrandt et al., 2016, Ustups et al., 2016, Aigars 2018, Rakauskas et

Evidence/ Assumption	Commercial/ recreational fish species (Common name)	Commercial/recreational fish species (Scientific name)	References describing the impact
			al., 2020, Henseler et al., 2021, Behrens et al., 2022
assumption	plaice	*Pleuronectes platessa*	Rakauskas et al., 2020
assumption	pikeperch	*Sander lucioperca*	Oesterwind et al., 2017, Więcaszek et al., 2020, Wallin et al., 2023
assumption	turbot	*Scophthalmus maximus*	Aigars 2018, Rakauskas et al., 2020, Ustups 2022
evidence	turbot	*Scophthalmus maximus*	Knospina & Ustups 2016
assumption	sprat	*Sprattus sprattus*	Wallin et al., 2023
evidence	sprat	*Sprattus sprattus*	Bzoma & Stempniewicz 2001
assumption	eelpout	*Zoarces viviparus*	Corkum et al., 2004

Table 7Table 7: List of commercial and recreational fish stocks affected by sea walnut and corresponding references.

Commercial/ recreational fish species (Common name)	Commercial/recreational fish species (Scientific name)	References describing the impact
Baltic cod	*Gadus morhua*	(Kube and Postel, 2008) – grey literature (Hüssy, 2011) (Jaspers *et al.*, 2011b) (Haslob et al., 2007) (Huwer *et al.*, 2008) (Schaber *et al.*, 2011b) (Schaber *et al.*, 2011a)
Atlantic herring	*Clupea harengus*	(Kube and Postel, 2008) – grey literature (Javidpour *et al.*, 2009)
Atlantic sprat	*Sprattus sprattus*	(Kube and Postel, 2008) – grey literature (Huwer *et al.*, 2008) (Schaber *et al.*, 2011a) (Javidpour et al., 2009)
Potentially other fish species due to indirect effects, but those have not been explicitly mentioned in the respective articles.		

Table 8Table 8: List of commercial and recreational fish stocks affected by mud crab and corresponding references.

Commercial/recreational fish species (Common name)	Commercial/recreational fish species (Scientific name)	References describing the impact
Perch	*Perca fluviatilis*	Fowler et al., 2013, Aarnio et al., 2015, Gagnon and Boström 2016, Puntila-Dodd et al., 2019
Roach	*Rutilus rutilus*	Fowler et al., 2013, Aarnio et al., 2015, Gagnon and Boström 2016, Puntila -Dodd et al., 2019
Pikeperch	*Sander lucioperca*	Fowler et al., 2013
Bream	*Abramis brama*	Aarnio et al., 2015

Table 9: List of commercial and recreational fish stocks affected by fishhook water flea and corresponding references.

Commercial/recreational fish species (Common name)	Commercial/recreational fish species (Scientific name)	References describing the impact
Atlantic herring	*Clupea harengus*	Arula et al., 2014 Einberg et al., 2020 Gorokhova et al., 2004 Gorokhova et al., 2005 Kotta et al., 2006 Kotta et al., 2004 Lankov, et al., 2010 Naumenko and Telesh 2019 Ojaveer et al., 2004 Ojaveer et al., 2017
Smelt	*Osmerus eperlanus*	Ojaveer et al., 2004 Ojaveer et al., 2017 Lankov, et al., 2010
Sprat	*Sprattus sprattus*	Lankov, et al., 2010 Gorokhova et al., 2004

3.1.1 Impact of round goby (*Neogobius melanostomus*)

Direct effects

Only few studies provide solid evidence for direct impacts of round goby on commercial fish stocks. Although top-down pressure on round gobies is relatively well studied, records of round goby feeding directly on commercial fish species are rare. However, round goby has been observed to feed on eggs of spring-spawning herring (*Clupea harengus*) along the German coast, while a consumption of small flounder (≤ 38 mm TL) has been observed under laboratory conditions in the Northern Baltic Sea (Schrandt et al., 2016, Wiegleb et al., 2018). A recent study shows that round goby prey on various commercial species including cod (*Gadus morhua*), pike (*Esox lucius*), pikeperch (*Sander lucioperca*), perch (*Perca fluviatilis*), herring, sprat (*Sprattus sprattus*) and salmonid species along the Swedish and Ålandish coast. These results are based on analysis of fish collected in the field using both eDNA as well as visual inspection of stomach content, and it is assumed that mainly early life stages of the commercial species are consumed by round goby (Wallin et al., 2023).

Karlson et al., (2007) documented a significant diet overlap between round goby and small flounder in addition to a reverse depth distribution of the two species along the Polish coast as well as a negative correlation between round goby and flounder abundances. Negative repercussions of round goby invasion for flounder are therefore assumed due to competition for habitat and food availability. Along the Latvian coast, field observations showed that abundances of juvenile turbot (*Scophthalmus maximus*) decreased after the invasion of round goby (Knospina & Ustups 2016), and spawning stock biomass of turbot has been three times lower since 1997 (Ustups 2022). Accordingly, it has been suggested that round goby competes with native species, such as turbot and flounder (*Platichthys flesus*) along the Latvian coast (Aigars 2018, Ustups 2022).

Round goby has become an integral part of the Baltic Sea coastal food web serving as a prey source for multiple organisms including birds and fish (Kornis et al., 2012, Liversage et al., 2019, Reckermann et al., 2022). The new trophic links provided by round goby are suggested to either benefit fisheries or to potentially reduce the quality of fish resources due to a lengthening of food chains (Rakauskas et al., 2020). Along the Lithuanian coast, round goby might have strengthened the trophic pathway of organic matter and energy flow from the lower benthic levels up to piscivores, which could enhance predator production and thus commercially important fish species benefiting coastal fisheries (Rakauskas et al., 2008).

Piscivorous fish all around the Baltic Sea have incorporated round goby in their diet, some even having round goby as a high proportion of their diet. For instance, medium-sized cod and perch in the Gulf of Gdańsk rely heavily on round goby as a primary food source (Almqvist et al., 2010). Since round goby represents the first mussel-feeding species perch and cod consume in this area, it has been suggested that round goby might provide a new energetic pathway from mussels to large piscivores. Next to cod and perch, several other commercial fish species prey on round goby in the Baltic Sea including pikeperch, turbot and pike, which is why positive effects of round goby on large piscivore fish have been suggested (Järv et al., 2011, 2018, Oesterwind et al., 2017, Liversage et al., 2017, Rakauskas et al., 2020, Więcaszek et al., 2020, Funk et al., 2021, Herlevi et al., 2023).

Due to a spatial overlap in the distribution of round goby and other fish species, potential resource competition has been indicated by several studies, usually in combination with highlighting a trophic niche overlap (Karlson et al., 2007, Kornis et al., 2012). A field study covering large parts of the Baltic Sea revealed a major overlap in the spatial distribution (up to 70%) of round goby and flounder (Behrens et al., 2022), while an overlap between round goby and juvenile pike habitat at the Swedish coast is assumed to negatively affect pike (Florin et al., 2018). In the outer Puck Bay at the Polish coast, round goby might compete for space with eelpout (*Zoarces viviparus*) (Corkum et al., 2004). Round goby also seem to possess similar feeding habits with the highest activity during the night (Christoffersen et al., 2019), although other results indicate that round goby is mostly diurnal (K. Skóra, University of Gdańsk, unpubl. data in Corkum et al., 2004). At the German coast, high abundances of juvenile round goby were observed in shallow vegetated areas, which serve as important spawning grounds for spring-spawning herring, suggesting potential negative effects of high round goby abundances on herring recruitment due to predation on herring eggs (Wiegleb et al., 2018, Henseler et al., 2020).

Round goby has become a commercial fish species itself in the eastern parts of the Baltic Sea (ICES, 2022a). In Latvia, a specialised round goby fishery has been ongoing since 2015 with landings of over 1000 tonnes in 2018. With regard to landings, round goby represents the second most important commercial species following herring in the Latvian coastal fishery. In Lithuania, round goby was first observed in commercial catches in 2010 with the highest landings (above 200 tonnes) reported in 2016 and 2017. In Estonian coastal fisheries, round goby has been caught since 2007 with the highest landings documented in 2021, with 256 tonnes (ICES, 2022a).

<u>Indirect effects</u>

The invasion of round goby may indirectly affect native commercial fish species by releasing them from predation pressure, as round goby is incorporated as a new food source. In the Gulf of Gdańsk, cormorants shifted their diet from eel (*Anguilla anguilla*) and sprat to round goby, resulting in an increase of eel and sprat abundances (Bzoma & Stempniewicz 2001).

By preying on benthic organisms, round goby may compete for prey with native fish species when diet composition is similar. For example, food competition with (small) flounder has been indicated in several Baltic Sea regions, due to a strong diet overlap with both species feeding on benthic macroinvertebrates, such as Baltic clam (*Macoma balthica*), cockles (*Cerastoderma* spp.) and blue mussels (*Mytilus* sp.) (Corkum et al., 2004; Järv et al., 2011, 2015; Schrandt et al., 2016; Ustups et al., 2016; Rakauskas et al., 2020; Henseler et al., 2021; Van Deurs et al., 2021). Indeed, round goby has been documented to reduce abundances of common benthic prey organisms (*Cerastoderma* spp., *Hydrobia* spp., *Mytilus* sp.) under field conditions (Henseler et al., 2021; Van Deurs et al., 2021). However, although evidence exists for diet overlap between flounder and round goby, the consequences for flounder populations are less well understood, and assumptions about these consequences are mainly based on a negative correlation of the distribution ranges of the two species (Karlson et al., 2007). A significant trophic niche overlap has also been identified for round goby and plaice (*Pleuronectes platessa*) at the Lithuanian coast in spring suggesting that round goby might also indirectly affect this flatfish species through food resource competition (Rakauskas et al., 2020). Along the Lithuanian coast, round goby might have strengthened the trophic pathway of organic matter and energy flow from the lower benthic levels up to piscivores, which could enhance predator production and thus commercially important fish species benefiting coastal fisheries (Rakauskas et al., 2008).

Intensity of the impact

In general, few studies provide an indication on how strong the impact of round goby could be on commercial fish species. Schrandt et al., 2016 assume that round goby is not likely to have a strong effect on blue mussels around the Åland Islands as long as abundances of round goby are still low during the early colonisation period. In contrast, the impact of round goby on flounder at the Polish coast based on diet overlap and negative abundance correlations is estimated to be rather high, although round goby was still in its early invasion period when the study was conducted (Karlson et al., 2007). The effects of round goby as an important prey component of larger piscivore commercial species, such as cod, perch and pikeperch, range from medium to highly positive in the Southern Baltic Sea around 13 to 16 years after the first observation of round goby (Almqvist et al., 2010, Oesterwind et al., 2017, Więcaszek et al., 2020). Thus, the intensity of round goby impact seems to vary rather inconsistently among regions and with regard to timing within the colonisation process.

The impact of round goby on commercial fish stocks and fisheries based on expert opinion given by those having read the papers varied between low and high, while no correlation between judged impact intensity and time within the invasion process could be identified.

3.1.2 Impact of the sea walnut (*Mnemiopsis leidyi*)

Direct effects

The sea walnut is a planktonic filter feeder. It feeds primarily on zooplankton but could potentially also ingest fish eggs and early larvae. While only one investigation quantifies direct feeding interactions in the Baltic Sea using different development stages and ages of Baltic cod eggs and larvae (Jaspers et al., 2011b), most investigations approximate direct interactions from field investigations using temporal and spatial distribution pattern to estimate overlap coefficients to conclude about direct effects (e.g. Haslob et al., 2007; Schaber et al., 2011a; Schaber et al., 2011b).

Two years after the first recordings of the sea walnut in the Southern Baltic Sea, no impact of the sea walnut on juveniles of sprat and herring (*Clupea harengus*, *Sprattus sprattus*) had been detected along the German coastline off Rügen based on temporal spatial distribution pattern (SD24, 37G3). Especially for herring, the commercially most important species in the area, no impact is expected, as spring herring spawn in March/April and do not overlap at all with high sea walnut population densities (Kube & Postel, 2008). For the southwestern Baltic Sea (SD 22), peak herring egg and larvae densities are attained from mid-June to mid-July, while the sea walnut shows peak abundances first during late summer and autumn as well as winter (Javidpour et al., 2009). Therefore, no direct interaction due to potential feeding on herring eggs and larvae is expected in this area either. Furthermore, fish eggs were not recorded in gut contents of the sea walnut in Kiel Bight (SD 22), which makes it unlikely that the sea walnut poses a considerable direct impact (Javidpour et al., 2009).

For sprat, no impact is suggested due to the temporal and spatial distribution pattern along the eastern German Baltic Sea coast off Rügen, but more investigations are needed to confirm this for later periods (Kube & Postel, 2008). In the Bornholm Basin (SD25), the overlap coefficient between the sea walnut and sprat eggs was low and only 1/4th of the coefficient found for cod eggs during May 2007 (Haslob et al., 2007). This is partly explained by buoyancy differences, as sprat eggs are distributed above the halocline, while the sea walnut as well as cod eggs are distributed well below the halocline (Schaber et al., 2011a). Hence, the overall spatial and temporal overlap with sprat eggs is limited, and no direct impact is expected in the Bornholm Basin (SD25) (Schaber et al., 2011a). For Baltic cod, the most important spawning ground is located in the Bornholm Basin (SD25). Although the predation risk for cod eggs is high (Schaber et al., 2011a), as both the sea walnut and cod eggs are found in the same depth range in the Bornholm Basin (SD25), the overall direct predation impact on cod eggs by the sea walnut is low (Kube & Postel, 2008, Schaber et al., 2011a, Schaber et al., 2011b) due to generally low sea walnut abundances in the lower saline areas of the Central Baltic Sea – even though cod eggs and larvae are more abundant during summer, the abundances of sea walnut are too low to pose a threat to cod eggs as it stands now (SD25, offshore Baltic Sea) (Kube & Postel, 2008). Moreover, laboratory-controlled experiments have shown low predation rates on cod eggs by sea walnuts (Jaspers et al., 2011b) – see details below.

Spawning times of cod are summarised in Hüssy (2011) and document that for the areas Kattegat, the Sound, Kiel Bay, Mecklenburg, peak spawning occurs from January to April, while for Gotland and Arkona, peak spawning occurs later during June/July and May (Hüssy, 2011). For the Bornholm Basin, which represents the most important spawning ground of cod, peak spawning occurs first during August (Hüssy, 2011). However, due to the limited abundance of the sea walnut in the respective areas during August (Haraldsson et al., 2013), direct (as well as indirect) effects on cod recruits are expected to be limited.

A high-resolution investigation in the Bornholm Basin (SD 25) during the first recordings of the sea walnut in the Baltic Sea documented a high overlap coefficient between cod eggs and the sea walnut in the Bornholm Basin during May 2007 (Haslob et al., 2007). Furthermore, sea walnuts were observed with cod eggs in their stomachs (Haslob et al., 2007). However, what cannot be excluded is the possibility that those eggs were ingested during capture in the cod ends due to direct interactions. On the contrary, direct feeding interactions have documented that the sea walnut selects other prey over cod eggs and that feeding rates on cod eggs at environmental conditions representative of the spawning area in the Bornholm Basin, where the overlap occurs, are very low (Jaspers et al., 2011b). In fact, feeding rates on different aged cod eggs were not significantly different from zero and crustacean zooplankton was positively selected for over cod eggs (Jaspers et al., 2011b). The mechanisms behind this selection are not fully understood, and it remains to be investigated whether passive prey such as fish eggs are generally rejected, as documented for Baltic cod eggs (Jaspers et al., 2011b) or if this is a species-specific interaction. Experiments in the native range have documented that the sea walnut scans the feeding current, and perception of hydrodynamic signals from moving prey or direct physical contact, induces a re-location of the feeding current over the sticky capture surfaces, which lead to successful prey capture in 90% of the cases (Colin et al., 2015). Accordingly, experiments have shown that non-motile fish eggs are negatively selected for by the sea walnut (Hamer et al., 2010). Similar to results from the Baltic Sea, feeding rates on fish eggs in the North Sea were not significantly different from zero (Hamer et al., 2010). Hence, two independent studies give support for fish eggs being not an important component of the diet of the sea walnut in Northwestern Europe (Hamer et al., 2010, Jaspers et al., 2011b). However, direct effects due to predation on herring and sprat eggs in the Baltic Sea have not been conducted to date, and we cannot rule out that direct interaction is not relevant for all fish species of the Baltic Sea.

Direct predation of sea walnut on early cod yolk sac larvae have been documented (Jaspers et al., 2011b). However, given the current spatial and temporal distribution pattern of cod larvae in the Bornholm Basin, the fact that first feeding cod larvae migrate to surface waters for first feeding and the low abundance of sea walnut in the Central Baltic Sea, the direct predation impact on cod larvae is currently negligible (Jaspers et al., 2011b). However, this impact might change in the future if the sea walnut attains higher abundances in the Baltic Sea in general and the Bornholm Basin in particular (see next section on indirect effects via large population sizes and its limitations, below).

<u>Indirect effects</u>

Indirect effects can impact fish species due to complex interactions such as competition. For the Southwestern Baltic Sea (SD22), large sea walnut population densities have been observed (Javidpour et al., 2009). In the same area, herring is characterised by a large spawning stock biomass. In 2006/2007, the mesozooplankton, ichthyoplankton and gelatinous zooplankton community was investigated in the Southwestern Baltic Sea, leading to the conclusion that peak abundances of the invasive sea walnut occur outside the time point of peak herring egg and larvae densities (Javidpour et al., 2009). Hence, no indirect effect due to food competition is to be expected (Javidpour et al., 2009). Similarly, during November 2007, direct food competition with fish recruits in the Bornholm Basin (SD25) was negligible due to very low sea walnut densities (Huwer et al., 2008). In the Black Sea, the sea walnut started to attain high population densities during the period when Anchovy landings collapsed. This collapse was then suggested to have opened an ecological niche for the sea walnut due to lower competition and higher food availability (Bilio & Niermann, 2004). Similarly, sea walnut population outbursts were feared to happen in the Baltic Sea.

In the early days of first sea walnut records in the Baltic Sea, most publications based their assumptions on biased distribution maps of sea walnut larvae, which were misidentified and actually belong to the native cydippid ctenophore species *Mertensia ovum* (Gorokhova & Lehtiniemi, 2009). Molecular species verifications helped to sort out population dynamics and population size estimates for the entire Baltic Sea (Gorokhova et al., 2009). In summary, sea walnut in the Baltic Sea does not occur outside the central Bornholm Basin further to the east (Haraldsson et al., 2013, Lehtiniemi et al., 2013), and observations of sea walnut larvae in low saline areas have been confirmed to be *M. ovum* (Gorokhova & Lehtiniemi, 2009). The change in sea walnut larvae distributions in relation to the native *M. ovum* can be approximated by salinity and temperature, where both species have an opposite habitat preference. While sea walnut larvae thrive in warm and high saline habitats, the native M. *ovum* prefers low saline and colder water temperatures (Jaspers et al., 2013). Therefore, the sea walnut is restricted to higher saline waters of the Southwestern and central Baltic Sea and does not occur in the largest area of the Baltic Sea (Jaspers et al., 2018). Furthermore, it has been documented by in situ ship-based reproduction experiments, laboratory-controlled salinity dependent egg production experiments and seasonal egg and larvae distribution data that active recruitment of sea walnut is restricted to higher saline areas of the Baltic Sea (SD 21/22/23/24/25) (Jaspers et al., 2013, Jaspers et al., 2011a). Hence, sea walnut observed at depth in higher saline waters of the Bornholm Basin (SD25) are likely a sink population, sourced from higher saline areas further west (SD21/22//23/24) (Haraldsson et al., 2013, Jaspers et al., 2018, Schaber et al., 2011a, Schaber et al., 2011b). Thus, high population densities of sea walnut in the low saline Bornholm Basin (SD25) and other areas of the low saline Baltic Sea (SD26/27/28/29/30/31/32) are unlikely. Hence, no expected indirect effect on fish populations via food competition as result of high sea walnut population densities are expected given the current environmental tolerance window of sea walnut genotypes present in the Baltic Sea.

However, as the genetic makeup of sea walnut in Northern Europe stems from the NE USA coast (Jaspers et al., 2021, Reusch et al., 2010), and a low saline thriving population is present in the Black Sea, the Caspian Sea and the Sea of Azov (Jaspers et al., 2021, Jaspers et al., 2018), we cannot exclude the possibility of potential future indirect impacts of sea walnut due to large population sizes as a consequence of hybridisation or southern genotype introduction into the Baltic Sea. Therefore, introduction events should be prevented to avoid potential negative impacts on fish populations in the low saline areas of the Baltic Sea due to the introduction of a novel sea walnut strain from southern origin (Jaspers et al., 2011a).

For higher saline areas such as SD21, negative impacts and cascading effects of sea walnut have been documented on calanoid copepod and diatom populations comparing years with and without sea walnut populations being present (Tiselius & Møller, 2017). Even though indirect effects of sea walnut on pelagic fish populations have not directly been investigated in the Baltic Sea and adjacent higher saline waters, we cannot exclude the possibility that an indirect effect due to food competition during sea walnut population blooms in late summer/autumn. Hence, an indirect effect on autumn spawning pelagic fish species such as herring cannot be excluded. The heavy grazing impact of sea walnut during abundance peaks have also been documented for other areas of Northern Europe, such as Limfjorden, a high saline fjord system connecting the North Sea with the Baltic Sea across northern Jutland in Denmark (Riisgård et al., 2012).

Another indirect effect on fish populations and especially aquaculture activities could be via the translocation of potential fish pathogens, sourced and seeded to the environment from the core microbiome of sea walnut to native fish or marine based aquaculture facilities (Jaspers et al., 2020). However, dedicated experiments are needed to confirm the pathogen status and virulence of detected suspected problematic microbial strains present in the core microbiome of sea walnut (Jaspers et al., 2020).

Intensity of the impact

The impact on commercial fish stocks is currently limited, especially in lower saline areas of the Baltic Sea. However, due to high abundances attained in higher saline areas such as the Kattegat and southwestern Baltic Sea, negative impacts on fish populations can be expected due to indirect effects via food competition. However, dedicated experiments, field observations and monitoring efforts are needed to confirm this hypothesis and also investigate potential fish species of concern outside commercial species investigated so far.

3.1.3 Impact of the mud crab (*Rhithropanopeus harrisii*)

Direct effects

The mud crab influences the food web and, based on solid evidence, has direct effects on local fish as a new source of prey. Several native fish, such as fourhorn sculpin (*Myoxocephalus quadricornis)*, perch (*Perca fluviatilis)*, ruffe (*Gymnocephalus cernuus*), pikeperch (*Sander lucioperca*), roach (*Rutilus rutilus*) and some other cyprinids consume these novel prey items, although the prevalence of mud crab in fish stomachs varied greatly among fish species (Fowler et al., 2013; Puntila-Dodd et al., 2019). Furthermore, predation pressure, especially on the larger crabs may be limited by predator size since larger fish tend to target larger crabs.

The mud crab has also been reported to consume soft tissues of European flounder (*Platichthys flesus*) in laboratory conditions, consumption rate increasing with temperature (Hegele-Drywa and Normant, 2014). However, there is no knowledge as to whether crabs eat flounder flesh in the wild.

Indirect effects

The mud crab has become an important element of the food web of the Baltic Sea in several locations. It is an omnivore that preys on various invertebrate grazers. Trophic position studies using stable isotopes have shown that large crabs (>12 mm carapace width) are grouped with fish as secondary consumers, thus using the same source of carbon (Aarnio et al., 2015). The presence of mud crabs there increases prey competition on invertebrate prey among these secondary consumers like perch, roach, bream and other species of fish.

An increase of mud crab abundance in partially empty niches of vegetated soft-bottom and hard bottom habitats will likely increase the predation pressure on important eelgrass (*Zostera marina*) mesograzers (Gagnon and Boström 2016) and on grazers of filamentous algae on bladderwrack (*Fucus vesiculosus*). This increase may lead to trophic cascades resulting in abundances of grazers deteriorating the spawning habitats of certain fish and decreasing invertebrate prey, e.g., amphipods for coastal fish (Liversage et al., 2019, 2021).

Intensity of the impact

Mud crab impact intensity is based on expert judgement as most of the impacts on fisheries are indirect and the direct effects observed are caused via mud crab performing as a novel prey for fish in the Baltic food web. The impact intensity is estimated to vary between low and medium and is related to the time in the invasion process when mud crabs have been established as part of the local communities.

3.1.4 Impact of the fishhook water flea (*Cercopagis pengoi*)

Direct effects

The fishhook water flea contributes significantly to the diet of herring, sprat and smelt in the Baltic Sea. While a few brackish, warm water mesozooplankton species (the copepods *Eurytemora affinis* and *Acartia* spp. and the cladocerans *Bosmina longispina*, *Podon* spp. as well as fishhook water flea) dominate the diet of pelagic fish in the Baltic Sea (Lankov et al., 2010), a number of studies have shown the importance of fishhook water flea as prey for these planktivores, e.g. sticklebacks *Gasterosteus aculeatus* and *Pungitius pungitius*, Atlantic herring *Clupea harengus* and European sprat *Sprattus sprattus*. The studies cover both Swedish coastal waters, the Gulf of Finland, Estonian coastal waters and the Gulf of Riga (Gorokhova et al., 2004, Kotta et al., 2006, Lankov et al., 2010, Ojaveer et al., 2004). For instance, in the Himmerfjärden Bay (Swedish coast, SD27), the fishhook water flea becomes a major prey constituent in August–September when abundances of the natural zooplankton prey decreases and the major zooplanktivores are young-of-the-year clupeoids (Rudstam et al., 1992). The fishhook water flea constitutes an important prey species to the extent that adult herring positively select for it along with the copepod *E. affinis* (Lankov et al., 2010). While smelt also selects for the fishhook water flea, sprat avoids it altogether although this species is a generalist feeder. In the Gulf of Riga, the fishhook water flea constitutes a larger fraction of the diet of herring during the warm months, where the water flea is also more abundant (Ojaveer et al., 2004).

By way of its special morphology (its long hook) the fishhook water flea can also influence the efficiency of fisheries when thousands of individuals become entangled and thus forming a paste-like substance which gets caught on fishing lines and in nets. This may cause substantial harm to fish farms and fishers - the estimated economic loss in one fish farm in the eastern Gulf of Finland averaged for 1996 -1998 at minimum 50 000 € (Panov et al., 1999).

Indirect effects

Since the fishhook water flea depends on the same zooplankton prey as planktivorous fish, they can be important competitors to species such as herring, sprat and smelt in the Baltic Sea. Abundances of the copepod *Eurytemora affinis* have declined by 90% since the invasion, and the seasonal timing of the maximum abundances of the cladoceran *Bosmina* spp. have shifted to earlier in the season (Einberg et al., 2020). Both species constitute main dietary constituents of herring, sprat and smelt in the Baltic Sea (Lankov et al., 2010; Livdāne et al., 2016; Peltonen et al., 2004). These changes were particularly conspicuous at higher temperature (>15 °C), which may indicate that the effects of the fishhook water flea on the prey of herring, sprat and smelt may be accentuated in a climate changed future (Einberg et al., 2020).

Prey competition effects may be limited to larger and older life stages. Herring larvae feed on copepod nauplii larvae at the time of their first feeding. However, data from the Gulf of Riga, 1958-2012, suggest that abundant presence of the fishhook water flea affected neither timing nor maximum abundance of copepod nauplii during the herring larvae first feeding period in May-July (Arula et al., 2014).

Intensity of the impact

The fishhook water flea invasion in the Baltic Sea seems to affect mainly three commercially important species: herring, sprat and smelt. Both direct and indirect effects are important. The cladoceran is a significant component of the prey especially for larger and adult herring but it may also constitute a significant competitor to larval and juvenile herring for smaller size zooplankton prey. Considering that the fishhook water flea has changed the zooplankton community to the point of a regime shift (see 2.1.4), it is safe to say that this cladoceran has a significant effect on the three planktivorous fish species. However, since its trophic role is complex (see 2.1.4), the direction of the impact of the fishhook water flea on planktivorous fish is difficult to predict. An increasing fishhook water flea biomass may constitute an additional food source but may also impose significant competition for prey.

In the Himmerfjärden Bay (SD27), the fishhook water flea contributes up to 60% of the prey biomass in stomachs of herring sized 10-15 cm (Gorokhova et al., 2004). The fishhook water flea accounted for ca. 10% of the stomach content in 10-15 cm sprat in that same study (Gorokhova et al., 2004). An earlier study showed that the fishhook water flea becomes a major prey constituent in August–September when abundances of the natural zooplankton prey decreases, and the major zooplanktivores are young-of-the-year clupeoids (Rudstam et al., 1992).

In Estonian coastal waters (SD28, SD29, SD32), the contribution of fishhook water flea in the diet of herring and smelt is high when the cladoceran has been present in the water column (June-September). Herring starts feeding on the cladoceran at a length of 4.1 cm, and the smelt at a length of 7.3 cm. Thus, the consumption of fishhook water flea by herring is size-dependent and the share of the fishhook water flea in the diet of large herring (15–16 cm) can reach over 10% by wet weight thus exceeding that of smaller individuals by a factor of 2–3 (Kotta et al., 2006).

In the Gulf of Riga (SD28) 1999-2006, the fishhook water flea contributed up to 60% of the diet (stomach content wet weight) in adult herring but comprised only a few percent of the diet of juvenile herring, sprat and smelt (Lankov et al., 2010).

The indirect effects through competition for prey may also be significant. The long-term study of the zooplankton community in the Gulf of Riga (SD28) (see 2.1.4) showing a shift in the regulation of the zooplankton community from bottom-up to more predominately top-down, also detected changes in herring larval abundance. Until 1990 there was no significant relationship between the density of zooplankton and herring larvae. This changed after the invasion where a negative relationship between the density of zooplankton and herring larvae was established. This suggests that the major shift in zooplankton community resulted in food limitation for herring larvae (Kotta et al., 2004).

3.2 Online survey

The survey was set up with the online tool 'LimeSurvey'[5] and was divided into four parts, each referring to one case study species, respectively (see survey file attached). Each part comprised two main questions. First, survey participants were asked to choose the commercial fish stocks that are affected by the case study species. For this purpose, the same list of commercial and recreational fish species (n=24) was provided as had already been used in the literature review (ICES 2022).

Next, participants had to specify the type of impact (impact category) and the degree, to which commercial fish stocks are affected on a qualitative scale from very low to very high (Table 10). Finally, the Baltic Sea area, to which the participants' knowledge referred to, was to be pinpointed on a map. Survey information was to be filled in based on the opinion, knowledge or experiences of the participants.

[5] www.limesurvey.org

Table 10: Impact categories used in the online survey to evaluate the impact of round goby, mud crab, sea walnut and fishhook water flea on commercial fish stocks using the following levels: very low, low, medium, high, very high, not applicable.

Impact categories	Round goby	Mud crab	Sea walnut	Fishhook water flea
Feeds on the adults	x	-	-	-
Feeds on the eggs, fry or juveniles	x	x	x	-
Competes for space	x	x	-	-
Competes for the same food resources	x	x	x	x
Serves as a new prey species	x	x	-	x
Introduces/spreads fish pathogens	x	-	x	-
Other (use of a comment field)	x	x	x	x

At the end of the survey, participants could provide some personal information about themselves including age, field of work (science, fisheries or other) and work experience (0-2, 2-4, 4-6, >6 years). The survey was set up in English and translation files were sent along with the survey link comprising all languages spoken in the countries bordering the Baltic Sea. The survey was open from June 12th to July 15th 2023 and sent to the regional coordination group of the Baltic Sea, the scientific network (universities, institutes) of all partners involved in this project and national/regional fisheries advisory councils around the Baltic Sea.

Based on the impact categories and levels chosen by the survey participants, impact scores of the case study species on the commercially/recreationally used fish species were calculated. To do so, impact levels were converted to a quantitative scale (not applicable = 0, very low = 1, low = 2, medium = 3, high = 4, very high = 5) and values averaged across impact categories for each commercial fish species. These impact scores should be handled with care as they do not depict how many participants voted for a certain species (i.e., replicate number) resulting in possibly high scores for a species, although only one participant chose a high impact category (e.g. impact of round goby on brill, Figure 9a). The impact scores should also not be compared between the case study species but should rather be regarded as a relative measure of impact.

The survey link was opened by 52 persons, of which 25 completed the entire survey. One survey participant checked the ‘I don’t know’ box regarding the impact of all four case study species, resulting in 24 answers to be considered in the evaluation.

The age of survey participants ranged between 32 and 64 (mean age = 44.4). Eighteen people claimed to be scientists, while two came from the fisheries sector. The majority of participants (n = 19) worked in their field for more than six years.

3.2.1 Round goby (*Neogobius melanostomus*)

Information on round goby impact obtained from survey participants showed a broad coverage of the Baltic Sea coastline including Danish, German and Polish waters in the Southern Baltic Sea, the Lithuanian, Latvian and Swedish coast in the Central Baltic as well as Northern Baltic Sea regions close to Finland. Based on survey results, 22 commercially used fish stocks are affected by round goby (Figure 8). Species that were judged to be impaired by at least five persons included cod, eelpout, flounder, herring, perch, pike, pikeperch and turbot.

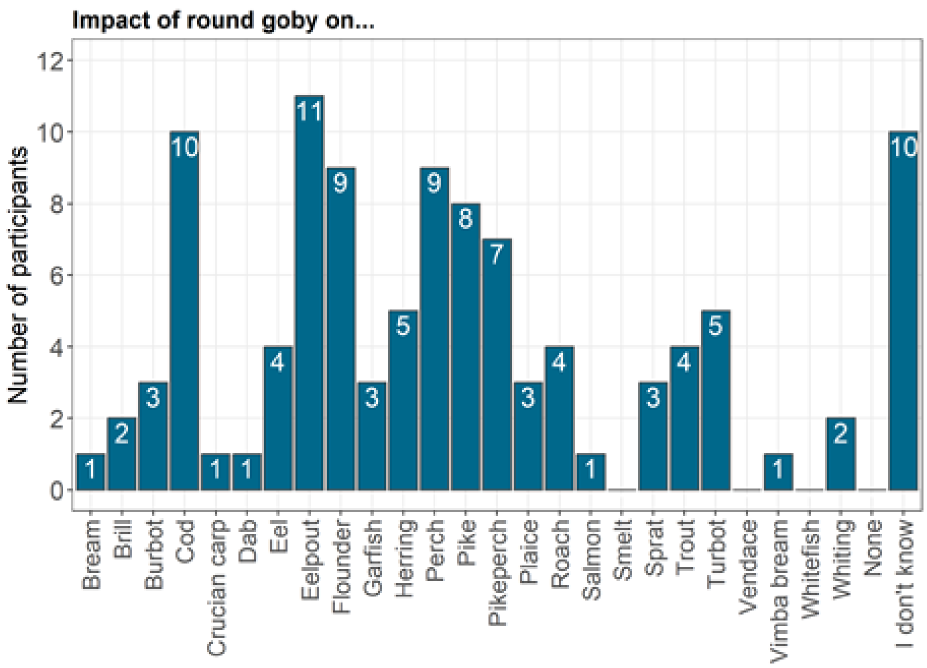
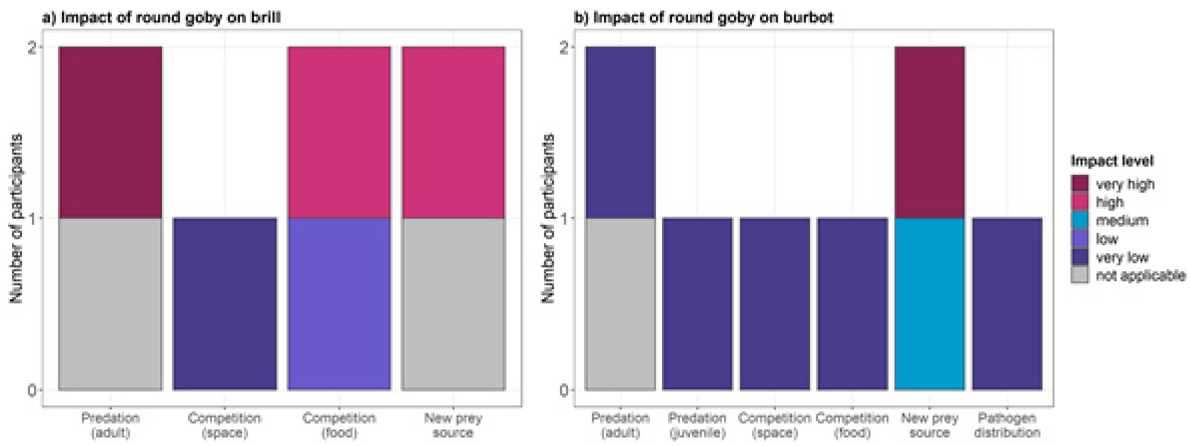


Figure 8: Impact of round goby on commercial/recreational-use fish species in the Baltic Sea based on participant opinion retrieved from the online survey. Impact is displayed as number of participants per fish species. The category 'None' was chosen when none of the species are assumed to be affected by round goby. 'I don't know' was chosen when survey participants did not have any knowledge regarding the overall impact of round goby.

Impact categories and levels for the fish species judged by more than one participant are shown in Figures 9-11 regarding round goby impact. The highest impact of round goby on cod was estimated to be due to its role as a new prey source for the commercially important species (Figure 9c), while eelpout is affected due to predation on adult and juvenile round goby on the one hand and due to competition for space and food resources on the other hand (Figure 9e). Flounder is mostly affected by competing for space and prey items with round goby (Figure 9f), while herring is assumed to be affected mainly due to predation on eggs, fry and juvenile stages (Figure 10b). Round goby is thought to strongly affect perch and pike by serving as a new prey resource and to a lesser degree through predation on juveniles and competition for space and food (Figure 10c, d). Similarly, pikeperch and turbot are judged to rely on round goby as a new prey species (Figure 10e, 11d). Additionally, turbot is supposed to be affected through predation on egg/fry/juveniles and competition for habitat and food. Survey participants commented that the inclusion of round goby as a new prey species is based on stomach content data of several fish, such as eelpout and perch.

The highest impact scores (≥ 2) of round goby were obtained for brill, eelpout, flounder, plaice and turbot (Table 11).



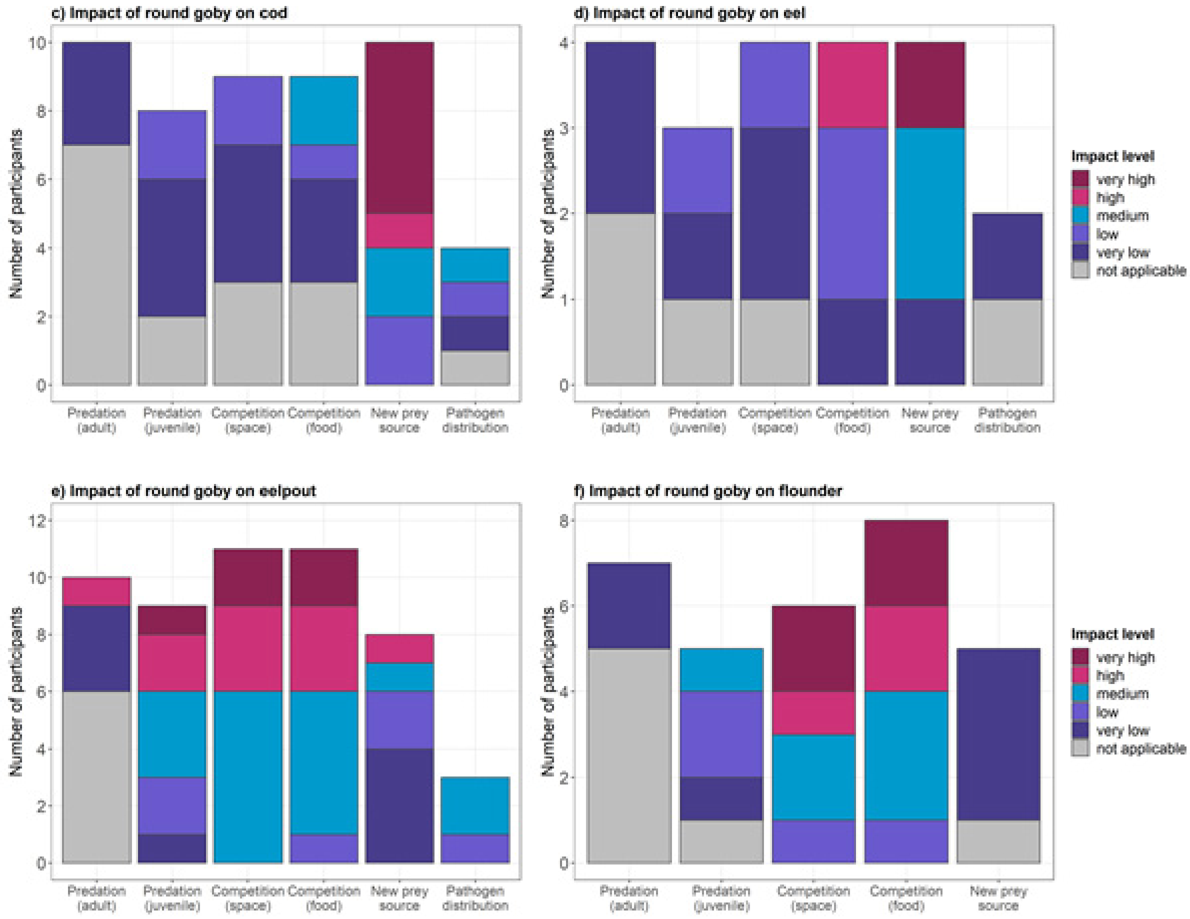


Figure 9: Level of impact of round goby on brill (a), burbot (b), cod (c), eel (d), eelpout (e) and flounder (f) based on survey participant opinion for different impact categories: predation on adult fish; predation on juveniles, eggs and/or fry; competition for space; competition for the same food resources; serving as a new prey species; and the introduction/spreading of fish pathogens. Impact is displayed as number of participants per impact category and level (from very low to very high).

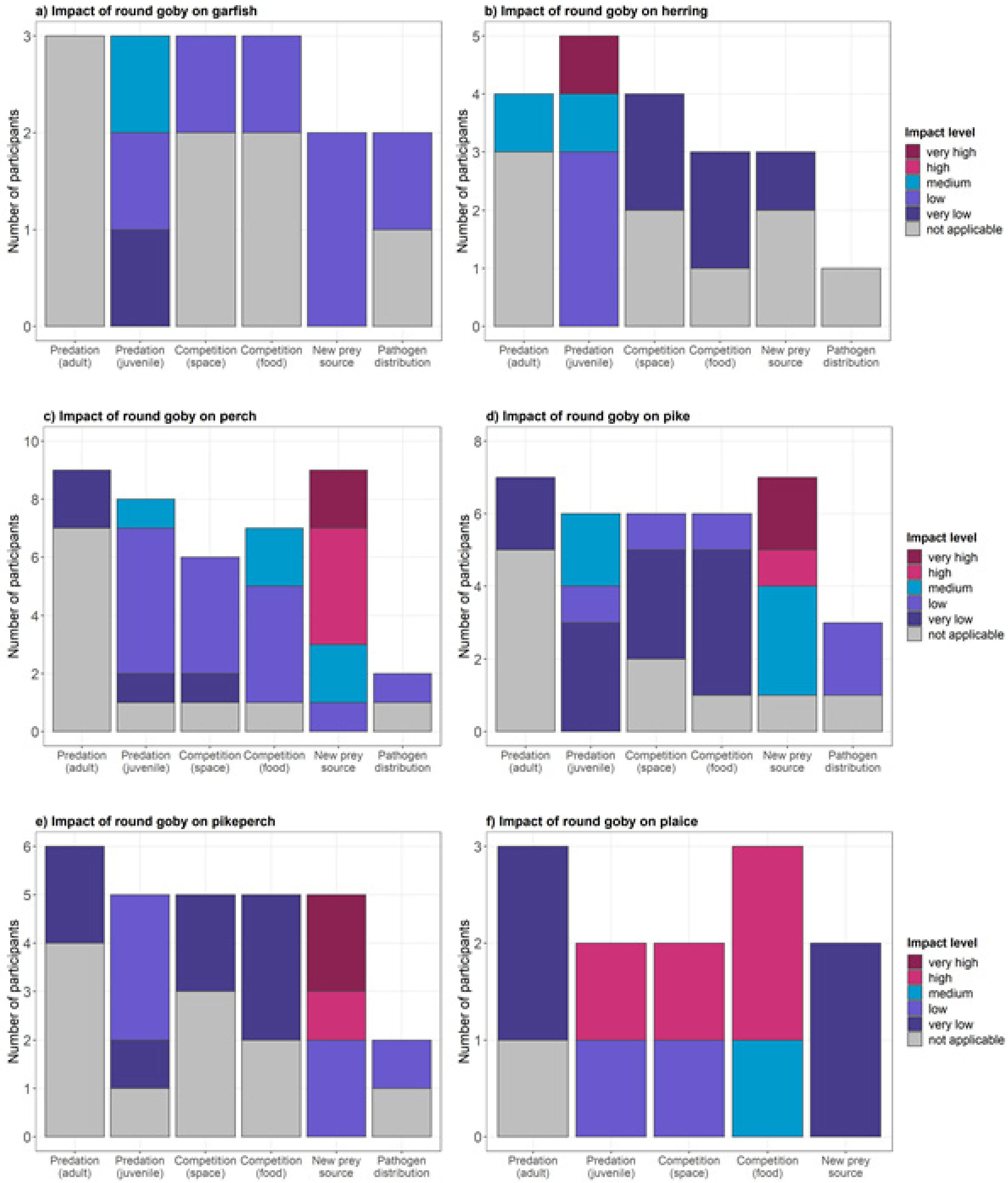


Figure 10: Level of impact of round goby on garfish (a), herring (b), perch (c), pike (d), pikeperch (e) and plaice (f) based on survey participant opinion for different impact categories: predation on adult fish; predation on juveniles, eggs and/or fry; competition for space; competition for the same food resources; serving as a new prey species; and the introduction/spreading of fish pathogens. Impact is displayed as number of participants per impact category and level (from very low to very high).

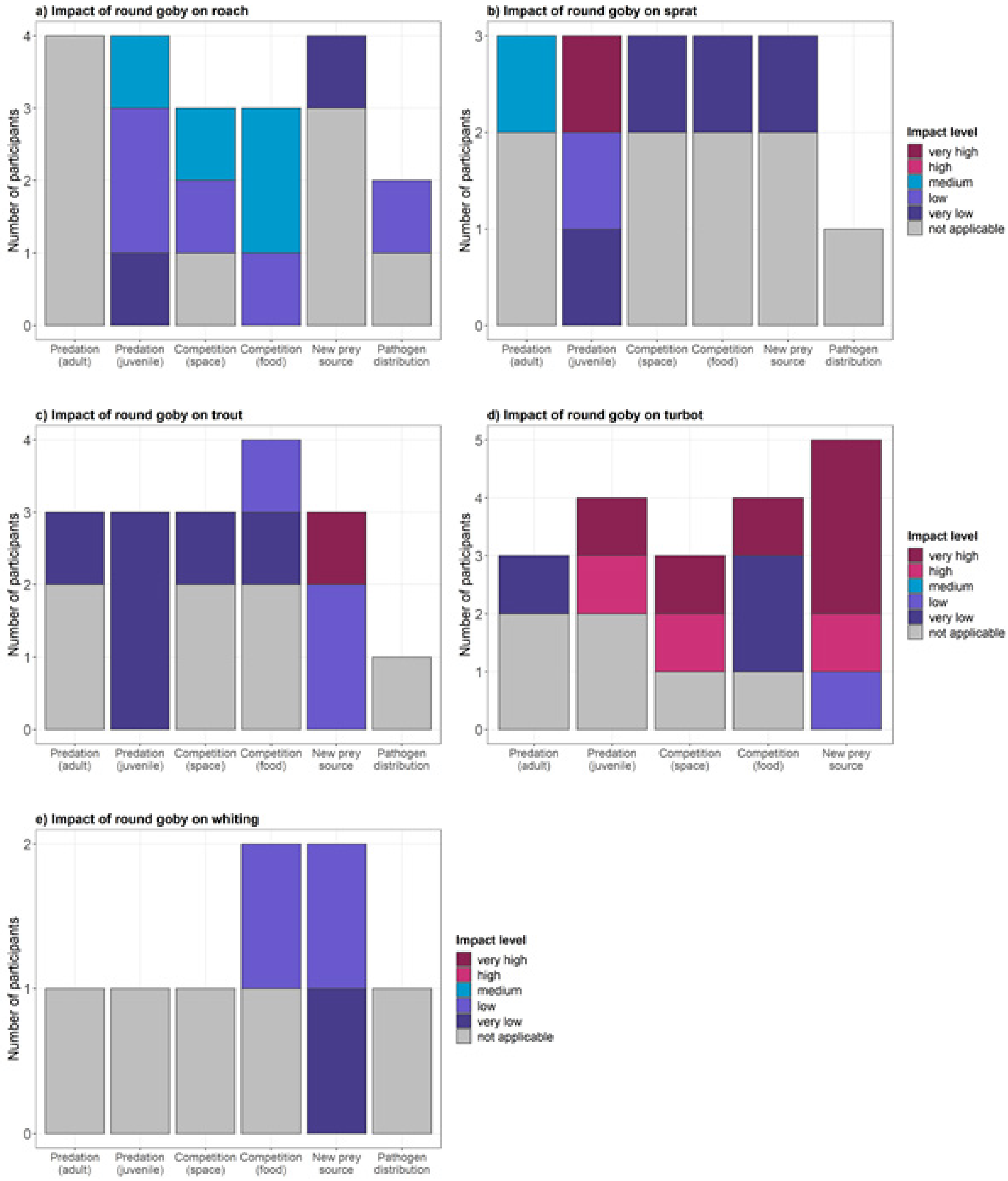


Figure 11: Level of impact of round goby on roach (a), sprat (b), trout (c), turbot (d) and whiting (e) based on survey participant opinion for different impact categories: predation on adult fish; predation on juveniles, eggs and/or fry; competition for space; competition for the same food resources; serving as a new prey species and the introduction/spreading of fish pathogens. Impact is displayed as number of participants per impact category and level (from very low to very high).

3.2.2 Sea walnut (*Mnemiopsis leidyi*)

Information on the impact of sea walnut retrieved from the survey stemmed from Danish and German waters in the Baltic Sea. Sea walnut was estimated to affect cod, flounder, herring, plaice and sprat (Figure 12), whereas the highest impact scores were obtained for herring (Table 11).

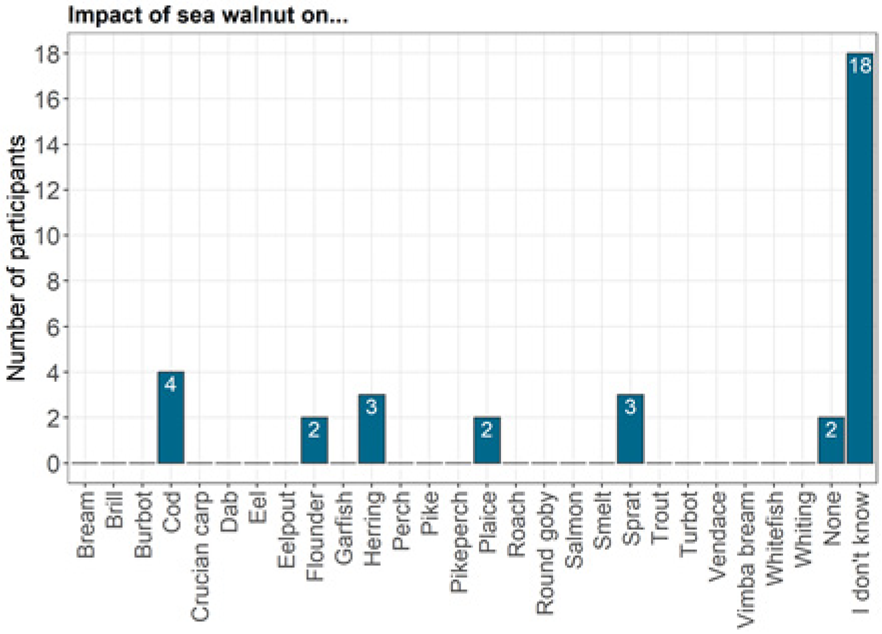


Figure 12: Impact of sea walnut on commercial/recreational-use fish species in the Baltic Sea based on participant opinion retrieved from the online survey. Impact is displayed as number of participants per fish species. The category 'None' was chosen when none of the species are assumed to be affected by sea walnut. 'I don't know' was chosen when survey participants did not have any knowledge regarding the overall impact of sea walnut.

Cod and herring are assumed to be mostly affected through predation on eggs/fry/juveniles as well as competition for food resources (Figure 13a, c). Sea walnut is also judged to have an impact on flounder and plaice through predation on juvenile stages (Figure 13b, d). Survey participants noted that food competition between sea walnut and cod, flounder and plaice is restricted to the larvae and early juvenile stages of the fish. Moreover, sea walnuts have been found in cod stomach contents.

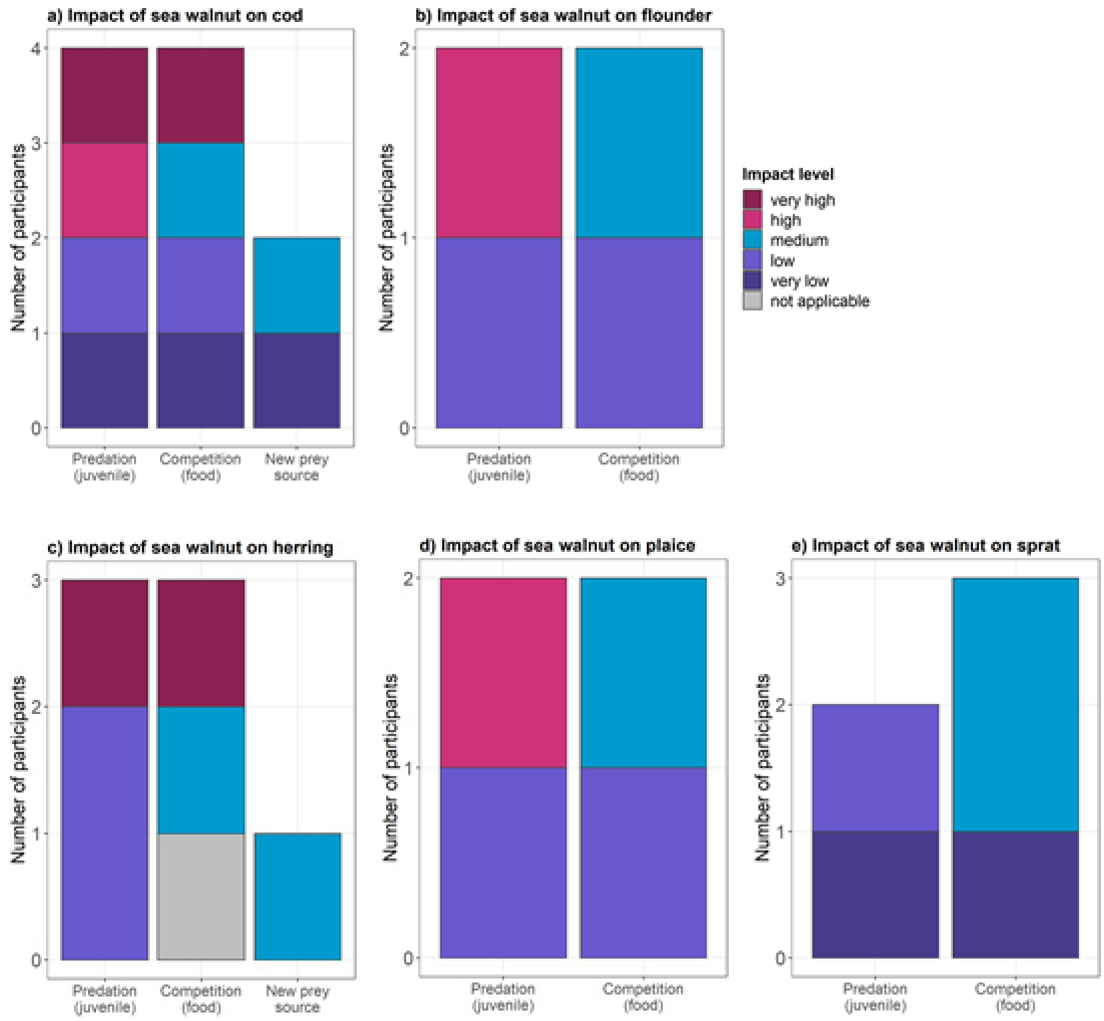


Figure 13: Level of impact of mud crab on cod (a), flounder (b), herring (c), plaice (d) and sprat (e) based on survey participant opinion for different impact categories: predation on juveniles, eggs and/or fry; competition for the same food resources; and serving as a new prey species. Impact is displayed as number of participants per impact category and level (from very low to very high).

3.2.3 Mud crab (*Rhithropanopeus harrisii*)

Survey participants estimated the impact of mud crab on commercial fish stocks based on their experiences from the Finnish, Swedish and German coast of the Baltic Sea. More than one survey participant judged the following fish species to be affected by mud crab: cod, perch, roach and round goby (Figure 14). Impact categories are only shown for these four species (Figure 15), which are assumed to be strongly affected by mud crab because they incorporate the non-native species as a new food resource in their diet. Participants commented that mud crabs are often found in perch stomach contents. The highest impact scores (≥ 2) of mud crab were obtained for bream, burbot, eel, flounder and turbot (Table 11).

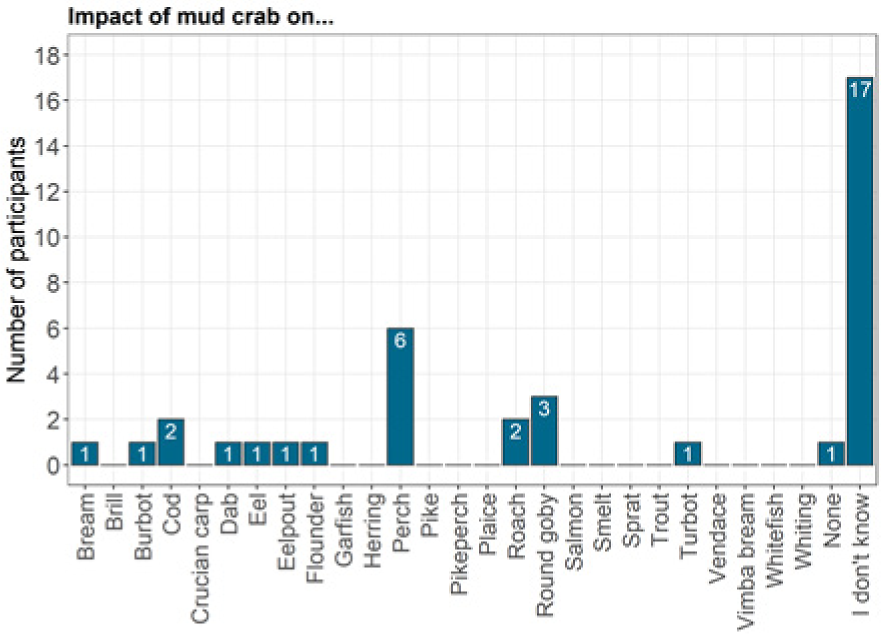


Figure 14: Impact of mud crab on commercial/recreational-use fish species in the Baltic Sea based on participant opinion retrieved from the online survey. Impact is displayed as number of participants per fish species. The category 'None' was chosen when none of the species are assumed to be affected by mud crab. 'I don't know' was chosen when survey participants did not have any knowledge regarding the overall impact of mud crab.

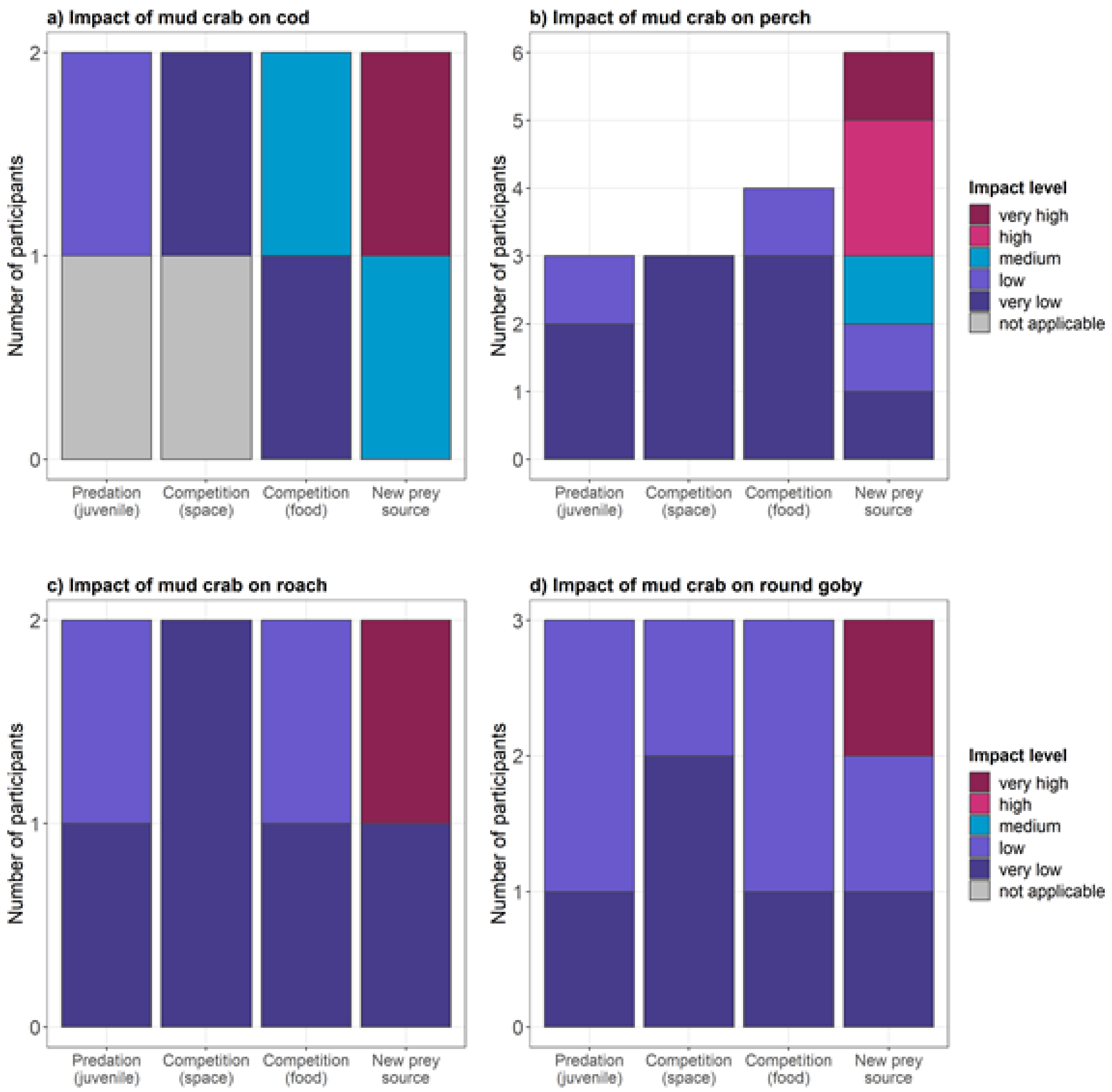


Figure 15: Level of impact of mud crab on cod (a), perch (b), roach (c) and round goby (d) based on survey participant opinion for different impact categories: predation on juveniles, eggs and/or fry; competition for space; competition for the same food resources and serving as a new prey species. Impact is displayed as number of participants per impact category and level (from very low to very high).

3.2.4 Fishhook water flea (*Cercopagis pengoi*)

The impact of fishhook water flea described by survey participants refers to Latvian and Finnish waters as well as the Gulf of Bothnia. Fishhook water flea was estimated to have an impact on three fish species: herring, sprat and whitefish (Figure 16). The highest impact score was obtained for sprat (Table 11).

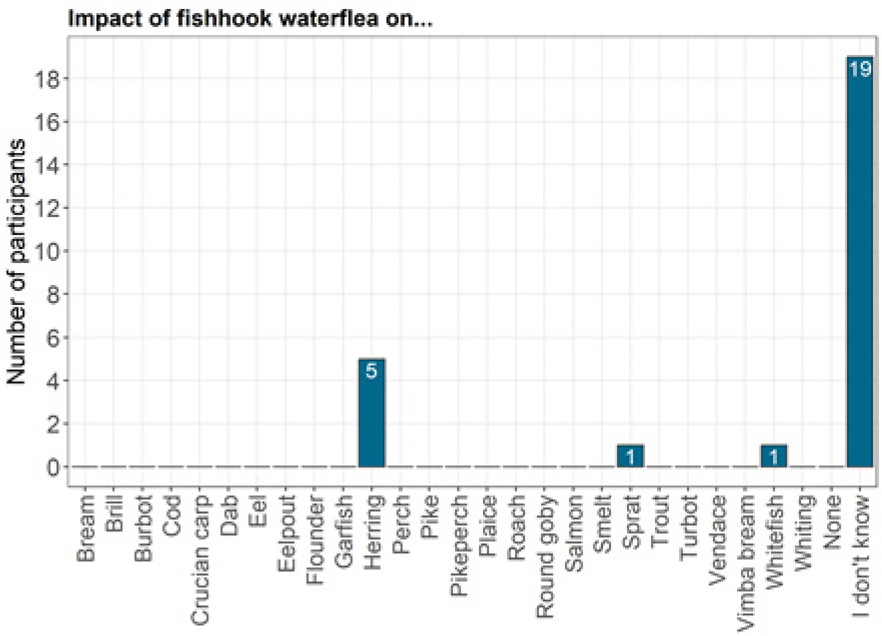


Figure 16: Impact of fishhook water flea on commercial/recreational-use fish species in the Baltic Sea based on participant opinion retrieved from the online survey. Impact is displayed as number of participants per fish species. The category 'None' was chosen when none of the species are assumed to be affected by fishhook water flea. 'I don't know' was chosen when survey participants did not have any knowledge regarding the overall impact of fishhook water flea.

Herring and sprat are assumed to be most strongly affected by fishhook water flea by exploiting it as a new food resource and, to a lesser degree, through food competition (Figure 17a, b). The impact on whitefish was estimated to be low regarding food competition and fishhook water flea serving as a new prey species (Figure 17c).

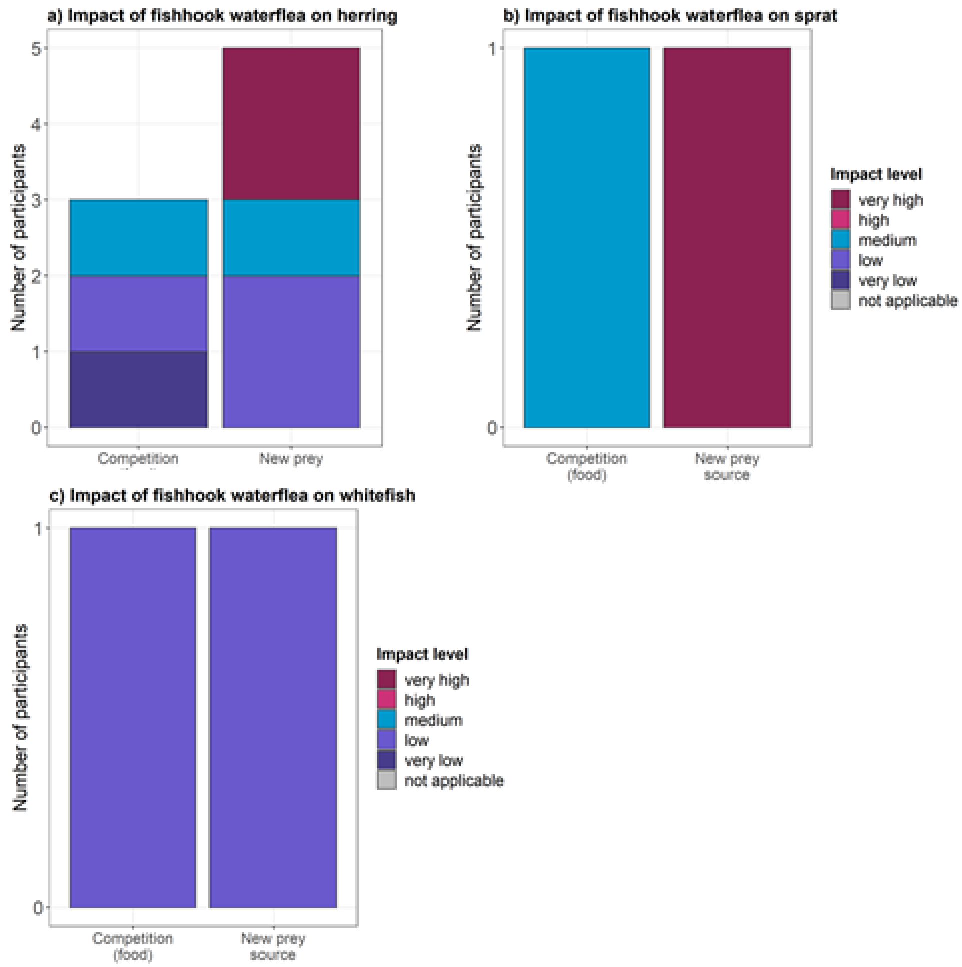


Figure 17: Level of impact of fishhook water flea on herring (a), sprat (b) and whitefish (c) based on survey participant opinion for different impact categories: competition for the same food resources and serving as a new prey species. Impact is displayed as number of participants per impact category and level (from very low to very high).

Table 11: Impact scores of the non-native species round goby, mud crab, sea walnut and fishhook water flea on commercial/recreational-use fish species in the Baltic Sea. Scores were obtained by converting impact levels into impact scores (not applicable = 0, very low = 1, low = 2, medium = 3, high = 4, very high = 5) and averaging these across impact categories per fish species. It should be noted that number of participants judging the impact of the case study species differs between the commercial fish species (cf. numbers in brackets).

Commercially/recreationally used fish species	Round goby	Mud crab	Sea walnut	Fishhook water flea
Bream	0.50 (1)	2.00 (1)	-	-
Brill	2.13 (2)	-	-	-
Burbot	1.42 (3)	2.00 (1)	-	-
Cod	1.47 (10)	1.88 (2)	2.58 (4)	-
Crucian carp	0.50 (1)	-	-	-
Dab	1.00 (1)	-	-	-
Eel	1.38 (4)	2.00 (1)	-	-
Eelpout	2.57 (11)	1.50 (1)	-	-
Flounder	2.00 (9)	2.00 (1)	2.75 (2)	-
Garfish	1.06 (3)	-	-	-
Herring	0.84 (5)	-	2.89 (3)	2.70 (5)
Perch	1.71 (9)	1.69 (6)	-	-
Pike	1.43 (8)	-	-	-
Pikeperch	1.22 (7)	-	-	-
Plaice	2.27 (3)	-	2.75 (2)	-
Roach	1.26 (4)	1.75 (2)	-	-
Round goby	-	1.83 (3)	-	-
Salmon	1.80 (1)	-	-	-
Sprat	0.78 (3)	-	1.92 (3)	4.00 (1)
Trout	0.90 (4)	-	-	-
Turbot	2.31 (5)	2.00 (1)	-	-
Vimba bream	0.33 (1)	-	-	-
Whitefish	-	-	-	2.00 (1)
Whiting	0.42 (2)	-	-	-

3.3 Conclusion

Overall, the literature review results and opinions of survey participants (scientists and fishers) seem to overlap to a large degree regarding the impacts of the four case study species on commercial fish stocks, although survey results generally indicate a greater number of species to be affected compared to literature findings. The incorporation of round goby in the diet of large piscivores, such as cod, perch, pike, pikeperch and turbot and competition for space and food resources between round goby and flounder/eelpout, respectively, are not only suggested by survey participants, but also described in literature. Round goby predation on herring eggs has been observed under field conditions and is, correspondingly, indicated as the strongest interaction between the two species in the survey. Brill, burbot, garfish, trout and whiting represent commercially used species supposedly affected by round goby invasion based on survey results, but are not explicitly mentioned in reviewed literature. While survey participants judged the impact of sea walnut to be rather high on cod and herring due to sea walnut predation on juvenile stages of these fish and their competition for food resources, literature suggests predation on cod eggs to be low. Similarly, published records indicate that food competition might represent a possible impact on pelagic fish species in the Baltic Sea, but has not been documented, yet. Literature review and survey results agree that the presence of mud crab as a new prey source for species such as perch and roach represents its highest impact on commercial fish stocks. While competition for food resources with, e.g., perch, roach and bream, is indicated as a possible impact in available literature, survey participants assigned a lower weight to this impact category. Fishhook water flea is assumed to mostly influence commercial fish stocks like herring and sprat by serving as a new food resource based on published records and survey results. Additionally, competition for the same prey items is suggested for herring and sprat.

General comments from the survey participants regarding the impact of the case study species stated that information on quantitative impacts hardly exist, which is why impacts are often judged based on correlations and spatial overlap between the species. It was also mentioned that national monitoring programmes should incorporate the recording of non-native species.

4 KNOWLEDGE GAPS

Knowledge gaps are by nature difficult to pinpoint. Specific mention of knowledge gaps from any of the reviewed were collected during the literature review (section 3.1). Knowledge gaps stemming from a lack of published information or lack of appropriate studies, which are probably substantial, were discussed based on the expert opinion of the authors of this paper.

In general, there is much published information on the first appearances of new NIS, as well as the discovery of already established NIS in new areas. Reports about the presence of the particular NIS are limited to the specific point in time and specific area and often only the presence of particular NIS in space and time has been reported, with no information on abundances. Some more advanced and sophisticated studies have been conducted, but these studies were limited in terms of time and space. There is a lack of information as to how a particular NIS has settled in a given location, how long it has been present and whether it is still present in the investigated area. Most studies are older, and there is a lack of regular updates on details related to areas of occurrence, abundance or impact on the ecosystem in the invaded area. Thus, several regular environmental monitoring activities have been implemented, for example by HELCOM (see section 7.1). Nevertheless, routine monitoring does not cover all invasion hotspots, habitats and taxonomic groups in many of the countries surrounding the Baltic Sea (HELCOM 2023). Moreover, the scope of the monitoring varies in different areas. Knowledge about abundances of NIS in particular places or depth strata, as well as the occurrence of NIS over time or among seasons, are crucial in the assessment of the impact of particular NIS on commercially important fish species, food webs and ecosystems.

Important knowledge gaps common for many widespread NIS reported from the Baltic Sea are related to the effect these organisms have on commercial fish stocks, as well as the fact that relationships between ecological impacts and changes in fish stocks are difficult to quantify. NIS may have both direct (e.g. prey on eggs of commercially important fish species) and indirect impact (e.g. competition for food). Depending on the species, NIS might have negative (e.g. competition related with food source or space) or positive (e.g. as a new component of a diet) influence on certain native commercial fish species. Data on the general impact are either lacking or very incomplete for the majority of the widespread NIS (Ojaveer et al., 2021).

The presence of parasites in wild fish is the norm rather than the exception, and expansion of NIS to new locations may carry with it an introduction of parasites not previously reported from the particular area. Information about the four case study species as a source of parasites or toxic compounds for piscivorous organisms is scarce.

The effects of NIS on the transfer and biomagnification of contaminants in Baltic Sea food webs is not well known. For instance, studies have shown a potential transfer of mercury from beach wrack to mud crabs, but the importance of this phenomena for commercial fish species is unknown (Graca et al., 2022). On the other hand, the mud crab is highly omnivorous, and other studies have found low mercury concentrations in its tissues (Wilman et al., 2019).

4.1 Round goby (*Neogobius melanostomus*)

The general distribution of round goby is relatively well documented for the Baltic Sea. However, many studies are limited to presence-absence data, and there is sparse detailed data on the present (within the past three to five years) distribution and abundance and on the depth distribution and temporal changes, including seasonal migration. Of the numerous publications on the topic, most studies have focused on new occurrences, often describing only presence and, to a lesser extent, abundance. Information on whether these new occurrences led to established populations over a longer period is also lacking.

While the direct impact of the round goby invasion on commercial fish species has received more attention and may be better known, there are no comprehensive studies on the impact on other species or entire habitats. The round goby may compete for prey with other species, including commercially interesting species, and knowledge of this kind of indirect effect is still scarce. For instance, in recent years, drastic reduction of distribution and abundance of eelpout (*Zoarces viviparous*) in the Baltic Sea has been observed. The question arises whether coexistence of round goby and eelpout is possible or reduction of the eelpout population is related to the increased presence of round goby. The diet composition of round goby has been described only in a few areas of the Baltic Sea (e.g. Karlson et al., 2007), and knowledge related to the local diet of round goby across the Baltic Sea is missing. Since the Baltic Sea holds strong gradients of both salinity and temperature, natural communities vary tremendously from south to north. The feeding regime of round goby from one area may therefore not reflect the feeding regime in other areas. Blue and zebra mussels are known as important elements in the diet of round goby, but the feeding rates on these are unknown. Round goby has also become an important ingredient in the diet of native fish and birds (mainly cormorants). One significant question arises: Has the relatively easy access to an abundant food base, which at some point became the round goby, reduced the pressure of predators (both fish and birds) on commercial fish species?

Seasonal migration patterns of round goby are well described in the Great Lakes in North America (Pennuto et al., 2012). Less is known about seasonal migration patterns in the Baltic Sea. One study reported retreat from the coastal area during winter (Rakauskas et al., 2020). Since round goby constituted the main prey of piscivorous fishes, this migration was reflected in variations of the importance of round goby as their prey. Due to this migration, round goby is becoming increasingly important to offshore piscivores in the Great Lakes (Luo 2019). Further research is needed to investigate if this is also true for the Baltic Sea offshore.

The potential for round goby to invade streams and lakes remains unknown. These areas overlap with the distribution of other gobids, and we have no knowledge on the risk of hybridisation among species.

4.2 Sea walnut (*Mnemiopsis leidyi*)

Although it is well known that sea walnuts cannot reproduce in low saline waters, it is still unclear whether they do indeed reproduce in the Baltic Sea and if their presence is an effect of dispersion only. Monitoring for larvae would establish if reproduction takes place.

While the sea walnut may not prey directly on fish eggs (Jaspers et al., 2011b), it can exert significant changes to the entire planktonic food web when it exists in great numbers. Thus, the sea walnut preys ferociously on zooplankton and may constitute an important competitor for prey to planktivorous fish such as herring and sprat. Significant impacts on the plankton food web have been observed in the Skagerrak (Tiselius and Møller 2017), but nothing is known on the possibility of this phenomenon also happening in the Baltic Sea.

4.3 Mud crab *(Rhithropanopeus harrisii)*

The limitations in our knowledge of the distribution of the mud crab in the Baltic Sea is much like those regarding the round goby. Although areas with mud crab as a common component of benthic communities are described, its abundance is rarely the subject of research. Many publications only describe presence and abundance in newly invaded areas, while even basic information such as the success of the invasion on longer terms is often lacking. Although the distribution of mud crab ranges from southern to northern waters in the Baltic Sea, survey information has been restricted to Finnish, Swedish and German waters, and there are significant spatial knowledge gaps regarding the impacts of this species mainly in the central and southwestern Baltic Sea.

Little is known on the importance of mud crabs as prey for commercial fish species in the Baltic Sea. In areas where they exist in high numbers, mud crab could be an important food source for some fish species, especially this known as crustacean consumers like perch, eel, flatfish, turbot, trout etc. According to Puntila-Dodd et al., (2019) some native fish species from the Northern Baltic Sea such as fourhorn sculpin (*Myoxocephalus quadricornis*), perch (*Perca fluviatilis*), ruffe (*Gymnocephalus cernuus*), pikeperch (*Sander lucioperca*), roach (*Rutilus rutilus*) and other cyprinids consume mud crabs, as mud crabs have been found in the stomachs of all of the above. However, there is no scientific evidence concerning potential predation on mud crabs by the main commercial fish species, and information is limited to personal communication of scientists with local fishers (Fowler et al., 2013). Moreover, the Baltic Sea is an important migration stopover and wintering site for numerous migrating birds. Little is known on the possible importance of mud crabs for these birds.

The mud crab is highly omnivorous, feeding on detritus and plant material, as well as small crustaceans, depending on the habitat. Its diet is mainly driven by food availability (Forsström et al., 2015). In laboratory conditions, mud crabs do consume the soft tissues of fish, such as flounder (Notmant and Gibowicz, 2009; Hegele-Drywa and Normant, 2014). However, mud crab is unlikely to be able to attack living fish, which are more mobile than the crabs, and no fish remains were identified among the analysed animal remains in the stomachs of mud crab in a study of the Baltic Sea (Hegele-Drywa and Normant, 2009).

An increase of mud crab abundance in partially empty niches of various habitats increases their predation pressure on important invertebrate grazers such as small crustaceans (amphipods and isopods), bivalves or snails (Gagnon and Boström, 2016; Kotta et al., 2018; Beleem et al., 2023). Also, as omnivores, mud crabs also consume algae (Aarnio et al., 2015). Thus, mud crabs may compete with native predatory and herbivorous fish in areas where they become abundant. At present, there is no knowledge on the importance of these indirect effects of mud crabs in the Baltic Sea.

4.4 Fishhook water flea (*Cercopagis pengoi*)

The trophic role of the fishhook water flea is complex. It preys on other zooplankton species and thus acts as a competitor for prey to planktivorous fish (Kotta et al., 2004); in addition, the fishhook water flea also constitute prey for these fish (Gorokhova et al., 2004; Kotta et al., 2006; Lankov et al., 2010). Trophic interactions are difficult to predict in such feeding triangles, and more research is needed on interdependent population dynamics of zooplankton, fishhook water fleas and planktivorous fish, such as herring, sprat and smelt. Information on these dynamics from all basins is needed because the distribution of the fishhook water flea in the Baltic Sea may be constrained by prey availability. For instance, fishhook water fleas are seldom observed in the Bothnian Bay. This infrequency has been related to the low zooplankton biomass in the bay, in particular potential prey (Rowe et al., 2016).

4.5 Knowledge gaps identified in the online survey

The online survey showed that the cumulative knowledge of participants on round goby impacts covers multiple regions of the Baltic Sea from Danish waters in the south to Finland in the north. The invasion problem of the round goby in the Baltic Sea seems to be well recognised in its entire Baltic Sea distribution range. This is also reflected in the good coverage of round goby studies across the entire Baltic Sea. The impacts of sea walnut on commercial fish stocks were judged based on participant opinion from Danish and German waters and thus restricted to the southwestern Baltic Sea, coinciding with the main distribution area of this non-native species.

Although the distribution of mud crab ranges from southern to northern waters in the Baltic Sea, survey responses were restricted to Finnish, Swedish and German waters, indicating spatial knowledge gaps regarding the impacts of this species in the central and southwestern Baltic Sea. Responses on fishhook water flea impacts were limited to Latvian and Finnish waters, as well as the Gulf of Bothnia, suggesting that knowledge on the species is spatially restricted to the northern parts of the Baltic Sea, though it has a much wider distribution range.

5 MOST PROBABLE EVOLUTION OF THE IMPACTS

Based on the information in Chapters 2 and 3, we here predict the most probable future evolution of the impacts of the four species in the future Baltic Sea.

5.1 Round goby (*Neogobius melanostomus*)

Round goby is a successful invader well established in many areas of the Baltic Sea. Based on its life cycle and environmental adaption, it is most probable that it will spread into new areas--if any--which have not previously been invaded. Round goby is as old invader, and it is now a rather permanent element of the ecosystem. Thus, their abundance, density and biomass fluctuate in patterns similar to native species which are driven by the same factors. However, in newly settled areas, it may increase the population size (abundance, biomass) in a way typical for invasive species. In areas where they exist in high numbers, round goby may influence native fish species negatively by disturbing spawning (Janssen and Jude, 2001), by consumption of roe and larvae (French and Jude, 2001; Roseman et al., 2006; Wiegleb et al., 2018), by prey competition (e.g., Lederer et al., 2006; Naddafi and Rudstam, 2014; Henseler et al., 2021; Van Deurs et al., 2021) or by competition for space or habitat. On the other hand, this species has become an important prey species for predatory fish and birds (Kornis et al., 2012; Rakauskas et al., 2013; Liversage et al., 2017; Happel et al., 2017), as well as marine mammals (e.g. seals, harbour porpoises) (Andreasen et al., 2017, Scharff-Olsen et al., 2018).

5.2 Sea walnut (*Mnemiopsis leidyi*)

The sea walnut cannot reproduce at low salinity (Jaspers et al., 2011). This is probably the main hindrance for an invasion into the Baltic Sea further than the Bornholm Basin (Haraldsson et al., 2013), and we do not anticipate invasions further north and east. Whether a real Baltic population is established is questionable; most probably, sea walnuts are seeded from the North Sea through the Danish straits but do not successfully reproduce to a larger extent in the Baltic Sea. Increasing temperatures due to climate change may increase the abundance of sea walnuts in the areas they now occupy due to a positive temperature effect on growth and development. However, decreasing salinities, also due to climate change, may counteract this and certainly hamper any further spread into the Baltic Sea. So far, the peak of abundance of sea walnut occurs outside the peak period of herring eggs and larvae and only partially overlap with sprat (Haslob et al., 2007; Kube and Postel, 2008; Javidpour et al., 2009). With increasing temperatures, temporal patterns may change and effects may increase, but the impact of the sea walnut will still depend on seeding from the North Sea. Also, extensive effects of sea walnuts on zooplankton biomasses may cause significant shifts in the prey field of planktivorous fish and fish larvae, with possibly negative effects on these fish stocks.

5.3 Mud crab (*Rhithropanopeus harrisii*)

As the round goby, the mud crab has become an important component of Baltic Sea benthic food webs. Comparing to native populations or populations from some other invaded regions, the presence of mud crabs in the Baltic Sea is not restricted to areas providing a large amount of natural shelters, what facilitates the spread of the species. Although some studies demonstrated that in the Northern Baltic Sea mud crabs prefer vegetated hard bottoms rather than unvegetated boulders and sandy habitats (Nurkse et al., 2015), it has been found in many different habitats, even living devoid of shelter (Fowler et al., 2013). This spatial flexibility might be connected to low availability of natural shelters in the Baltic Sea but also with a lack of predators/low predation pressure and competition (Fowler et al., 2013). This plasticity in habitat choice, as well as its wide tolerance to both salinity and temperature (Costlow et al., 1966), will facilitate the mud crab to spread into areas in the Baltic Sea not yet invaded (if any).

Both direct and indirect effects might escalate with increasing abundance of mud crabs in invaded areas. They have become important prey for native species (Roche and Torchin, 2007, and references therein) and themselves prey on anything from small invertebrates to macroalgae. The effect on the abundance of invertebrates that are prey for mud crabs may be modulated by the temperature, as in higher temperatures the food intake increases (Hegele-Drywa and Normant, 2014; Beleem et al., 2023). Thus, ocean warming may result in increasing predation pressure by mud crab.

In the Caspian Sea, mud crabs have been reported to cause economic loss to fishermen by spoiling fishes in gill nets when they occur at high abundances (Zaitsev and Ozturk, 2001).

5.4 Fishhook water flea (*Cercopagis pengoi*)

In regions where the fishhook water flea exists in high abundances, highest abundances are often found during the warmest months of July through September. It seems high temperature favours this cladoceran, and it is likely that the impacts on commercial fish species of this species will increase in affected areas with increasing ocean warming. Although predicting the actual direction of the changes is difficult, since impacts are both direct (prey) and indirect (competitor for prey), both positive (food source for fish) and negative (competition with larval fish) impacts on the commercial fish species may escalate. But all things being equal, the fowling of fishing gear will increase, should population sizes increase with increasing temperature.

6 POSSIBLE FUTURE INVASION SCENARIOS

Each of the four invasive species has different expansion requirements. Environmental conditions (e.g. salinity, temperature, oxygen concentration, depth, photo period, bottom substrate preferences, etc.) and, as a consequence, the conditions favourable to the expansion of particular NIS in the Baltic differ among regions of the sea. Therefore, three distant regions with different conditions were chosen: the Danish straits, the Central Baltic Sea and the Bay of Bothnia.

The Danish straits are located in southwestern Baltic Sea, where the salinity is the highest, above ten PSU (Hagen and Feistel, 2005) among analysed regions due to the connection with the North Sea. Shallow sills in the Danish Sounds limit the inflow of Atlantic (saline and oxygen rich) water to the Baltic Sea. That region is also characterised by high current velocities (She et al., 2007) that promotes dispersion of organisms and potentially settling new areas.

The offshore area of the Central Baltic Sea has a topographic structure with three deep basins separated by shallow sills hindering the water exchange with the North Sea. These areas differ in their water balance and hydrographic conditions (MacKenzie et al., 2000). The Central Baltic Sea is characterised by salinity, about seven PSU in near-surface layers (Hagen and Feistel 2005). In the Central Baltic deep basins (Bornholm Basin, Gdańsk Deep and Gotland Basin), the hydrographic conditions are strongly dependent on the renewal of the bottom water through inflowing highly saline and oxygenated water masses from the North Sea and the Skagerrak/Kattegat (Möllmann et al., 2000). Vertically, a permanent halocline restricts the water exchange between the bottom water and the surface layer. Salinity and temperature in upper water layers are more influenced by freshwater runoff (Launiainen and Vihma 1990).

The Bothnian Bay represents the Northern Baltic Sea, where the salinity is the lowest among analysed regions. Near-surface layers show typical values of three PSU in the nethermost part of the Gulf of Bothnia (Hagen and Feistel 2005). The influence of inflowing river water is strongest here among the analysed Baltic regions. That area is characterised with long wintertime and the seasonal ice cover can last up to seven months (Seinä and Peltola 1991).

The estimated invasion scenarios for each of the case study species are presented in Table 12 for each geographical region.

Table 12: Invasion scenarios for each of the case study species proposed in selected areas.

Species / area	Danish straits	Central Baltic Sea	Bay of Bothnia
round goby	high	high	high
sea walnut	high	low	no
mud crab	high	high	moderate
fishhook water flea	high	high	low

6.1 Round goby (*Neogobius melanostomus*)

Since the round goby is already established in all areas of the Baltic Sea characterised by favourable conditions, its further spread is hardly possible. However, it may continue to increase in abundance due to its flexible feeding preferences and high tolerance to various environmental factors (Borcherding et al., 2013; Nurkse et al., 2016). The limiting factor might be competition with fish representing the same lifestyle (Kornis et al., 2012) or predation by piscivorous predators (Kornis et al., 2012; Rakauskas et al., 2013; Liversage et al., 2017; Happel et al., 2017). When it exists in high abundances, competition for food might be the limiting factor or a driver for further expansion. Its direct predation on macroinvertebrate communities may lead to significant changes in food webs in invaded ecosystems (e.g., Lederer et al., 2006; Naddafi and Rudstam, 2014; Skabeikis et al., 2019; Henseler et al., 2021; Van Deurs et al., 2021). Increasing dispersion and abundance of that species in the Baltic Sea can have two effects: an increased negative impact on commercially important fish species and / or a widened food base for piscivorous organisms, with important and valuable commercial fish (pikeperch, cod, turbot, perch, pike) among them.

6.2 Sea walnut (*Mnemiopsis leidyi*)

The sea walnut may expand in the Western Baltic Sea. However, since salinity drastically affects reproduction (Jaspers et al., 2011), there is only a low likelihood of expansion to the main basin and further north (Haraldsson et al., 2013). Another limiting factor is lack of tolerance to even the short cold winter period (Jaspers et al., 2018). The occurrence of the self-sustaining populations of sea walnut in other parts of the Baltic Sea would be possible in case of introduction of the populations from the Black Sea, Caspian Sea or the Azov Sea, which tolerate much lower salinities (Ivanov et al., 2000; Shiganova et al., 2001; Jaspers et al., 2021). Increasing dispersion and abundance of that species in the Baltic Sea may increase the negative impact on commercially important fish species in both directions, expanding the geographical scope of impact and strengthening the pressure with increasing abundance.

6.3 Mud crab (*Rhithropanopeus harrisii*)

The mud crab may continue expansion in the Baltic Sea and increase its abundance due to its high tolerance to diverse ranges of salinity, temperature and its habitat flexibility. Since the mud crab already has established populations in all areas of the Baltic Sea characterised with favourable conditions, its further spread is hardly possible. However, due to the requirements related with salinity during the reproduction period, there is no possibility of reproduction in the very northernmost areas of the Baltic Sea, although it cannot be entirely excluded that mud crab may migrate to that area. A flexible diet range is a factor favouring expansion. On the other hand, Nurkse et al., (2015) concluded that the availability of suitable habitats and food availability can influence the abundance of the species in the invaded area.

Invasion of mud crab may lead to significant changes in food webs in invaded ecosystems: reduction of bladderwrack-associated native invertebrate species (Jormalainen et al., 2016, Forsström et al., 2015) or changes from community dominated by herbivorous and periphyton-grazing gastropods and crustaceans to a mussel-dominated community (Jormalainen et al., 2016). Increasing dispersion and abundance of that species in the Baltic Sea may increase the negative impact on commercially important fish species.

6.4 Fishhook water flea (*Cercopagis pengoi)*

The fishhook water flea may regulate the zooplankton communities, and the high abundance of fishhook water fleas is often related to a lower abundance of other cladoceran species (Kotta et al., 2004; Ojaveer et al., 2004) and a higher abundance of copepods (Kotta et al., 2004). The fishhook water flea may also influence the seasonality of zooplankton abundances (Ojaveer et al., 2004). Increasing dispersion and abundance of that species in the Baltic Sea may increase the negative impact on commercially important fish species.

7 RECOMMENDATIONS

7.1 Recommendations for monitoring of existing NIS

Monitoring the presence and impacts of NIS is considered an important part of marine environmental management and sustainable development. However, despite the stated intention of focusing on NIS in the MSFD, apart from a few baseline surveys, monitoring targeting NIS specifically is scarce. Important management objectives include the early detection of NIS in dispersal hubs and bridgeheads, as well as long-term monitoring for tracking the effects of NIS within recipient ecosystems especially vulnerable to introductions (Lehtiniemi et al., 2015). Hence, the strategy should be double-edged, and although rapid assessments of target species in important invasion areas are important, it should not replace long-term monitoring. To support legislative requirements, collected data should be verified and stored in a publicly accessible and routinely updated database/information system. Moreover, public involvement should be encouraged as part of monitoring programmes where it is feasible (Lehtiniemi et al., 2020).

In 2021, the COMPLETE project[6] finalised recommendations for monitoring NIS in the Baltic Sea. These recommendations were adopted as a programme topic by HELCOM (2021b). In addition, new methodological guidelines were included to complement traditional biological monitoring methods currently in place.

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[6] The COMPLETE project is an Interreg funded project, tackling several knowledge gaps regarding introduction and spread of non-indigenous and potential invasive species by shipping (2017-2021). https://www.balticcomplete.com/

HELCOM's COMBINE monitoring programme (Cooperative Monitoring in the Baltic Marine Environment) is currently used to record the presence-absence and densities of NIS in phytoplankton, zooplankton and benthic animals in all Baltic sub-basins (HELCOM 2017). Unfortunately, several habitats and taxonomic groups are not included in the monitoring programme. Additionally, the programme is not sufficient in monitoring NIS on a temporal and spatial scale (fixed sampling stations), which is why HELCOM suggests using other additional surveys to monitor NIS presence and spread:

1. The HELCOM coastal fish monitoring and the Baltic International Trawl Surveys (BITS) provide information on NIS presence-absence, spread and abundance/biomass. Non-indigenous fish and mobile epifauna are often caught, and records should be made available for the national authority responsible for managing NIS. However, while information retrieved from these surveys are important, the records are non-systematic and may not reflect actual density or distribution of mobile epifauna.
2. The HELCOM/OSPAR port survey protocol provides information on NIS found in ports to support decisions on granting exemptions (HELCOM 2013). The protocol includes detailed sampling information, with a focus on different port habitats and species groups (also including plankton surveys). In addition, this protocol has been well tested in several ports around the Baltic Sea and North Sea and is regularly updated and routinely used.
3. Coastal monitoring for mobile and sessile epifauna uses should include fouling plates and so-called habitat collectors, which are three-dimensional structures deployed to the sea floor to attract mobile benthic animals such as crustaceans and fish, but which also attract sessile organisms like barnacles and bivalves (HELCOM 2021a).
4. Molecular methods are rapidly evolving and are expected to become established within pre-existing and future monitoring protocols (e.g. Pujolar et al., 2022). These methods are useful for early detection, detection of original invasion and secondary spread and determination of the genetic makeup of founding populations (e.g. Jaspers et al., 2021). A particular strength is the detection of NIS from genetic profiles within water, so-called eDNA (e.g. Dias et al., 2017). Molecular methods are particularly useful for NIS detection at early life-history stages (due to difficulties in their identifications), at initial stages of invasions and when occurring at low densities and in limited areas (Xia et al., 2017; Holman et al., 2019; Miralles et al., 2019; van den Heuvel-Greve et al., 2021).

HELCOM has released specific guidelines for 1) monitoring NIS using molecular tools, 2) monitoring NIS in biofouling, 3) monitoring NIS in ballast water and 4) citizen involvement in NIS monitoring. These are all described in HELCOM's Monitoring Guidelines[7].

7.2 3.2Species-specific recommendations for future monitoring

7.2.1 Round goby (*Neogobius melanostomus*)

Ship ballast water is an important dispersal pathway for round goby (Brown and Stepien 2009; LaRue et al., 2011). For this reason, the HELCOM Baltic Sea Action Plan (BSAP) will contribute to round goby monitoring, at least regarding its distribution development. The potential origin of invasions in ports was considered in the HELCOM BSAP, and an early warning system to detect new invasive species is expected to be in place by 2024 as a tool in the AquaNIS database (see also the section 'Recommendations for monitoring of existing NIS' in HELCOM Baltic Sea Action Plan, 2007). In addition to dispersal with ballast waters, spread between areas may also occur via active migration of the fish (Behrens et al., 2022; Christoffersen et al., 2019). This is something that needs further study, e.g. via tagging efforts or capture-recapture studies, to identify the best monitoring strategies for

[7] https://helcom.fi/action-areas/monitoring-and-assessment/monitoring-guidelines/

identifying 'hotspots' for active dispersal, both in time and space. To support effective management, there is a need to predict NIS distribution and identify areas with the highest invasion risk (Florin et al., 2018). Mapping of shipping routes would be important to determine likely dispersal routes of round goby throughout the world.

Currently, for most regions and in most cases in the Baltic Sea, only presence data are available to obtain an overview of the distribution of round goby, while abundance data are very limited or non-existent. The most accurate abundance data are available from commercial fisheries in Latvia. However, regular monitoring to estimate round goby abundance is necessary to assess its region-specific impacts. Since this information is not available yet, we were not able to assess round goby impacts as a function of abundance in this report. We therefore recommend the development and establishment of regular monitoring programmes for round goby, taking into account seasonal migration pattern into deeper waters (Behrens et al., 2022). For effective round goby monitoring, gillnets and eel traps appear to be the most effective trapping methods that most reliably document round goby abundance (ICES 2022). Round gobies are also found in port monitoring surveys and coastal NIS monitoring in baited minnow traps and habitat collectors (Outinen et al., 2019).

For early detection and monitoring of range expansion, eDNA can be an efficient tool for round goby (cf Snyder & Stepien, 2020; Snyder et al., 2020). The scarcity of abundance data for round goby may be partially overcome through the use of eDNA. The method can be used in any substrate type and is not limited by fishing gear. However, before applying eDNA as a systematic monitoring or quantification tool, for each species we must understand how DNA is released to the aqueous environment and the interactions of DNA with various biotic and abiotic factors. Thus, specific studies on release rates and environmental decay have been conducted for round goby (Nevers et al., 2018).

7.2.2 Sea walnut (*Mnemiopsis leidyi*)

The presence of the sea walnut in the Baltic Sea is still confined to the higher saline areas west of the Bornholm Basin (Jaspers et al., 2011; Haraldsson et al., 2013; Jaspers et al., 2013; Jaspers et al., 2018). This limited presence is explained by drastic effects of salinity on reproduction rates, where low saline waters of the central and eastern Baltic Sea have been documented to limit population persistence (Jaspers et al., 2011; Jaspers et al., 2013). The sea walnut reaches exceptionally high abundances in the southwestern Baltic Sea and the Danish straits Kattegat and Skagerrak (Jaspers et al., 2018). So far, regular monitoring to estimate its abundances is limited to the BITS survey and local research projects (see Jaspers et al., 2018). We therefore recommend the development and establishment of regular monitoring programmes for *M. leidyi*, taking into account seasonal distribution pattern and salinity impacts on distribution ranges. For effective monitoring, bongo and multinet casts are suggested.

Although it is well known that sea walnuts cannot reproduce in low saline waters, it is still unclear if they do indeed reproduce in the Baltic Sea and if their presence is an effect of dispersion only. Monitoring for larvae would establish whether reproduction takes place.

7.2.3 Mud crab (*Rhithropanopeus harrisii*)

Routine biological monitoring in the Baltic Sea does not include monitoring of coastal mobile fauna. The most commonly used method to collect mud crabs is with habitat collectors, i.e. cages filled with bivalve or oyster shells or ornamental stones (Roche et al., 2009; Fowler et al., 2013), in which the crabs may enter and leave the trap during the deployment period. During summertime, the crabs usually inhabit the trap until it is retrieved in late summer. This method is presently used in HELCOM/OSPAR port surveys (HELCOM, 2013) and habitat collectors have also been included in new method guidelines in the HELCOM NIS monitoring programme (HELCOM, 2021a). We recommend developing this method for all applicable regions. Monitoring of crabs is not routinely conducted in all Baltic Sea countries yet, but as habitat collectors are presently included into the monitoring manual, the situation will probably improve in the future.

The eDNA sample analysis has also been tested for mud crab monitoring (Forsström and Vasemägi, 2016). These tests showed that DNA from mud crab can be successfully amplified in aquarium water samples and detected in the brackish water environment. However, the detection rate was low, which suggests that, in contrast to freshwater vertebrates, it may be more challenging to develop a highly sensitive eDNA method for detecting crustacean species in a marine environment (Forsström and Vasemägi, 2016).

Since the mud crab has pelagic freely swimming larvae, we also recommend collecting and cataloguing observations of larvae with the routine HELCOM COMBINE mesozooplankton monitoring (Kotta and Ojaveer, 2012; HELCOM, 2021c).

7.2.4 Fishhook water flea (*Cercopagis pengoi*)

Fishhook water flea is an abundant zooplankton species during summertime in warm water temperatures. It mainly occupies the water column above thermocline, but individuals are also found in deeper water layers (Lehtiniemi and Gorokhova 2008, Naumenko 2018). HELCOM COMBINE monitoring programme includes a manual for mesozooplankton sampling (HELCOM 2021) which all countries surrounding the Baltic Sea follow and have been following since 1979. Mesozooplankton sampling is conducted two to twelve times a year, depending on the sub-basin and country, and summertime is included in the sampling scheme in the whole Baltic Sea. Fishhook water flea is thus monitored routinely, as it is trapped in the net used (WP-2 plankton net) in monitoring among other zooplankters and identified from the preserved samples. Fishhook water flea numbers are counted from the samples; therefore, data show both abundance and distribution of the species in the Baltic Sea. Fishhook water flea monitoring is currently well conducted in the whole Baltic Sea.

The ecological role of the fishhook water flea is complicated by the fact that it both functions as prey for planktivorous fish, such as herring, sprat, smelt and stickleback, as well as the fact that it competes for zooplankton prey with these same fish species. Trophic interactions are difficult to predict in such feeding triangles and more research on interdependent population dynamics of zooplankton, fishhook water fleas and planktivorous fish is needed.

7.3 Possibility of minimising impact on commercial fish stocks and fisheries (including eradication effort and fisheries on NIS)

Although impacts may vary temporally and spatially, it seems that the impact of round goby and mud crab lies primarily in changing the prey field of demersal predators such as cod, perch and pikeperch. The two species may become important prey items in areas where they exist in abundance. The invasions of sea walnut and fishhook water flea mainly affect herring, sprat and smelt. Fishhook water flea may become a major prey item for all three species (Ojaveer et al., 2004) and is actively selected as prey. Both fishhook water flea and sea walnut constitute an important competitor for zooplankton prey to all three species in areas where they are abundant; for *M. leidyi*, this means the primarily higher saline waters west of the Bornholm Basin (Jaspers et al., 2011; Haraldsson et al., 2013; Jaspers et al., 2013; Jaspers et al., 2018).

Eradication of established invasive populations is unlikely and has been achieved only in rare cases where the presence of the NIS was detected early. The two most noticeable examples are the eradication of the black-striped mussel *Mytilopsis sallei* in Darwin Harbour, Australia (Willan et al., 2000) and the macroalga *Caulerpa taxifolia* in Agua Hedionda Lagoon and Huntington Harbour, California (Anderson, 2005). The aims of management should therefore focus on reducing populations to levels that exert lower impacts considered acceptable (Usseglio et al., 2017). The most realistic option is to suppress invasive populations to levels below which significant harm on native ecosystems is avoided and where the resilience of these ecosystems is secured (Green et al., 2014). A comprehensive approach to invasive species management should consider: the expected impacts of these species on native ecosystems, the available technical intervention options, their expected likelihood of success and their cost, the risks associated with management and, finally, the extent of public support and stakeholder support for the proposed interventions (Hulme, 2006).

To evaluate possible options for the management of the four species, we conducted a survey of opinion among all authors of the present report. Knowledge on NIS in the Baltic Sea is extensive among the authors, and their judgement of possible means of management is that of experts. The survey followed the method of Giakoumi and colleagues (2019). Eleven different management actions were judged:

Action 1: Physically (mechanically) remove the species.
Action 2: Rehabilitate the environment (e.g. protect and/or restore marine areas).
Action 3: Encourage the targeted removal and commercial and/or recreational utilisation of dead specimens (trading live specimens for use in aquaria is not included).
Action 4: Deploy biocides in the sea, tactically applied.
Action 5: Promote native consumers (predators or grazers) that feed on the invasive species (e.g. by restocking predator populations).
Action 6: Encourage native diseases and/or parasites that affect the invasive population.
Action 7: Apply biological control, using alien parasites and/or diseases.
Action 8: Apply biological control, using alien consumers (predators or grazers).
Action 9: Apply genetic approaches that affects only the invasive species.
Action 10: Education and public awareness.
Action 11: Do nothing.

Management Actions 5-9 have been previously applied in freshwater environments and have been included here to explore their potential in the Baltic Sea. The respondents were asked to evaluate the eleven management actions using the following criteria: a) the effectiveness of the action, b) its technical feasibility, c) its social acceptability, d) its negative impacts on native communities and e) its direct cost. Scores from 1 to 5 were given to each criterion for each action. A value of 5 was given to highest effectiveness, highest technical feasibility, highest social acceptability, minimal impact on native species and lowest cost, respectively. A value of 1 was given to lowest effectiveness, lowest technical feasibility, lowest social acceptability, maximal impact on native species and highest cost, respectively. Results are shown in Figure 18.

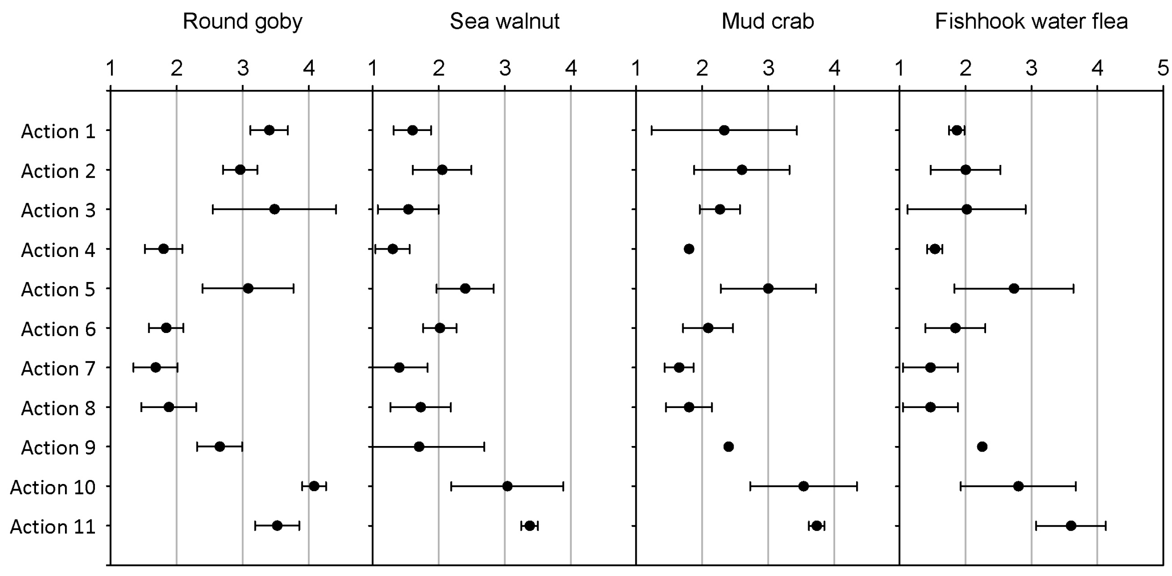

Figure 18: Expert evaluation of the eleven proposed actions to control the four species in the Baltic Sea. Values ranging from 1 to 5 indicate increasing effectiveness, technical feasibility, social acceptability and decreasing impact on native species and cost. See the text for a detailed description of the actions and the method of assessment.

Across all four species, the two soft management actions 10 and 11 elicited the highest scores (Figure 18). This was mainly because of high scores for social acceptability, technical feasibility and cost. On the other hand, the effectiveness of these measures was naturally judged very low (averages across species of 1.7 and 1.1, respectively). Actions 1, 2 and 3 also received relatively high scores for the two benthic species round goby and mud crab, whereas these actions were judged low for the two pelagic species sea walnut and fishhook water flea. These actions are worth considering for benthic nearshore species, such as round goby and mud crab, but physical removal, rehabilitation of the environment or commercial exploitation are, logically speaking, not valid options for planktonic species. Actions 4, 6, 7 and 8 all received low scores. Thus, deploying biocides, encouraging native diseases or applying alien diseases, parasites or consumers are not advisable options. Action 9 (applying genetic measures affecting only the invasive species) got scores in only eight out of fifteen expert/species combinations, and results should be judged with caution. Promotion of native consumers were judged as a more effective and feasible action with relatively minor impact on native species or communities. The establishment of invasive species in a given habitat is often promoted by a prior decrease in species diversity, which opens up for empty ecological niches to be exploited by the invader. Sound environmental management achieving good ecological status with abundant top predators should therefore minimise the impact of invasive species.

For round goby, Action 3 (encouraging targeted removal and commercial and/or recreational utilisation of dead specimens) was judged as an effective and feasible option for management by three of five experts. This action encompassed the option for targeted fishery (see below).

7.4 Recommendations on fisheries on NIS

Fisheries in the Baltic Sea primarily target other commercially valuable species, such as herring, cod, salmon and sprat. However, round goby abundances are high, and it is becoming an important species for coastal fishing in some regions (ICES 2022). Round goby is currently fished commercially with pound nets and trap nets along the shores of Latvia, Lithuania and Estonia (SD 26, 28.1, 28.2, 29 and 30). Since 2012, landings have increased from a few kilos to more than 900 tonnes in Latvia, ca. 150 tonnes in Lithuania and more than 250 tonnes in Estonia in 2021 (ICES 2022). Catches were over 400 tonnes in the Gulf of Riga alone in 2021. In Latvia, round goby is the second most important commercial fish species after herring, and catches reached over 1000 tonnes in the record year of 2018.

In Latvia, this fishery constitutes an important income for local fishers, recent years have seen the round goby become the second-most-fished species after herring (Ustups 2021), and the round goby fishery has created additional income possibilities for local fishers. Presently, with decreasing populations of eastern Baltic cod and many other locally important species, the additional fishing opportunities for round goby can compensate for income loss. However, round goby fishing is heavily dependent on the market. Fishers mainly export frozen fish to Ukraine. Only a minor amount is also sold on the local market. In order for this resource to be used successfully, the round goby should also be integrated into the market and cuisine of the Baltic Sea countries.

It is difficult to judge whether this kind of fishery could be used as a general measure to limit round goby populations throughout the Baltic Sea. At present, there are no general stock assessment, and the overall biomass of populations in the Baltic Sea is unclear (ICES 2022). However, local stock assessment of round goby along the Latvian coast have showed indications that fishing may be able to control round goby populations locally. This assessment showed a period of fast population development from 2014 to 2015, which led to high catches some two years later. The continuing increase in fishing pressure since then has decreased the round goby population biomass by more than half (ICES 2022). Modelling results suggest this was primarily driven by decreases in spawning stock biomass and recruitment. Thus, the recruitment index has decreased to less than a third. Concurrently, the fishing mortality index increased from 0.02 to 1.22, a high value indicating that the fishery's role in the overall stock reduction could be significant. So

Latvian round goby fishery is an example of a successful mechanism to limit population density of round goby, at least locally. An increase in round goby population size, emerging market opportunities and national fisheries policy have all promoted the rapid growth of the specialised goby fishery in Latvia. The more than 50% reduction of the population size shows that the population would no longer be able to recover to the same abundance, should the fishery continue (BIOR 2022). In Latvia, several fishing management activities have been implemented to minimise bycatch while maximising round goby catch efficiency:

1. *Gear and method development*. Experiment with gear modifications to optimise round goby capture. Round goby specialised fishery using round goby gillnets was started back in 2015. Fishing season and gear mesh size were estimated based on results from scientific coastal gillnet surveys. The effectiveness of round goby trap nets was tested in cooperation with the local fishers, which resulted in the development of more efficient round goby gillnets (60-70 mm mesh size, diagonal width) and round goby trap nets (24-36 mm mesh size, diagonal width). These specialised gears are similar to other coastal gears – the main difference is smaller mesh size, gillnet height limit (1.5 m). Some catches are also taken using herring pound nets and trap nets and eelpout fyke nets.
2. *Regulatory Compliance*. For NIS, catch quotas are not set, but this could be regulated by season and with effort. The fishing season for the specialised round goby fishery was set from April to July. After this period the activity of round gobies declined and bycatch rate was up to 90%. Based on these findings, the autumn fishery was not implemented. The fishing effort is regulated by the number of issued fishing gears in municipalities.
3. *Monitoring and Assessment*. Continuously monitor round goby populations and adjust fishing practices and regulations as needed to maintain sustainability. The Latvian coastal fisheries management scheme involves annual data collection from the commercial and scientific fishery followed by information analysis and biological parameter estimates to assess stock status of round gobies. All available information is used to develop annual scientific advice for the local policymakers suggesting necessary changes in fishing policy and defining allowable fishing gear limits in each coastal municipality. There is no current information available on active round goby fishery management in other Baltic Sea countries (ICES 2022).

Increased fishery for round goby will inherently increase the bycatch of native fish species inhabiting the same biotope. As a result, in Latvia, regulations have been implemented to reduce bycatch in round goby fisheries. Studies in Karlskrona and Muskö have shown a bycatch of herring between 40–50% in gillnets, while the round goby catch contributed only 38% at most (ICES 2022). On the contrary, round goby dominated fyke net catches in the same area with 84%. Based on these results, modified fyke nets have been tested, in which escape patches were installed in order to allow bycatch species, mainly eel, to escape. We recommend that, if a commercial fishery for round gobies is to be established in larger parts of the Baltic Sea, experts and authorities must collaborate with each other in order to effectively research species status and ecology. It is essential to develop regulations to ensure long-term ecological balance and minimise bycatch and habitat damage.

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