University of Latvia
Faculty of Biology

Ēriks Krūze
Doctoral Thesis

Round goby *Neogobius melanostomus* (Pallas 1814) population development and role on the demersal fish community

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Supervisor: Dr. biol. Didzis Ustups

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Abstract

The Baltic Sea unique physical and ecological characteristics makes it very vulnerable to various environmental and anthropogenic pressures, such as invasive species. The successful invasion of the round goby (*Neogobius melanostomus*) gives a considered example of how a new species adopts and develops a stable population by occupying a niche of great importance for the local fish communities. In this study, the spatiotemporal development of the round goby population in Latvian waters is characterized for the first time. Native demersal fish response via population long-year trends are analyzed in periods before and after the advancement of the invasion (1979-2021). Aspects of the potential interspecific interactions of the round goby with the native fish are described through food basis analysis. The results describe shifts in cyprinid and piscivore population trends after 2009. While turbot (*Scophthalmus maximus*) juvenile recruitment significantly decreased following the invasion of round goby through food competition, along with decreasing biomass trends of benthic fish and invertebrate species that appeared in the Gulf of Riga offshore. Considering a possible shift in the ecosystem functioning, possible further management features are included which could be directly applicable for monitoring recommendations for the round goby as its role in the local ecosystem persists and becomes significant for the local fisheries.

Keywords: The Baltic Sea, round goby, invasion, effects on local fish, feeding analysis, coastal fish monitoring

Kopsavilkums

Baltijas jūras unikālās fiziskās un ekoloģiskās īpašības padara to jutīgu pret dažādu vides un antropogēno faktoru ietekmi, piemēram, tādu kā invazīvo sugu izplatīšanos. Veiksmīgā apaļā jūrasgurduļa (*Neogobius melanostomus*) invāzija dod uzskatāmu piemēru tam, kā jauna suga pielāgojas un attīsta stabilu populāciju, ieņemot nišu, kas ir svarīga vietējām zivju sabiedrībām. Šajā pētījumā pirmo reizi raksturota apaļo jūrasgrunduļu populācijas attīstība Latvijas ūdeņos. Izmantojot populāciju ilgtermiņa tendences, analizēta vietējo bentisko zivju sugu iespējamā atbildes reakcija, laika periodos pirms un pēc invāzijas (1979-2021). Barības bāzes analīze apraksta to, kā savstarpēji mijiedarbojas apaļais jūrasgrundulis ar vietējām zivīm. Rezultāti liecina par izmaiņām karpveidīgo un plēsīgo zivju populāciju tendencēs pēc 2009. gada. Bet akmeņplekstu (*Scophthalmus maximus*) mazuļu pieaugums ievērojami samazinājās pēc tam, kad bija sākusies apaļā jūrasgrunduļa invāzija barības konkurences ietekmē. Novērota bentisko zivju un bezmugurkaulnieku sugu biomasas tendenču samazināšanās Rīgas jūras līča atklātajā daļā. Ņemot vērā iespējamās izmaiņas ekosistēmas darbībā, ir aprakstītas iespējamās turpmākās pārvaldības iezīmes, tostarp tieši piemērojami ieteikumi attiecībā uz piekrastes zivju monitoringu, jo apaļais jūrasgrundulis turpina ietekmēt vietējo ekosistēmu un tas ir kļuvis par nozīmīgu zvejas objektu.

Atslēgvārdi: Baltijas jūra, apaļais jūrasgrundulis, invāzija, ietekme uz vietējām zivīm, barošanās analīze, piekrastes zivju monitorings

Abbreviations

BIOR – Institute of Food Safety, Animal Health and Environment "BIOR"

BITS – The Baltic International Benthic Trawl Survey

BSAP – The Baltic Sea Action Plan

CFP – European Union common fisheries policy

CPUE – The Catch per Unit Effort

DAU – Daugavgriva monitoring station

EBA – Ecosystem-based approach

EBM – Ecosystem-based management

EEZ – The Latvian exclusive economic zone

EMFAF – European Maritime, Fisheries and Aquaculture Fund

EU – European Union

FAO – Food and Agriculture Organization of the United Nations

FL1 – Flounder juveniles to 3.5cm

FL2 – Flounder juveniles 3.5-5cm

FL3 – Flounder juveniles 5.5-9.5cm

FL4 – Flounder juveniles 10-15cm

GLMM – Poisson generalized linear mixed model

HELCOM – The Baltic Marine Environment Protection Commission

ICES – International Council for the Exploration of the Sea

IEAs – Integrated ecosystem assessments

JUR – Jurkalne monitoring station

MBU – Monciskes/Butinge monitoring station in Eastern Gotland Basin

MSFD – The Marine Strategy Framework Directive

RG1 – Round goby 3-5cm

RG2 – Round goby 7-14cm

RG3 – Round goby 15-21cm

TAC – Total annual catch

TRIM – Statistical Trends & Indices for Monitoring Data Analysis

TU1 – Turbot juveniles to 4cm

TU2 – Turbot juveniles 4-8cm

TU3 – Turbot juveniles 9-18cm

WRS – Wilcoxon rank-sum test

Contents

1 Introduction

1.1 Actuality of the research

1.1.1 Current management of the Baltic Sea fish stocks

The Baltic Sea with its low water exchange and high anthropogenic pressures makes its ecosystems vulnerable to various impacting factors (Dobrzycka-Krahel & Bogalecka, 2022). Its young age, physical and geographical characteristics are unique, so there are not many examples in the World to compare (Snoeijs-Leijonmalm et al., 2017). The brackish water type of the Baltic Sea is suitable for both marine and freshwater species, so the diversity is high in terms of species richness (H. Ojaveer et al., 2010), (Plikss &Aleksejevs, 1998), (Hunt, 2022), nevertheless, most of the dominant fish populations are under heavy fishing pressure and their stocks are strictly supervised by the responsible authorities at the international level (Lado, E. P. 2016), (European Commission, 2007). Therefore, lots of funding is invested in cross-border scientific monitoring programs to record its condition across the whole Baltic Sea, for example, the BONUS program (Andrusaitis et al., 2016) and the common data collection framework (European Commission 2017a), (Palialexis et al., 2021). This makes the Baltic Sea one of the most explored Seas in the world with predominantly identified ecological challenges and possible actions for solutions (E. Ojaveer, 2017), (Dobrzycka-Krahel & Bogalecka, 2022). The Baltic Sea is compared with a time machine to look into the future of other Seas (Reusch et al., 2018). However, the colonization of the invasive round goby (*Neogobius melanostomus*) in the Baltic Sea and its successful integration into the local ecosystem obliges new kind of challenges in monitoring systems and the development of new aspects for the future fisheries management of the demersal fish communities (H. Ojaveer et al., 2015).

In the central Baltic Sea, as well as the Latvian exclusive economic zone (EEZ), there are internationally developed strategies for managing fisheries and coordinated monitoring programs to provide critical data within the multiannual plan for fisheries (European Commission 2020). Latvia is a member of the European Union (EU) and therefore must comply with EU regulations and policies related to fisheries (FAO fishery law 1995). As well as adopts the European Maritime, Fisheries, and Aquaculture Fund (EMFAF) program, for implementing the EU common fisheries policy (CFP) (European Commission, 2017b), which aims to promote sustainable fisheries management practices in Europe. The CFP seeks to ensure that fishing activities are environmentally, economically, and socially sustainable, while also providing maximum long-term yields within an ecosystem approach that considers the precautionary principle. It sets the framework for fisheries management in Europe and includes measures such as setting fishing quotas, regulating fishing gear and practices, and promoting sustainable aquaculture and the fishing industry (Eero et al., 2021). Decisions are made based on independent scientific advice provided by the International Council for the Exploration of the Sea (ICES) (Linke et al., 2023). Also, as a member of ICES Latvia is providing the best available data and expertise to ensure the highest standards of independent scientific advice. ICES influences the fisheries in the Baltic Sea by providing independent scientific advice to policymakers and stakeholders which is a basis for setting the annual total allowed catch (TAC) for the most important commercial fish species (ICES, 2012). ICES evaluates the status of fish stocks, provides advice for sustainable fishing levels, and assesses the impact of fishing activities on the marine ecosystem by developing recommendations. Considering the ICES scientific advice and EU regulations on the most commercially important fish species, such as cod *Gadus morhua*, European eel *Anguilla anguilla*, salmon *Salmo salar*, herring *Clupea harengus*, sprat *Sprattus sprattus*, flounder *Platichthys flesus,* and Sea trout *Salmo trutta*, local management can be fulfilled in the form of regulations on fishing efforts and implementation of ecological indicators target values into policy-making (Linke et al., 2023). A key role in developing and using such indicators is a variety in fisheries independent monitoring and reliable commercial statistics, for example, in the Baltic and North Sea regions, the demersal Eelpout *Zoarces viviparus* serves as a bioindicator of local pollution and is a suitable species for the assessment of the Good Environmental Status of the Baltic Sea (Hedman et al., 2011). Such a single-species approach involves a systematic examination of individual species, considering their biological characteristics, population dynamics, and interactions with the environment, to provide informed guidance and management strategies that prioritize the sustainable utilization and conservation of specific fish populations (Vinther et al.,2004). However, it is important to assess the sensitive local fish communities at the national level to make the conservation measures more efficient (Vullioud, 2016). Latvia has its own fisheries management system, which is implemented through the Ministry of Agriculture. In the form of scientific advice, management of local fish populations is performed based on scientific observations and commercial log-book records (zm.gov.lv).

1.1.2 Implementation of a new approach in fisheries management

A mixed-type species approach should be developed because multiple fish species are caught in the same area, and different fleets catch differing proportions of the different fish species therefore significantly increasing the fishing mortality (Vinther et al., 2004). The overall aim is to implement an ecosystem-based approach (EBA) in Maritime Spatial Planning, monitoring, and fish stock assessment thus it is important to expand the research in different species, trophic levels, and spatial areas in the Baltic Sea (European Commission, 2021). Integrated ecosystem assessments (IEAs) have been developed as formal synthesis tools to analyze information on relevant natural and socio-economic factors for specified management objectives. Ecological indicators are crucial to develop IEAs which serve as quantitative measures to capture key ecological processes, species populations, and environmental conditions within a given ecosystem (Eero et al., 2021). It is important to focus on implementing the IEA approach for the Baltic Sea fish stocks, combining tactical and strategic management aspects into a single strategy that supports the present Baltic Sea fish stock advice conducted by the ICES (Möllmann et al., 2014). IEAs are a key tool for implementing Ecosystem-Based Management (EBM) approaches to the management of fish resources to make scientifically based decisions that balance environmental, social, and economic objectives. Well-developed Ecological indicators are important to ensure EBM because they serve as proxies for several complex ecological processes and are representations of the ecosystem state to promote more sustainable and resilient ecosystems while ensuring the continued provision of ecosystem services for current and future generations (Tam et al., 2017). It is important to use a variety of sampling methods so ecological indicators can better capture the variability of the ecosystem and improve the accuracy and reliability of the assessment.

Overall, the use of multiple sampling methods and a combination of data in ecological indicator development can enhance the effectiveness and usefulness of indicators for ecosystem management and decision-making (Sparrow et al., 2020). Fish population trends are crucial in developing ecological indicators, that assess and monitor the health of aquatic ecosystems, they are typically based on spatiotemporal data collected through fishery-independent surveys, that provide information on the abundance, biomass, and distribution of various fish species (Coll et al., 2016). Ecological indicators rely on the responsiveness of fish population trends to environmental changes, including habitat quality, pollution, climate change, fishing pressure, and the presence of invasive species. By using ecological indicators, policymakers can make informed decisions and take appropriate actions to protect the marine environment and make the EBA operational. For example, the piscivore indicator is globally applicable to most aquatic systems and is linked to commercially valuable fish availability and food web functionality as piscivores play a role in regulating the food web. Higher values of this indicator indicate a healthier environmental state. In contrast, the Cyprinid indicator is associated with eutrophication and nutrient-enriched areas, and higher values suggest a more deteriorated state, it is taxonomically limited to freshwater species and can be only applied in fresh and brackish waters. In marine coastal areas, it may potentially be substituted by other predominating meso-predators (Bergström et al., 2019).

Ecological indicators play a crucial role in the implementation of the Marine Strategy Framework Directive (MSFD), (Marine Strategy Framework Directive 2008/56/EC) which holds the European Union policy aims to protect the marine environment and ensure its sustainable use. ICES maintains substantial international long-term databases on marine living resources and the marine environment required for defining targets and setting thresholds for MSFD indicators (Cardoso et al., 2010), (European Commission 2008).

1.1.3 Relevance to the environmental framework

Latvia as the engaged party of a regional agreement– The Baltic Sea Action Plan (BSAP), developed by the Baltic Marine Environment Protection Commission (HELCOM) is involved in assessing the environmental issues facing the Baltic Sea. This outlines specific measures and targets for reducing pollution and restoring the ecological health of the sea. The plan includes a set of ecological indicators to monitor progress toward the targets, which are used to assess the effectiveness of the measures taken (HELCOM, 2021). While the MSFD sets overarching goals and principles, the BSAP provides a more detailed and tailored approach to address the specific environmental challenges faced by the Baltic Sea ecosystem. The BSAP aligns with the MSFD by integrating its objectives and measures into the regional context, ensuring consistency and cooperation among the Baltic Sea countries in implementing the MSFD.

This study, as well as the whole round goby case in the Baltic Sea, is relevant to the assessment of the MDFD Descriptors 1 ”Biological diversity is maintained”(MSFD D1); Descriptor 2 “Non-indigenous species introduced by human activities are at levels that do not adversely alter the ecosystems” (MSFD D2), Descriptor 3 “Populations of all commercially exploited fish and shellfish are within safe biological limits” (MSFD D3); Descriptor 4 “All elements of the marine food webs, to the extent that they are known, occur at normal abundance and diversity” (MSFD D4) and Descriptor 6 “The sea floor integrity at a level ensuring benthic ecosystems not adversely effected” (MSFD D6) (Behrens et al. 2019).

In a situation where a commercially valuable invasive species creates a bioeconomic paradox (Harris et al. 2023), the Baltic Sea round goby case creates a complex condition for the potential outcome of multiple MSFD Descriptors assessment results. Therefore, it is important to implement the descriptors possibly contradictory target values cautiously on the species.

1.1.4 Management aspects of a new invasive fish species in the Baltic Sea

Within the Baltic Sea, more than 100 invasive species have been identified, although only a fifth of these have managed to establish a widespread presence (Ojaveer and Kotta 2015). One of the widespread and most successful invasive species in the region is the round goby that has established large populations in the Baltic Sea (Behrens et al.,2022a), (Kornis et al. 2012), (Van Deurs et al., 2021). Originally arising from the Ponto–Caspian region the species was introduced with ships ballast waters and swiftly spread into the Baltic Sea. Starting in the Gulf of Gdansk in 1990 (Sapota 2004), later invading neighbouring coastal waters in the 2000s (Puntila et al., 2018) and spreading across most of the Baltic Sea coastal areas in the 2010s (Behrens et al.,2022b). With a dispersal rate of 30 km per year (Azour et al., 2015) and its aggressive behavior (Marentette et al., 2011) round goby executed an easy assimilation into the vulnerable ecosystem of the Baltic Sea. As an invader, the round goby negatively impact native species and alter ecosystem dynamics (Järv et al., 2011). Effective management strategies are needed to control its spread and mitigate its ecological and economic impacts. Therefore developed monitoring programs should include activities: to assess population trends and distribution; to implement control measures for prevention of further spread; to raise awareness among stakeholders to encourage cooperation in managing this invasive species (Ojaveer et al., 2015). Additionally, international collaboration and coordination are crucial for addressing the administration aspects and challenges associated with management strategies and evaluating the effectiveness of control measures (Reusch et al., 2018). Understanding these factors will give input in the development of effective management strategies to control the round goby impact on native species and assess its interactions with commercially important fish species which enables to predict and mitigate the potential negative effects on local fish populations and fisheries (Behrens et al., 2022a), (Liversage et al., 2017).

The round goby management should be started with attaining validated estimates of the current status of the population based on an appropriate monitoring program. Additionally, standardized further observations should be established under supervision at a regional management body level such as HELCOM (H. Ojaveer et al., 2015). The Latvian round goby case is a suitable basis for the development of new guidelines for widely applicable management strategies due to the local population size of the species and the availability of knowledge from well-adapted targeted fisheries experience together with independent scientific observations (Ustups, 2021).

1.2 The Aim of the Study

The aims of this study are: to describe the colonization of the local ecosystem by an invasive fish species; to assess the demersal fish community changes; to develop methods for further fisheries management based on gained new knowledge.

1.3 Research hypothesis

The invasion of the round goby triggered a shift in the demersal fish community, through temporal changes in the food web functioning.

1.4 The main tasks of the study are to:

1. To characterize population development of the round goby by combining data sets from different monitoring methods.
2. To compare the fish population trend changes before and after the invasion of round goby.
3. To describe the interspecific interactions between the round goby and native fish species via food niche analysis.
4. To develop recommendations on the improvement of the existing coastal fish monitoring to better understand the round goby population dynamics.

1.5 Thesis for defense

The successful invasion of the round goby irreversibly changed the native demersal fish species community by affecting the population's temporal size and the food web functioning.

1.6 Approbation of the research results

1.6.1 The thesis is based on the following Papers:

(I) Kruze, E.; Avotins, A.; Rozenfelde, L.; Putnis, I.; Sics, I.; Briekmane, L.; Olsson, J. 2023. The Population Development of the Invasive Round Goby *Neogobius Melanostomus* in Latvian Waters of the Baltic Sea. Fishes, 8, 305. **IF 3.17** https://doi.org/10.3390/fishes8060305

(II) Kortsch, S., Frelat, R., Pecuchet, L., Olivier, P., Putnis, I., Bonsdorff, E., Ojaveer, H., Jurgensone, I., Strake, S., Rubene, G., **Kruze, E.,** Nordstrom, M. C. 2021. Disentangling temporal food web dynamics facilitates understanding of ecosystem functioning, Journal of Animal Ecology, 90, 1205-1216. **IF 5.608** https://doi.org/10.1111/1365-2656.13447

(III) Ustups, D., Bergstrom, L., Florin, A. B., **Kruze, E.**, Zilniece, D., Elferts, D., Knospina, E., Uzars, D. 2016. Diet overlap between juvenile flatfish and the invasive Round Goby in the central Baltic Sea. Journal of Sea Research, 107, 121-129. **IF 2.029** https://doi.org/10.1016/j.seares.2015.06.021.

(IV) Bergström, L., Heikinheimo, O., Svirgsden, R., **Kruze, E.**, Lozys, L., Lappalainen, A., Saks, L., Minde, A., Dainys, J., Jakubaviciute, E., Adjers, K., Olsson, J. 2016. Long term changes in the status of coastal fish in the Baltic Sea. Estuarine, Coastal and Shelf Science, 169, 74-84. **IF 3.229** https://doi.org/10.1016/j.ecss.2015.12.013.

1.6.2 Conferences

Baltic Sea Science Congress 15-19 June 2015 Riga, Latvia; "Transitional fish classification index (TFCI) adaptation for Latvian transitional waters"; Perkons V., **Kruze E.**, Strake S.

74th International Scientific conference of the University of Latvia 1. February 2016 Latvijas ūdeņu vides pētījumi un aizsardzība," Mencu (*Gadus morhua*) barošanās izmaiņas Baltijas jūras centrālajā daļā"; **Kruze E.**

75th International Scientific conference of the University of Latvia 2. February 2017 Latvijas ūdeņu vides pētījumi un aizsardzība," Apaļā jūrasgrunduļa ietekme uz Baltijas jūras piekrastes ekosistēmu"; Putnis I., Briekmane L., Jermakovs V., Knospina E., **Kruze E.**, Strake S., Ustups D.

BONUS Symposium 17-19 October 2017 Tallinn, Estonia; Science delivery for sustainable use of the Baltic Sea living resources, Session 3: Ecosystem internal and external drivers of change affecting biodiversity "The round goby *Neogobius melanostomus* colonization and potential impact on the coastal food web in Latvia"; Knospina E., Putnis I., Briekmane L., **Kruze E.**, Ustups D.

BONUS Symposium 17-19 October 2017 Tallinn, Estonia; Science delivery for sustainable use of the Baltic Sea living resources, Session 4: Temporal dynamics in biodiversity "Has climate change affected the body condition of Baltic cod *Gadus morhua L.* In the eastern Baltic Sea?" Plikshs M., Amosova V., Baranova T., Elferts D., Karpushevskaya A., Karpushevskiy I., **Kruze E.**, Patokina F., Sics I., Statkus R., Vasilijeva T., Zezera A., Casini M.

BIOR International Scientific Symposium 30-31 January 2020 Riga, Latvia; Science to Strengthen Sustainable and Safe Food Systems," Has climate change affected feeding and body condition of Baltic cod *Gadus morhua* L. in the Gotland basin of the Baltic Sea" Plikshs M., Baranova T., **Kruze E.**, Sics I.

11th International Conference on Biodiversity Research, 20-21 October 2022, Daugavpils, Latvia; "Diet, growth and body condition of Baltic cod (*Gadus morhua*) in response to ecosystem changes in the Eastern Baltic Sea" **Kruze E.**, Baranova T., Sics I., Putnis I., Rozenfelde L., Plikss M., Deksne G., Ustups D.

1.6.3 This dissertation includes research results and funding

The Latvian Work Plan for data collection in the Fisheries and aquaculture sector.

Annual Contract with the Ministry of Agriculture the Republic of Latvia on research, regulation of use, and reproduction of fish resources.

The Fundamental and Applied Research program project "Baltic cod (*Gadus morhua*) condition and health status in the changing ecosystem of Eastern Baltic: CODHEALTH" (lzp-2021/1-0024)

1.6.4 Scientific novelty

This dissertation offers a new original overdue per-viewed reference on the round goby invasion history in Latvian waters as well as characterizes its impact on local fish communities as well as demonstrates a so far overseen practically applicable method of comparison and statistical evaluation of different sampling methods for characterization of overall trends in changes in fish populations.

1.6.5 Aspects of environmental policy

The implementation of scientific marine fish monitoring results in fisheries management is critical for ensuring the long-term sustainability of fish populations and the local communities that depend on them.

This dissertation provides peer-reviewed methodological guidance on assessing results and planning for future monitoring of demersal fish altogether as well as can be considered in decision-making at the National level in the form of the Institute of Food Safety, Animal Health and Environment "BIOR" recommendations on sustainable use of fish resources in the Latvian waters and is intended to be used in developing a pioneering stock assessment for the round goby in The Baltic Sea. The content of this dissertation will be integrated into the HELCOM 4th International Baltic Sea thematic assessment of coastal fish in November 2023 (HELCOM FISH– PRO III 2018-2023) serving in the development of new indicators (like the round goby population trend), filling knowledge gaps on the species and in updating the coastal fish monitoring guidelines.

1.6.6 Practical significance

1. Widely applicable recalculation coefficients between "Coastal net series" and "Nordic Coastal Multi-mesh" type monitoring nets data are provided allowing the use of the historical data of the round goby.

2. An easy-to-use statistical tool that has been created for wildlife monitoring data, is introduced first time in the field of fisheries

3. Specific recommendations on better future monitoring design for the coastal fish communities are developed to include the round goby

4. The results of this study will be integrated into:

- A new INTERREG project" Promoting commercial fishing of round goby in the Baltic Sea" in 2024 (https://interreg-baltic.eu/toolkit/bamos/) where commercial round goby fishing possibilities will be evaluated across the whole Baltic Sea region to assess commercial fishing opportunities of the species as well as the effects on the reduction of the population.
- As well as it adds practical knowledge in an ongoing (2020-2025) Project LIFE19 NAT/LV/000973 REEF "Research of marine protected habitats in EEZ and determination of the necessary conservation status in Latvia" in activities Action C2: Development of the management plan for MPA, action C3: Development of an action plan for limiting impact of invasive marine species and development of mitigation measures to reduce seabird and marine mammal bycatch in coastal fisheries and action C4: Development of scientific advice for updating of national fishery management in Latvian coastal waters to reduce seabird and marine mammal bycatch (https://reef.daba.gov.lv/public/eng/).

2 Materials and Methods

2.1 Study area and the temporal coverage of the data

This study was performed in the Latvian EEZ waters, encompassing the Central Baltic Sea, the Eastern Gotland subbasin, and the Gulf of Riga. Both offshore and coastal areas of the Gulf of Riga and the open sea were surveyed (Figure 1).

Four distinct fish sampling methods were employed in this study: coastal fish monitoring (1995-2021); Gulf of Riga bottom trawling (1980-2021); open sea bottom trawling as part of the Baltic International Benthic Trawl Survey (BITS) (2015-2021); an annual beach-seine survey (1998-2014). Hydrological parameters: temperature, salinity, and oxygen levels were registered in the stations during the sampling of fish and no abnormalities were observed over the study period (BIOR unpublished hydrographical data until 2021).

2.2 Demersal fish sampling methods

2.2.1 Beach-seine survey1998-2014 (Paper III)

The beach-seine study was conducted annually in late spring or early summer at the southwestern corner of the Latvian coast of the eastern-central Baltic Sea (Figure 1A.). Each sampling occasion involved five hauls per location perpendicularly to the shoreline using a seine with a mesh size of 10mm in the wings and 5mm in the cod-end. The wings had a width of 12.5m, with a vertical opening of 1.5m. All captured fish and invertebrates were sorted by species, counted, weighed (total weight per species), and immediately preserved in ethanol (80%) for further detailed analysis and stomach content examination in the laboratory. Mysid and decapod abundance obtained in the samples were encountered as bycatch.

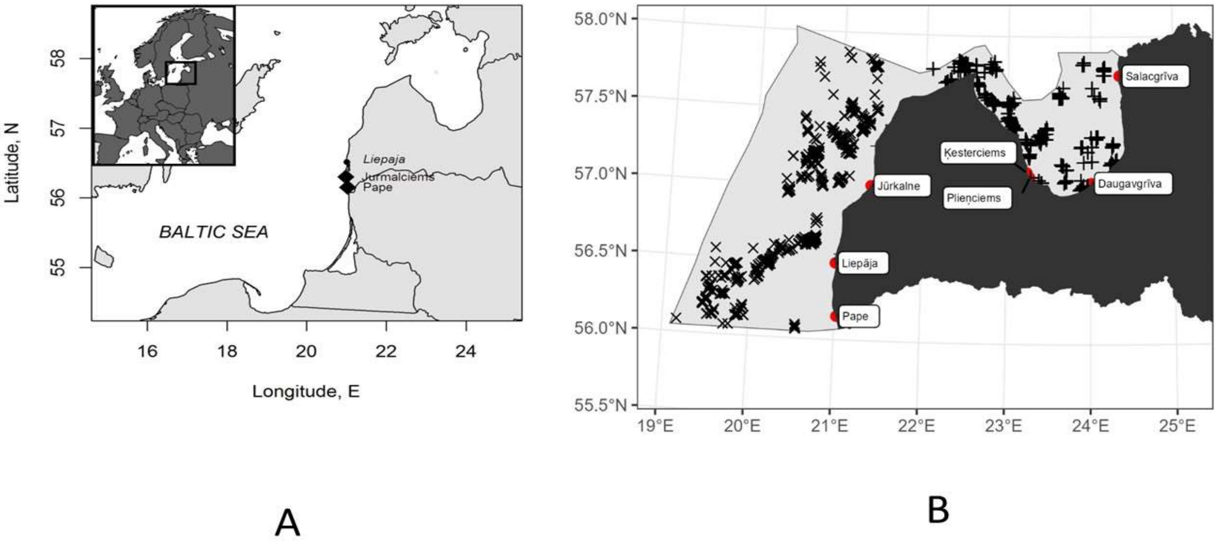


Figure 1. Map of the study area: black diamonds– beach seine stations (**A**) (Paper **III**), red dots– coastal fish monitoring stations, crosses– Gulf of Riga and X Open Sea trawling sites (**B**) (Paper **I**).

2.2.2 Coastal fish monitoring1991-2021 (Papers I and IV)

The coastal fish monitoring from 1991 to 2013 was performed using only “Coastal net series” in Daugavgriva (DAU) and Jurkalne (JUR) (Figure 1b.), but for the round goby population development study additional coastal monitoring data from Liepaja, Pape, Kesterciems, Plienciems and Salacgriva was used from 2005-2021. For the standard “Coastal net series”, the gillnets linen was made of multifilament twine (“Capron” or “nylon- 6”) and it has six 30m long panels with mesh sizes in order 17; 22; 25; 30; 33; 38mm. After 2016 “Nordic Coastal Multi-mesh” was applied which consists of nine 5m long panels with mesh sizes in order 30; 15; 38; 10; 48; 12; 24; 60; 19mm whose linen is made of nylon monofilament twine. Both methods were intercalibrated and coefficients were developed for “Nordic Coastal Multi-mesh” nets (Annex 1). Simultaneous application of the methods was used in 2014-2016 for calibration of the catches between the two gears.

2.2.3 Gulf of Riga bottom trawling 1979-2021 (Papers I and II)

The Gulf of Riga bottom Trawl surveys were performed annually in May, August, and October in the Gulf of Riga ICES Sub-division 28.1 (Figure 1B, Annex 2, Annex 3) according to the standard BITS manual. Sampling was performed with a special demersal trawl that is 18m wide and 1.5m high and has a mesh size that ranges from 6mm to 17mm in the cod-end (Paper **I)**. To characterize the benthic fish and zoobenthos species population trends in the Gulf of Riga, surveys that were performed in May and in stations deeper than 20 m were involved in the analyses including sampling stations of the northern part of the Gulf of Riga before the year 1991 when surveys were performed also in the Estonian EEZ (Annex 3, Paper **II)**.

2.2.4 Baltic International Benthic Trawl Survey 2015-2021 (Paper I)

The surveys were conducted annually in March and December in the open sea area of Latvian waters of the Baltic Sea (Figure 1B, Annex 2), following a random stratified station selection design in areas with trawlable bottom types. Besides biological measurements, detailed information on the hauling site and environmental parameters were recorded according to the international protocol (ICES, 2017).

2.3 Data processing and statistical analysis used for achieving the tasks of the study

2.3.1 Population development estimates of the round goby (Paper I)

To characterize changes in the round goby population inter-calibration between data sets from two similar coastal sampling methods was performed. The historically applied "Coastal net series" (1995-2013) and newly adopted "Nordic Coastal Multi-mesh" nets (2014-2021) were used simultaneously in 2014-2016 in seven monitoring sites. The recalculation coefficients (Annex 1) were obtained per 1cm length groups for 5-26 cm long round goby to be further multiplicated with "Nordic Coastal Multi-mesh" catchability values. Secondly, the newly obtained round goby trends from coastal fish monitoring were combined with trends from two directly incomparable offshore monitoring methods using the statistical Trends & Indices for Monitoring Data (TRIM) analysis (Bogaart et al., 2020). Yearly indices were calculated from one value per monitoring site per year and obtained trends were combined using model variance-covariance matrices. The combined round goby population trend was used in further characterization of the population development.

2.3.2 Native fish population changes before and after the invasion (Papers III, IV, and II)

While comparing shallow-water beach seine monitoring fish abundance, the data were divided into two periods: before (1998-2008) and after (2009-2014) the round goby colonization in the study area. Changes in the abundance of native fish species between the periods were assessed using a Poisson generalized linear mixed model (GLMM) where the year was added as a random factor (Paper **III)**.

There were two indicators used to assess the overall status of the coastal fish communities: Piscivores (predators) and Cyprinids (predominating mid-trophic level group). The indicators were assessed for trends within ten-year intervals in DAU and JUR. The Catch per Unit Efforts (CPUE) were calculated as the mean biomass per net and fishing day, based on total annual landings and gillnet efforts, and further aggregated to the level of the sub-basin area. The trends were developed by describing the relative changes occurring over time in each area, employing a sliding window approach spanning 10 years. To analyze the trends, linear regression was applied utilizing square-root transformed and normalized data. Additionally, the frequency of observed trends was assessed through a chi-square test. Species included in the piscivore indicator were perch (*Perca fluviatilis*), cod, pike (*Esox lucius*) and pikeperch (*Sander lucioperca*), turbot, salmon, garfish (*Belone belone*), greater sandeel (*Hyperoplus lanceolatus*) and asp (*Aspius aspius*). The Cyprinids indicator represented species within the taxonomic family Cyprinidae of which the main species included in the analysis were roaches (*Rutilus rutilus*) and breams (*Abramis* spp.). Both indicators were selected to be independent of species identity to ensure comparability across geographical areas despite potential natural differences in species composition (Paper **IV**). Trends of demersal fish species in the open part of the Gulf of Riga were achieved from the Gulf of Riga bottom trawling surveys (see section *2.2.3*). Times series data were obtained over 38 years from 1979 to 2016 for benthic fish (Annex 3). Although complex modelling of the Gulf of Riga food web was performed in the study (Paper **II**) only benthic fish and zoobenthos biomass trends were characterized in this doctoral thesis.

2.3.3. Interspecific interactions via food niche analysis (Papers II and III)

Besides spatiotemporal observations of demersal fish populations stomach contents of 9 different fish species (round goby, flounder, turbot, three-spined stickleback *Gasterosteus aculeatus*, greater sandeel (*Hyperoplus lanceolatus*), lesser sandeel (*Ammodytes tobianus*), perch, sand goby (*Pomatoschistus* spp.) and the European smelt (*Osmerus eperlanus*) and in total 2 793 individual stomachs were analysed. The analysis of fish diet composition was performed for two time periods: before the invasion of round goby in the area (1998-2004) and during the actual invasion (2013-2014). Round goby, flounders, and turbots were assigned in size groups: for flounder to 3.5cm (FL1), 3.5-5cm (FL2), 5.5-9.5cm (FL3), and 10-15 cm (FL4); for turbot juveniles to 4cm (TU1), 4-8cm (TU2), and 9-18 cm (TU3); for round goby to 5cm (RG1), 7-14 cm (RG2), and 15-21cm (RG3). The frequency of occurrence of each food item was expressed as a percentage of stomachs per haul. For flounder, turbot, and round goby feeding success was assessed by the proportion of empty stomachs to understand the feeding patterns and competition among fish species. Food items were identified and categorized into nine groups: Amphipods, Bathyporeia, Decapods, Fish, Molluscs, Mysids, Polychaetes, Zooplankton, and unidentified food items. Wilcoxon rank-sum test (WRS) was used to analyze the differences in food composition among length groups of flounder and turbot and as multiple tests per group were performed, p-values were adjusted using the Bonferroni correction. To describe the food niche of the benthos-eating fish species the environmental data of macro zoobenthos organisms were obtained in the beach seine survey as bycatch (Paper **III**). In the open part of the Gulf of Riga (Station 119) (Annex 3) benthos biomass ($g/m2$) was recorded within the national monitoring program (https://latmare.lhei.lv/). From 1979 to 2016 samples were collected annually in the spring from February to June and later trends of zoobenthos organisms were compared in the periods before and after the round goby invasion (Paper **II**).

2.3.4. Developing recommendations for the improvement of the existing coastal fish monitoring (Paper I)

Monthly distribution of the average relative catches across years 2005 to 2021 for the round goby were obtained from the coastal monitoring data to describe their activity and catchability in passive fishing gears across the whole year. A total of 42 stations distributed within seven areas across the Latvian coastline were included in the study. After accounting for the maximum number of fishing occasions per site and month, a total of 1 141 data points were available for further analysis (Annex 4).

To determine the abundance of individuals caught in different fishing gears at separate length groups, 1cm length categories were employed for individuals measuring above 10cm. For smaller fish length groups and fish larger than 21 cm, the weighted mean body length based on counts was calculated.

3 Results

3.1 Population development of the round goby *Neogobius melanostomus* (Paper I)

The first record of round goby on the Latvian coast was made in 2004 near Liepaja (Minde, 2007). However, the first coastal commercial catches of the species appeared two years later, when the total annual catch was registered as 6.3 kg. In the coming years, an increase in the population size occurred, and logbook records from the fishery showed a rise from less than one ton in 2011 to over 1 112 tons in 2018, recording a slight decrease after this year (Figure 2). Recently, commercial landings increased in the eastern part of the Gulf of Riga (Annex 6).

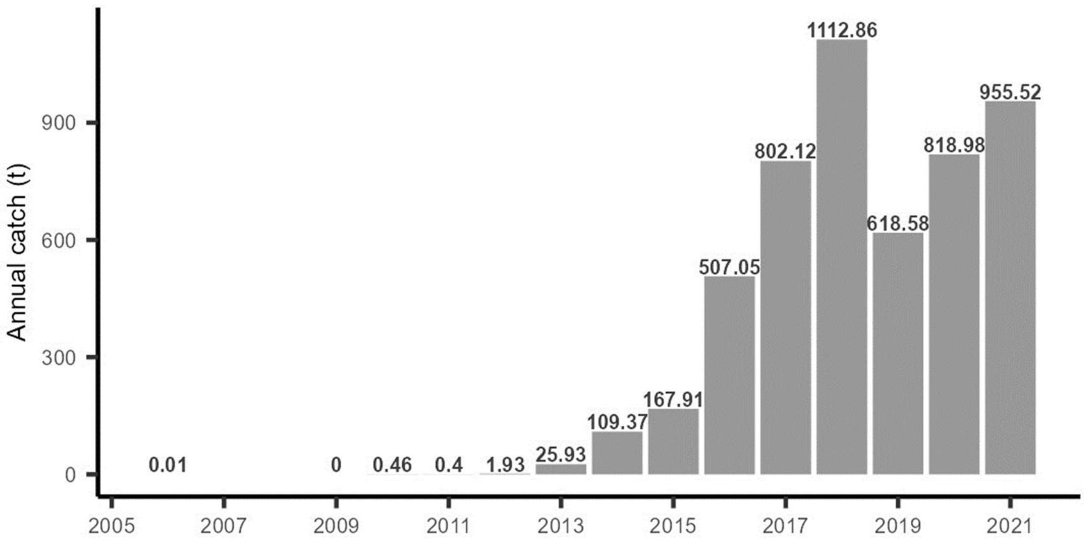


Figure 2. Annual commercial catches of the round goby (*Neogobius melanostomus*) in Latvian coastal waters (Paper **I**).

Tough a combined TRIM model results show a population increase until 2017, followed by a rapid decline for round goby population estimates within three different scientific monitoring methods in the Latvian EEZ (Figure 3). The estimated population size in 2021 was about 7.6 times higher than that of 2006, but 30 times lower compared to that recorded in 2017 (Paper **I**).

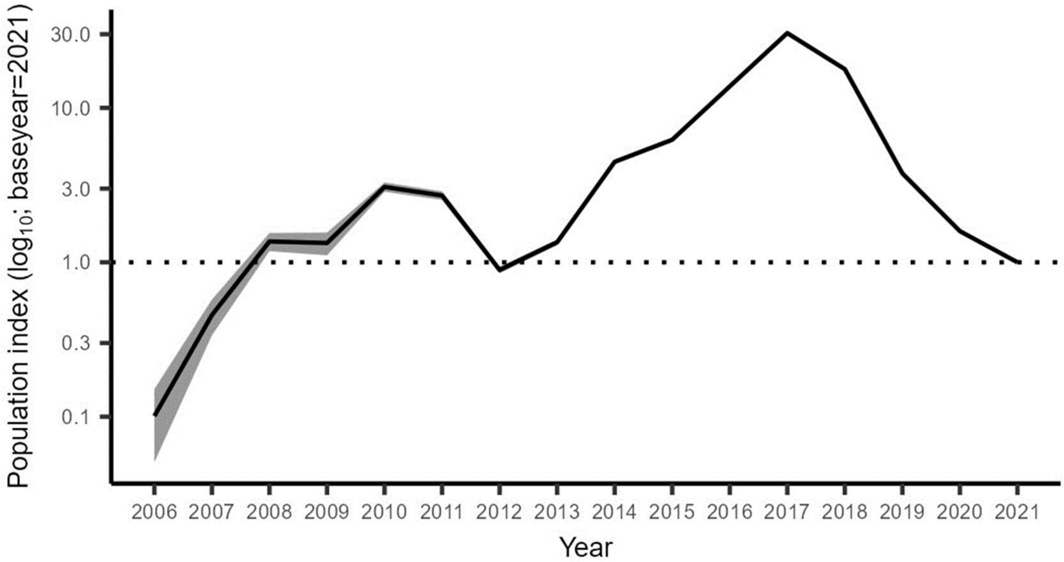


Figure 3. The combined trend of the population development (yearly indices with standard error) of the round goby (*Neogobius melanostomus*) in Latvian EEZ. Y– axis represents population size relative to the population in 2021 on a logarithmic scale. The dotted line represents the relative population size at the base year (2021) (Paper **I**).

3.2 Fish population changes before and after the invasion (Papers II, III and IV)

Flounder were the dominant fish species in the samples caught with the beach seine in the period of the study, except in 2014 when an increase in the abundance of the round goby was observed. Round goby biomass has significantly increased since this species first appeared in the study area in 2009. The turbot was the second or third most common fish species in all years. Other abundant fish species were lesser sandeel, smelt, vimba *Vimba vimba*, roach, and greater sandeel (Figure 4).

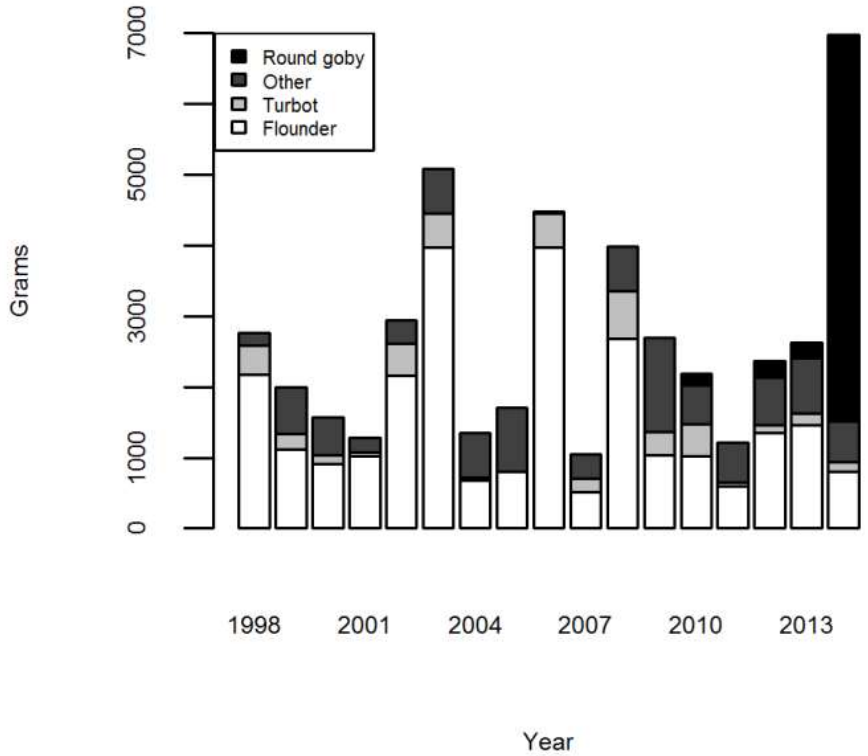
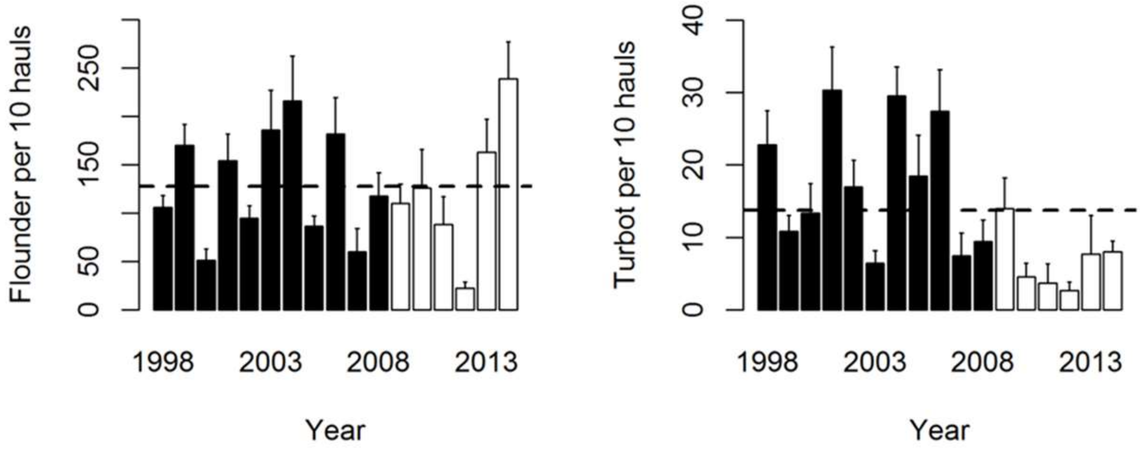


Figure 4. Average biomass (g/haul) of flounders (*Platichthys flesus*), turbots (*Scophthalmus maximus*), round goby (*Neogobius melanostomus*), and other fish species combined in the study area from 1998 to 2014 (Paper **III**).

The invasion of round goby had a significant negative impact on the abundance of juvenile turbot (GLMM, p = 0.003). Furthermore, in the earlier part of the time series, there were relatively high abundances observed every 2-3 years, but in the later period, only the year 2009 showed moderate abundance, while all subsequent generations exhibited relatively weaker numbers (Figure 5). Nevertheless, for flounder no significant difference was observed between the two time periods (GLMM, p = 0.441) (Paper **III**) and a slight increase in the abundance was observed in 2013-2014.



A B

Figure 5. The number of one-year-old flounder (*Platichthys flesus*) (A) and juvenile turbot (*Scophthalmus maximus*) (B) per 10 hauls of beach-seine. The solid bars show the period before the invasion of the round goby (*Neogobius melanostomus*) (1998-2008) and the open bars represent the period after the invasion (2009-2014). The calculated abundances are means of aggregated samples formed by combining spring and summer surveys. The dotted lines represent the long-term averages (Paper **III**).

While assessing the coastal fish monitoring results in the entire Baltic Sea, the results showed predominantly declining trends in Piscivores and increase in Cyprinids during the study time. Both observations indicate a decline in the overall condition or health of the ecosystem (Figure 6). The decreasing trends in Piscivores prevailed in all time windows between 1994-2003 and 2002-2011 and a stronger decrease was observed in the period 1999-2008 to 2002-2011. The pattern was however reversed in the most recent years of the study 2012-2013 (Paper **IV**) particularly in the Latvian EEZ. While in the Southern part of the Gulf of Riga DAU, the Piscivore trend is relatively unchanged; in the Eastern Gotland basin open sea stations JUR a minor ($p>0.05$) increase of piscivorous fish abundance was observed after 2008 (Figure 7), (Annex 5). As for the Cyprinid trend in both DAU and JUR stations, there was a hump-shaped trend observed with a similar peak in 2011(Figure 8).

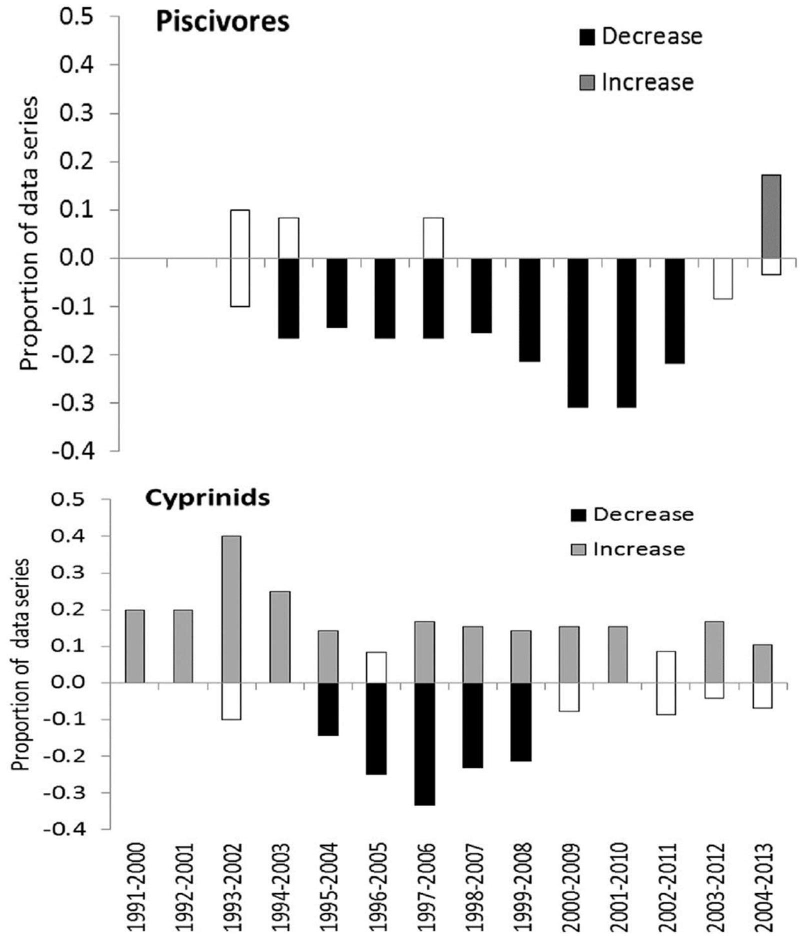


Figure 6. Summarised trends in Piscivores and Cyprinids from 32 coastal monitoring stations in the Baltic Sea. The proportion of data series showing a linear trend within each time window (linear regression $p<0.05$, proportion of increasing trends shown as positive values and proportion of decreasing trends as negative values). Black = predominance of decreasing trends, Grey = predominance of increasing, and White = within the expected range (Paper **IV**).

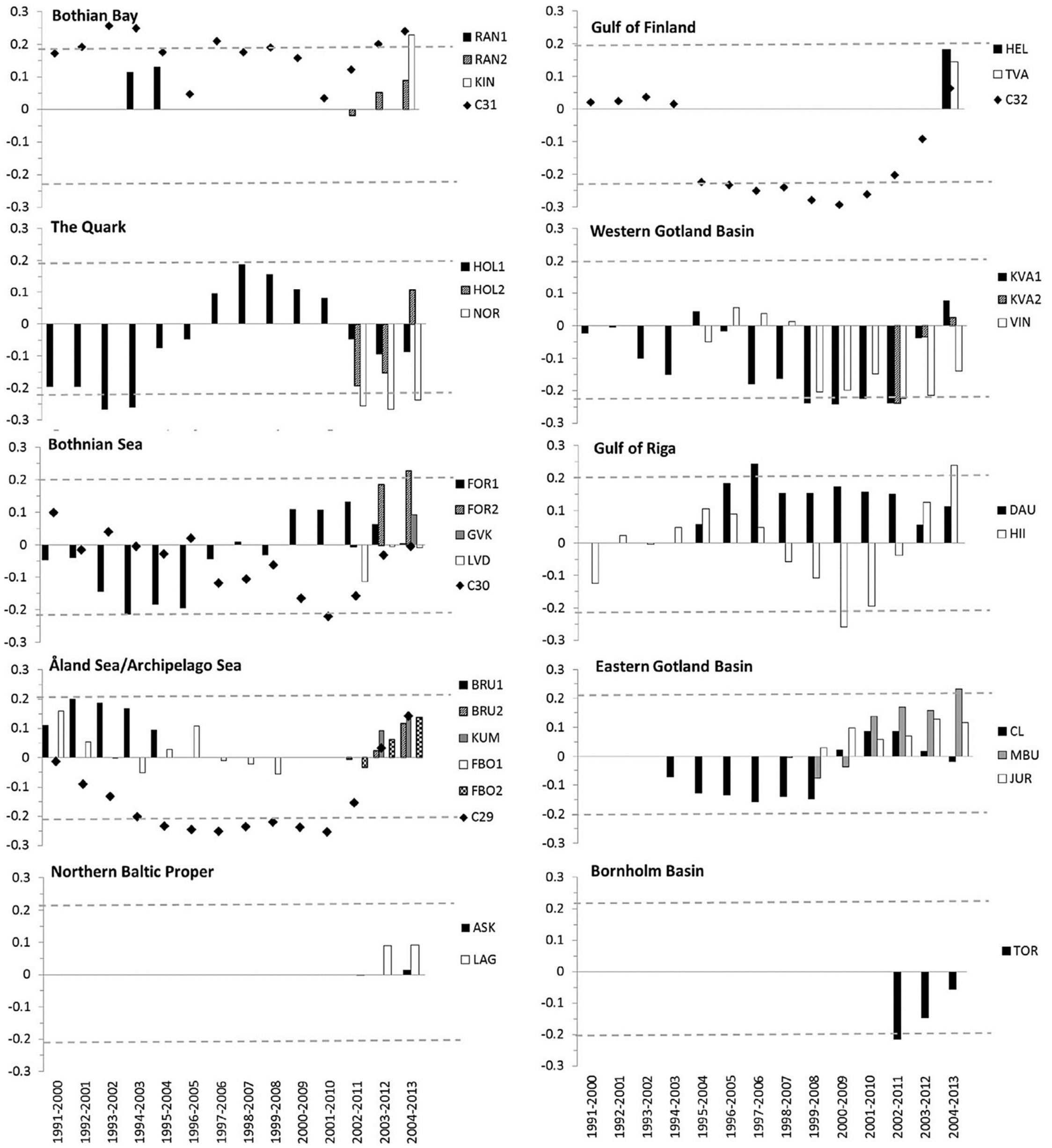


Figure 7. The temporal development of Piscivores in the Baltic Sea is shown separately for each data series (the Latvian EEZ stations are DAU and JUR). Trends were assessed within time windows of 10 years from 1991 to 2013, moving one year at a time. Vertical axes show the linear regression slope based on standardized values. Hatched lines indicate where the slope value corresponds to a significant trend at $p<0.05$ (Paper **IV**).

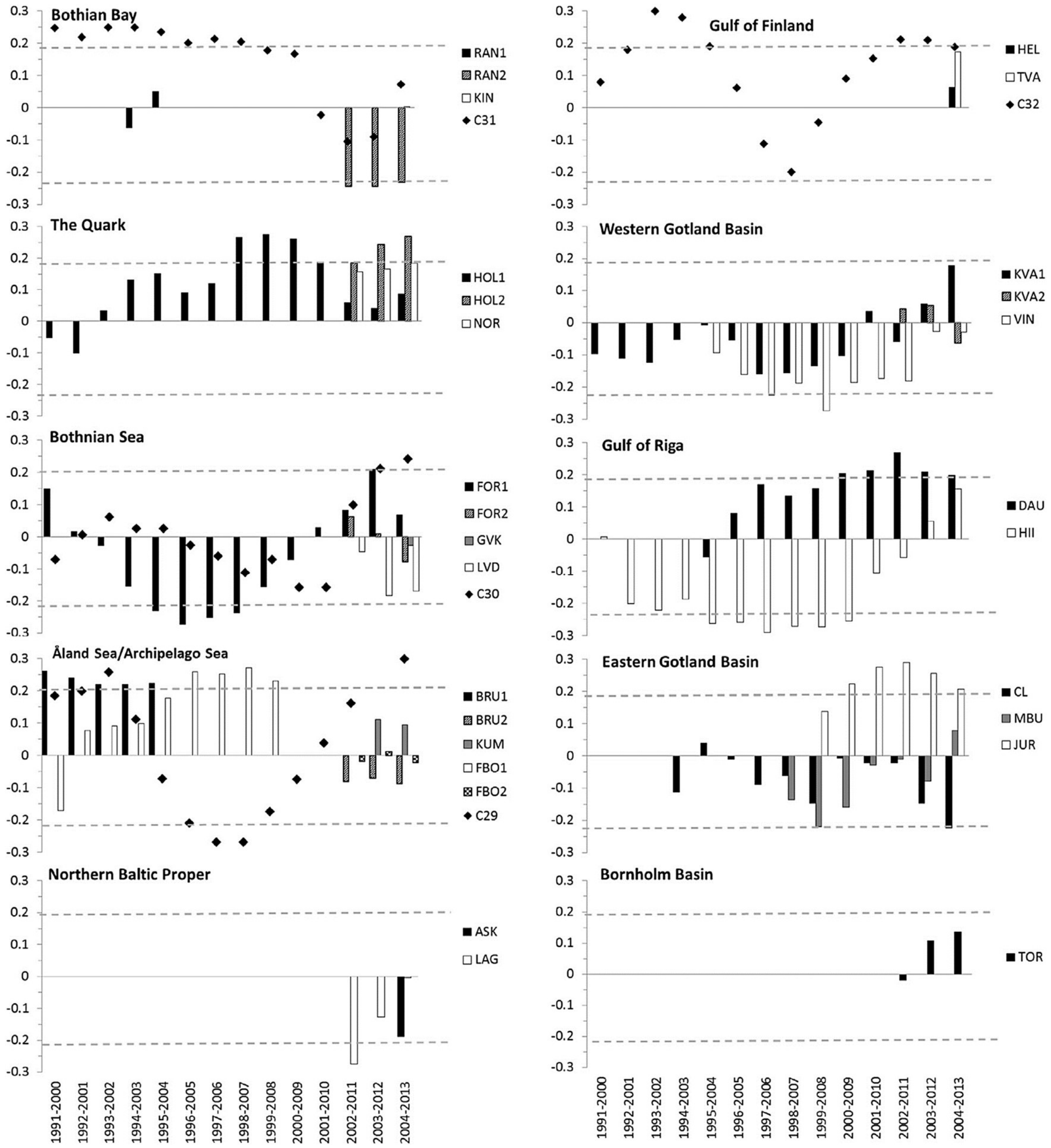


Figure 8. The temporal development of Cyprinids in the Baltic Sea is shown separately for each data series (the Latvian EEZ stations are DAU and JUR). Trends were assessed within time windows of 10 years from 1991 to 2013, moving one year at a time. Vertical axes show the linear regression slope based on standardized values. Hatched lines indicate where the slope value corresponds to a significant trend at $p<0.05$ (Paper **IV**).

Generally, in the Gulf of Riga offshore, the frequency of occurrence and biomasses of several taxa across functional groups increased in the 2000s. For example, pelagic fish species such as three-spined stickleback and sprat, and benthivorous fish species such as the common seasnail *Liparis liparis* and fourhorn sculpin *Myoxocephalus quadricornis* all had high biomasses. By 2009, the presence of round goby became evident in the observations. In the period 2009-2014 there was a decrease in biomass trends observed for traditional demersal fish species like the common seasnail, eelpout, shorthorn sculpin *Myoxocephalus scorpius*, flounder and sand goby. While trends of whitefish *Coregonus* spp, fourhorn sculpin, and round goby were increasing (Figure 9).

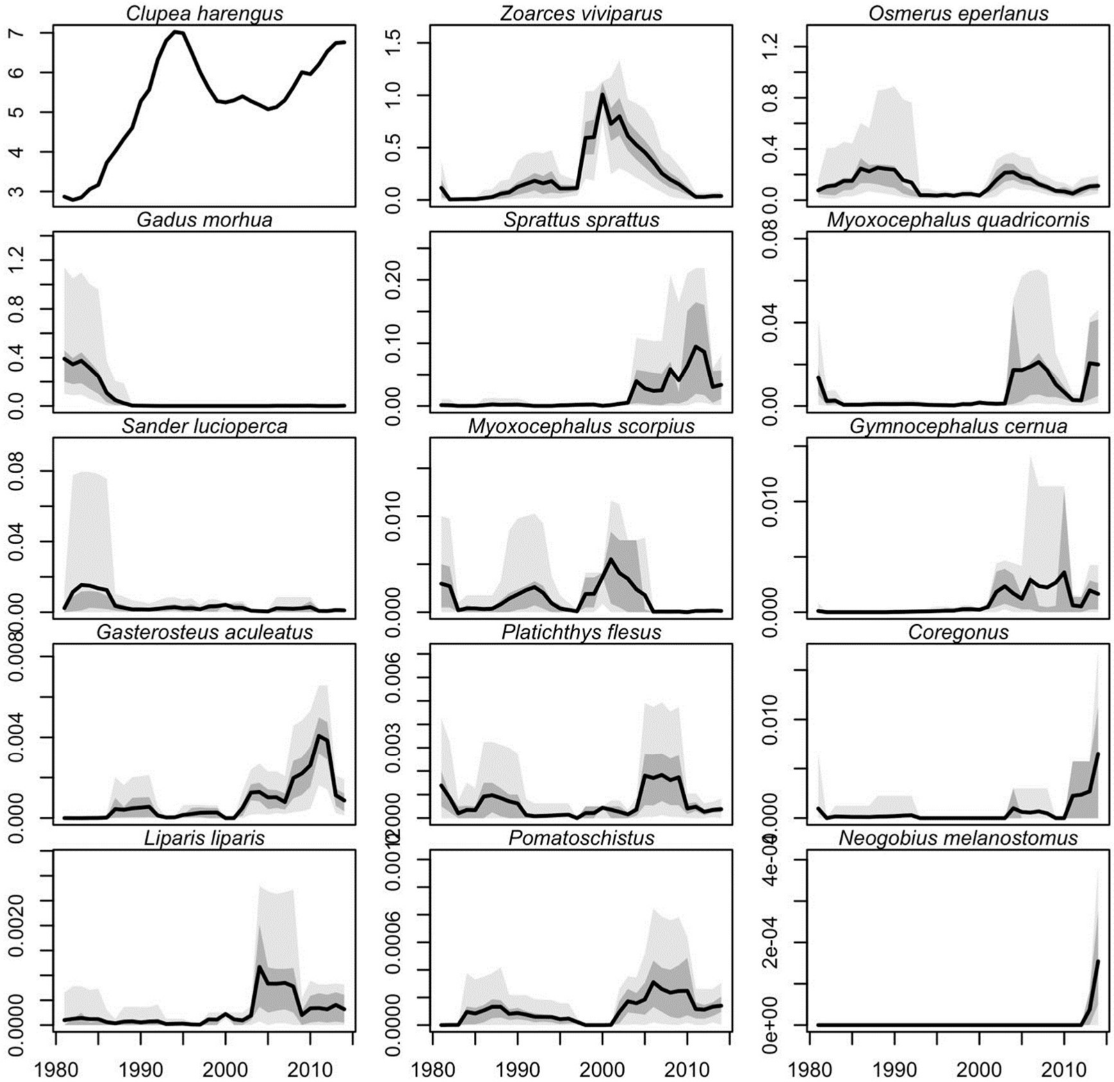


Figure 9. Time series of fish biomass ($g/m2$) for the study period 1979-2016: Herring (*Clupea harengus*) (based on stock assessment data), eelpout (*Zoarces viviparus*), European smelt (*Osmerus eperlanus*), cod (*Gadus morhua*), sprat (*Sprattus sprattus*), fourhorn sculpin (*Myoxocephalus quadricornis*), zander (*Sander lucioperca*), shorthorn sculpin (*Myoxocephalus scorpius*), ruffe (*Gymnocephalus cernua*), three-spined stickleback (*Gasterosteus aculeatus*), flounder (*Platichthys flesus*), whitefish (*Coregonus* spp.), common seasnail (*Liparis liparis*), sand goby (*Pomatoschistus* spp.), and round goby (*Neogobius melanostomus*). The scales on the Y– axes differ due to the different biomasses of taxa. Taxa are sorted from top left to bottom right by decreasing biomass. The bold line is the mean biomass over the 1000 repetitions of constant sampling (random selection of eight stations over the 5-year window). The dark and light grey areas represent the interquartile range and 95% interval, respectively (Paper **II**).

3.3 Interspecific interactions between the round goby and native fish species via food niche analysis (Papers II and III)

When analyzing the feeding patterns of the round goby in shallow coastal areas caught with the beach seine it was observed that the smallest round goby length group (RG1) was exclusively feeding on zooplankton and was standing out from the other length groups. For the larger individual groups (RG2 and RG3), the primary food items were mysids and decapods. As the round goby length increased, the number of decapods in their stomachs decreased, and there was a gradual shift towards an increased abundance of molluscs instead (Figure 10).

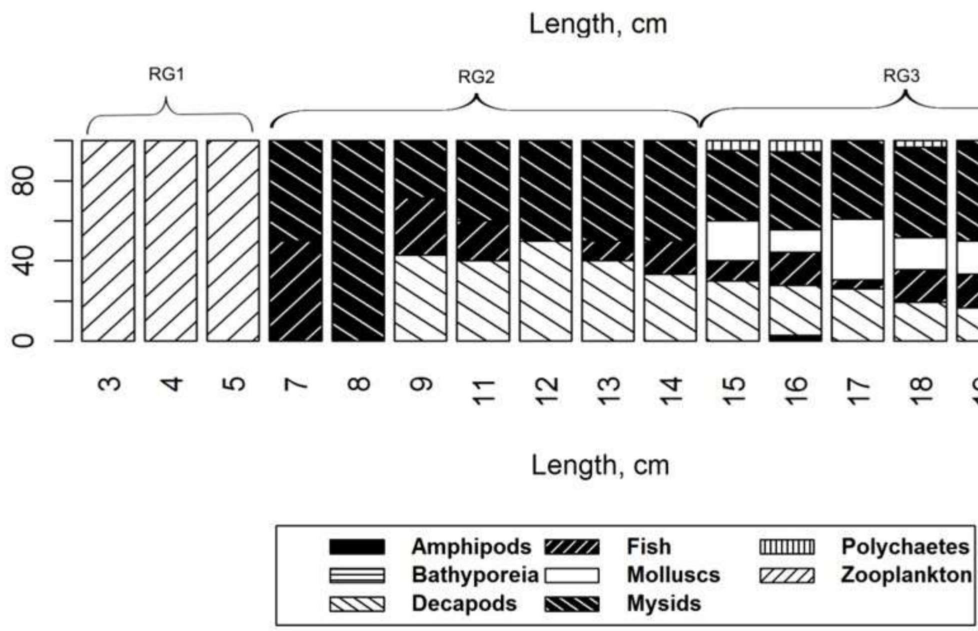


Figure 10. Feeding composition of round goby (*Neobobius melanostomus*) in size groups RG1 (3-5cm), RG2-(7-14cm) and RG3 (15-21 cm) (Paper **III**).

The feeding analysis results elucidate that for turbots (TU2 and TU3) the most important food item before the invasion of round goby was mysids, 92% and 67%, respectively. After the invasion, the occurrence of this food item decreased to 67% for TU2 (WRS test, p=0.08) and to 50% for TU3 (p=0.06). The importance of decapods (mostly the common shrimp *Crangon crangon*) increased significantly in the second period (TU2, WRS, p=0.005). For flounder (FL2 and FL3) the most important food item in the first period was the amphipod *Bathiporeia pilosa*, conversely, in the second period of the study 2013-2014, the abundance of amphipods in the flounders diet decreased. Furthermore, there was a full diet overlap between the smallest flounders FL1 and the smallest round gobies RG1 by feeding on zooplankton (Figure 11).

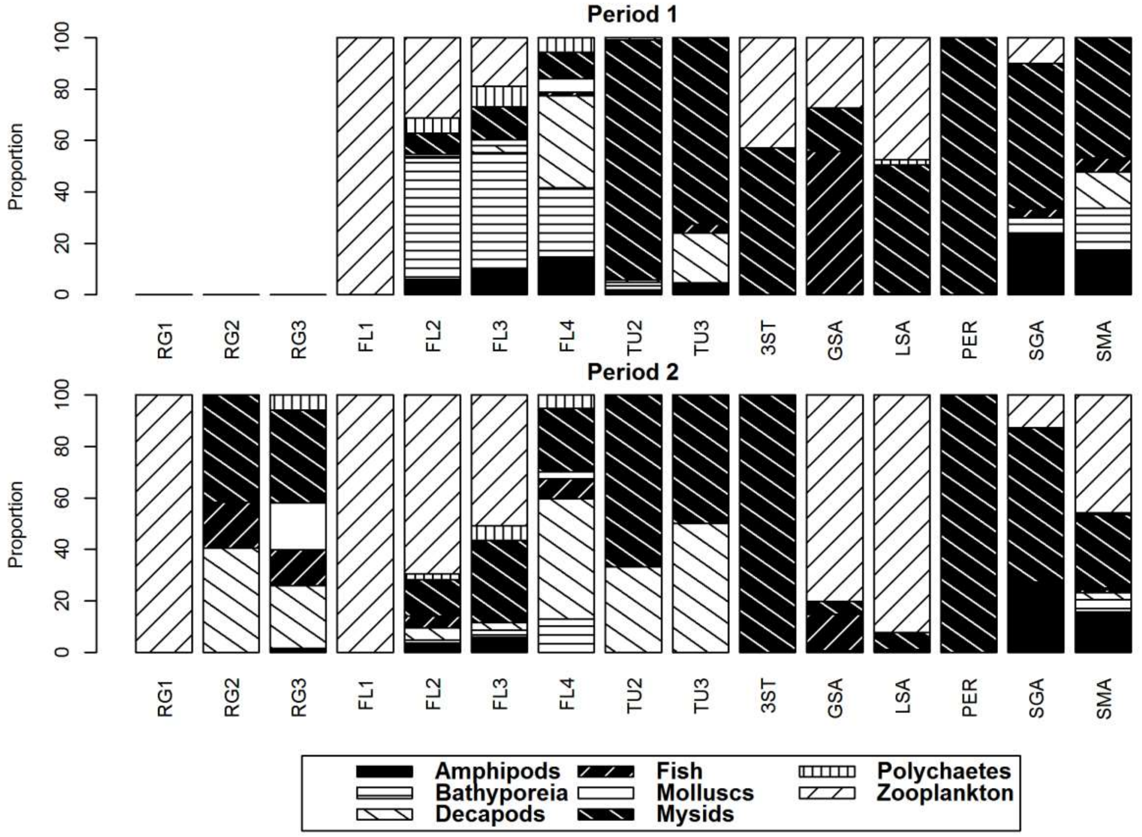


Figure 11. Food composition for the main coastal fish species caught in the shallow coastal beach seine sampling during 1998-2004 (Period 1 – before the invasion of round gaby) top and 2013-2014 (Period 2 – after the invasion of round goby) bottom. RG1-3 are three length groups of round goby (*Neogobius melanostomus*) as in Figure 10. FL1-4 are four length groups of flounder (*Platichthys flesus*) juveniles < 3.5cm (FL1), 3.5-5cm (FL2), 5.5-9.5cm (FL3), 10-15cm (FL4), and TU2-3 are two length groups of turbot (*Scophthalmus maximus*) juveniles (4-8 cm (TU2) and 9-18 cm (TU3)). The species not disaggregated by length group are three-spined stickleback (*Gasterosteus aculeatus*) (3ST), greater sandeel (*Hyperoplus lanceolatus*) (GSA), lesser sandeel (*Ammodytes tobianus*) (LSA), perch (*Perca fluviatilis*) (PER), sand goby (*Pomatoschistus* spp.) (SGA), and smelt (*Osmerus eperlanus*) (SMA) (Paper **III**).

The number of mysids caught in the beach seine hauls varied from year to year, reaching its peak in 2002, with an average of 6 956 individuals per haul (Table 1). In the first period, there were, on average, 1 392 mysids caught per beach seine haul. Conversely, in the second period, the mysid abundance dropped significantly by three levels of magnitude, with only 1.4 individuals per haul only in 2013. The difference in mysid abundance between the two periods was highly significant (GLMM, p<0.001). In contrast, the common shrimp *Crangon crangon* showed a significant increase in abundance during the latter period compared to the period before the round goby invasion (GLMM, p=0.01). The mean abundance of the common shrimp was 269 individuals per haul in the latter period, compared to an average of 49 in the first period of the study (Table 1) (Paper **III**).

Table 1.

The average abundance of individuals per haul with ± standard error of the common shrimp *Crangon crangon* and Mysids in beach-seine survey as bycatch.

Year	Period	*C. crangon*	Mysid
1999	1	78.4 ± 32	1120 ± 351
2000	1	35 ± 12	469 ± 157
2001	1	32 ± 19	69 ± 53
2002	1	19 ± 13	6956 ± 6777
2003	1	25 ± 5	161 ± 47
2004	1	115 ± 28	1219 ± 973
2005	1	13 ± 7	3.0 ± 1
2013	2	70 ± 11	2.9 ± 1.9
2014	2	351 ± 206	0 ± 0

The zoobenthos biomass trends in the Gulf of Riga showed an overall decrease in Amphipods *Monoporeia affinis* and *Pontoporeia femorata* in the period from 2009 to 2014. When comparing the biomass volumes between species *M. affinis* with approximately 10 g/m2 was the second largest group after *Saduria entomon* in the 2000s (Figure 12).

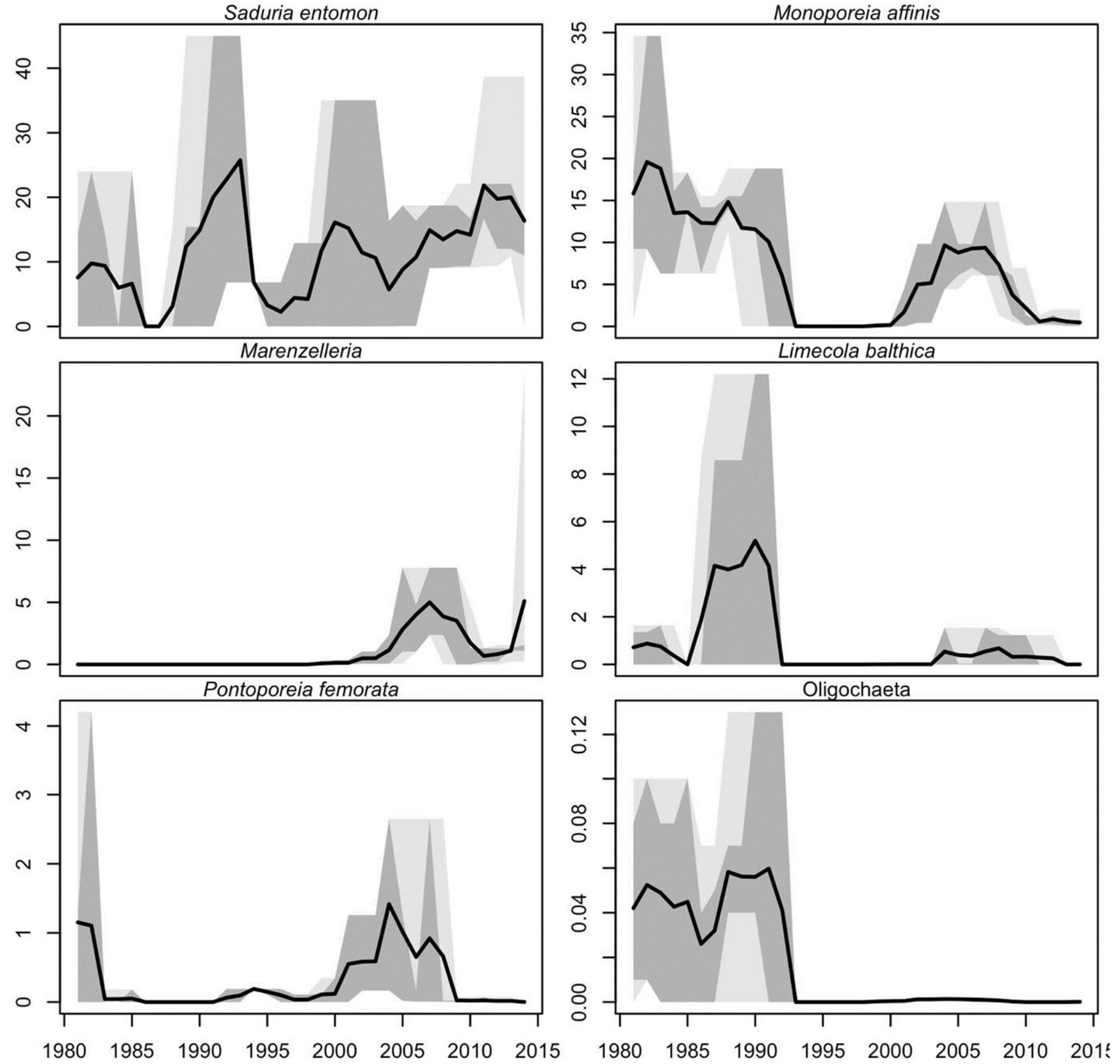


Figure 12. Time series of benthos biomass ($g/m2$) in station 119 in Gulf of Riga from 1979 to 2016: Isopods *Saduria entomon,* amphipods *Monoporeia affinis,* and *Pontoporeia femorata,* the invasive bristle worm *Marenzelleria sp,* Molluscs *Limecola balthica* and earthworms *Oligochaeta*. The scales on the Y– axes differ due to the different biomasses of taxa. Taxa are sorted from top left to bottom right by decreasing biomass. The bold line is the mean biomass over the 1 000 repetitions of constant sampling (random selection of one station over the 5-year window). The dark and light grey areas represent the interquartile range and 95% interval, respectively (Paper **II**).

3.4 Reasoning for recommendations on further monitoring of the round goby (Paper I)

When comparing the monthly catch rate of round goby in coastal monitoring the highest catches were observed in May, being approximately 10 times higher than those recorded in late summer and autumn. The values in April and June were about half of the peak catches recorded in May. In the cold-water period (February-March) there were practically no round goby caught (Figure 13).

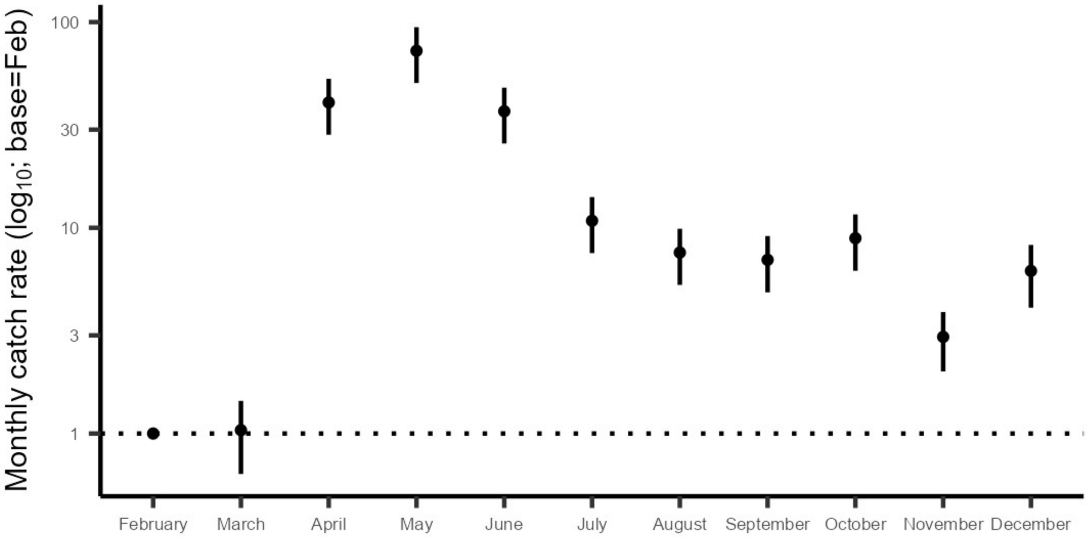


Figure 13. Multiplicative coefficients (base month is February) of the round goby catchability in coastal fisheries monitoring stations during the years 2006-2021 on a logarithmic scale. For each month, the average relative catches across years were plotted with a standard error bar (SE). The dotted line represents relative catchability at the base month of February (Paper **I**).

There was a strong catchability preference in "Nordic Coastal Multi-mesh" nets for smaller fish, and a noticeable shift was referenced towards "Coastal net series" starting from the 12cm length group (Figure 14). Catchability, beginning with a fish body length of 12cm, can be considered relatively stable (within confidence interval), being approximately 5.35 times higher in "Coastal net series" than in "Nordic Coastal Multi-mesh" nets (Figure 14 and 15). As the "Coastal net series" are 180m long, while the "Nordic Coastal Multi-mesh" nets are 45m, this results in making a catching surface ratio of 4, which was lower than the observed proportion (>5 timers at sizes 12 cm), suggesting a clear preference for catchability. This gear length ratio was, however, well within the confidence interval of correction values.

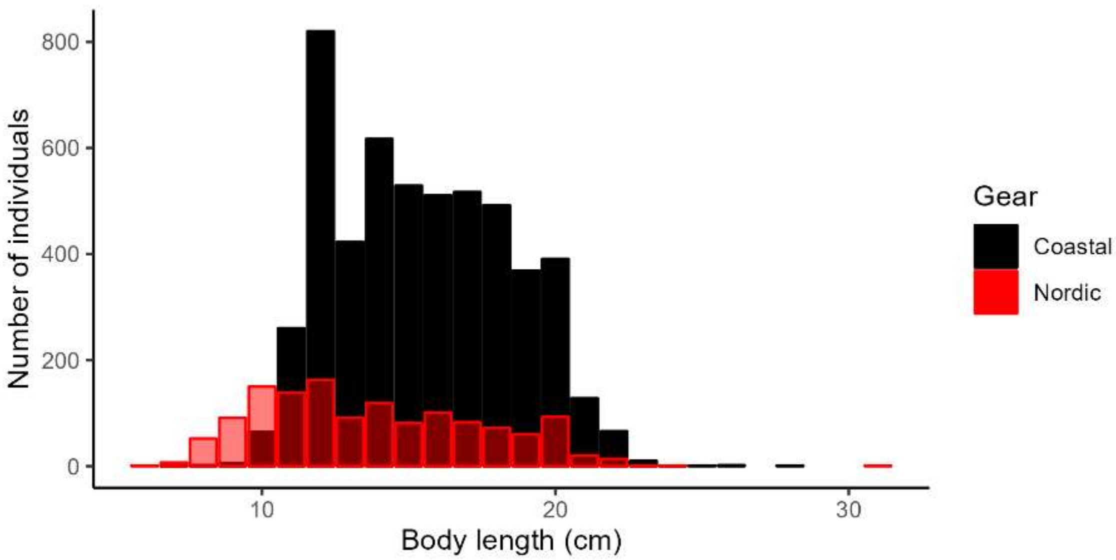


Figure 14. Total number of round goby *Neogobius melanostomus* individuals per length group (cm) captured for two different monitoring fishing gears (Paper **I**).

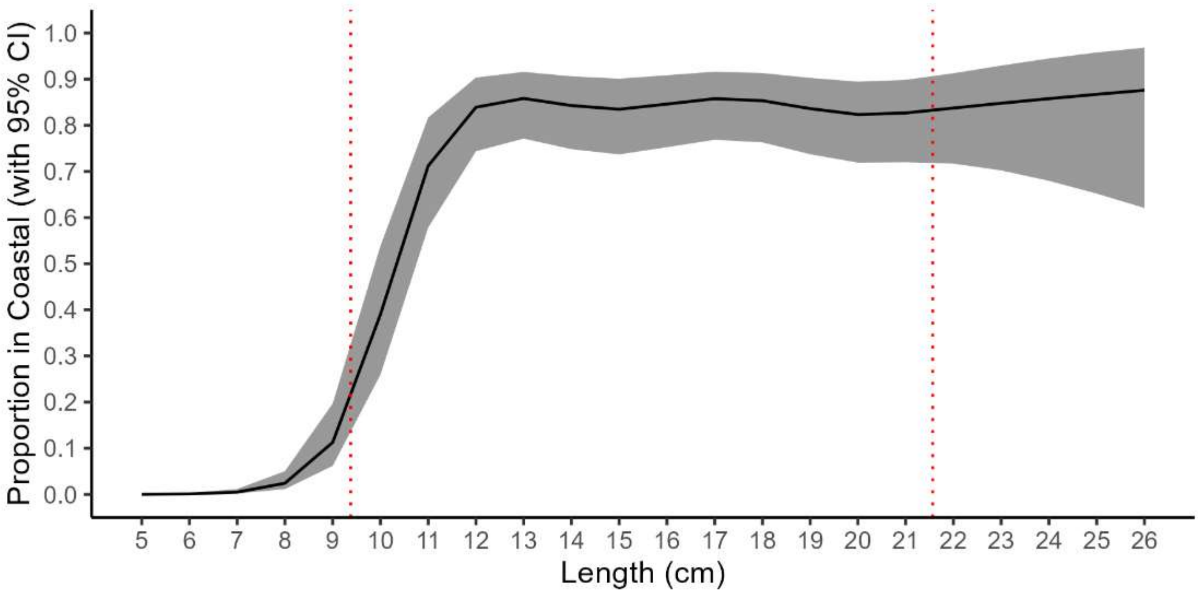


Figure 15. Round goby *Neogobius melanostomus* population-level proportion of individuals per length group expected to be captured in "Coastal net series" assuming that they are caught simultaneously with "Nordic Coastal Multi-mesh" nets. Dotted vertical lines represent weighted mean lengths of individuals smaller than 10cm or larger than 21cm (Paper **I**).

4 Discussion

4.1 The round goby (*Neogobius melanostomus*) invasion in Latvian EEZ

Typically, Latvian marine fish research is based on long-year standard observations within the Latvian Work Plan for data collection in the fisheries and aquaculture sectors (Latvian Work Plan 2022-2024) and fragmented studies based on different scientific project outputs, for example the projects: EVIDEnT, INSPIRE, BLUEWEBS (see project links in references). Whereas for other Baltic Sea countries fisheries data is collected mostly within specific projects capacity, subsequently lacking long-year comparable observations. Nevertheless, the Latvian applied historically unchanged methodology and the employed consistency provides one of the highest quality long-year data sets in the Baltic Sea region (Ustups D. personal comment). As a result, besides peer-reviewed publications and various project reports, unique long-year data sets are accumulated on various fish population trends, that when combined, provide a new knowledge on changes in the demersal fish communities.

Continuing data collection using an unchanged methodology ensures a consistent and comparable basis for future research, but it is necessary to draw a line and assess what conclusions can be done with the existing knowledge, especially in identifying the invasive round goby's impact on the local fish. The results of this study suggest that by demarcating a boundary at the onset of the round goby invasion in 2009 a baseline for an unaffected ecosystem is defined and further by assessing changes in various long-term monitoring trends, shifts become apparent after the emergence of round goby in the environment.

The first signals of the round goby invasion appeared in national monitoring surveys and later were followed by reports in commercial coastal logbooks (Minde, 2007). The further rapid increase in the population, evidenced by both the scientific observations and fisheries log books leads to the question of how the local ecosystem was affected and can there be any indirect indications detected in local demersal fish and zoobenthos trends.

After its peak in 2017, the round goby population experienced a decline, resulting in a notable reduction that was thirty times lower by 2021 (Paper **I**), even as commercial fishing landings remained relatively unchanged (Figure 2.), (Behrens et al., 2022a), inquiring possible causes of such development of the two different trends. Nevertheless, most of the commercial fishing is carried out in consistent coastal areas (Annex 6) with favourable coastal habitats for the species. Conversely, the population growth and later decline were observed in both coastal and offshore combined population trends (Figure 3), showing a general prevalence and arising spillover effect of the round goby to other living spaces as the population grew. The abundance of natural predators, as well as the progressing fisheries' adaptation to the new resource, are major limitation factors of the species (Ojaveer et al., 2015). Despite the identified round goby population decline after 2017, the following decline in commercial fishery landings was less pronounced which could be related to unevenly distributed coastal specialized fishery and its limited capacity in catching round goby to the full extent at the population peak period in 2017. According to the scientifically observed population decline detrimental changes in commercial catch success are suspected at the point where the capacity of the fleet catches up to the maximum population level of the round goby. However, as the stock decreases further mosaic spatial dispersal is expected for the round goby population in the Latvian EEZ. While fishing efforts could potentially be used to reduce round goby abundance in most of the Baltic Sea countries, this species is not yet considered a valued species for human consumption. To effectively manage and control the abundance of round goby, it becomes crucial to support natural resilience by ensuring that the predators of this fish are present in adequate numbers (Behrens et al., 2019), (Ojaveer et al., 2015). For the moment in the EEZ, the conscious predatory fish species on the round goby in the open part of the sea are cod and turbot and mostly perch in the Gulf of Riga coastal zone (D.Ustups personal communication, E.Kruze unpublished data). Since round goby migrates between coastal and offshore niches (Andres et al. 2020), it becomes essential to assess the population in both areas simultaneously. So far assessments were focused only on the coastal areas (Behrens et al., 2022b), while the present study initially covers both coastal and offshore waters. By considering the possible different population dynamics of this invasive species in both habitats, there is a potential to develop more comprehensive and effective management strategies to mitigate round goby impact and maintain a balanced ecosystem in the Baltic Sea.

4.2 Changes in local fish population trends

The presence of non-native species can affect local ecosystems, particularly fish populations and the establishment of the round goby has slight impact on the local fish community (McAllister et al., 2022). Understanding the trend shifts in native fish populations before and after the invasion of the round goby invasion was essential to comprehend its ecological implications and plan effective management strategies. By comparing the periods before and after the invasion of the round goby, it was possible to gain valuable insights into the ecological consequences of this invasive species and its interactions with native fish communities in the region. In the central Baltic Sea, the focus in analyzing trends is based on the dominant and commercially valuable pelagic fish populations for Sprat, Herring, and Cod (ICES 2012). In this study, other available coastal fish species population trends are analyzed. Coastal fish population trends refer to the general direction or pattern in which the abundance or size of a fish population is changing over a specific period, which indicates whether the population is increasing, decreasing, or remaining stable (Paper **IV**). There is a lack of a comprehensive cross-study overview of the results achieved by different monitoring methods of long-term changes to provide a scientifically approvable insight into the current situation through the round goby invasion perspective.

The aim of developing indicators for coastal fish communities in the Baltic Sea is to assess the potential impacts of anthropogenic and natural environmental factors. In the Latvian case the Gulf of Riga DAU station represents an area with high anthropogenic pressure and in contrast the Open Sea JUR station is a relatively minimal disturbed environment (Neuman et al.,1999). The Cyprinids indicator is mainly an indicator of eutrophication as it is benefited from decreased water transparency, whereas the Piscivore indicator is primarily represented by species of high interest for commercial or recreational fisheries. The Baltic Sea is experiencing continuous climate-induced temperature increases, which have been linked to a positive influence on individual fish growth rates and contribute to repeated years of successful reproduction and generational productivity (Paper **IV**). A continued predominance of increasing trends in Cyprinids but to a slightly lesser extent than in the early 2000s agree with recent eutrophication assessments and analyses of nutrient monitoring data (Snoeijs-Leijonmalm et al. 2017), which elucidate that eutrophication is a persisting issue in all areas of the Baltic Sea. Both indicators are potentially sensitive to habitat loss and changes in the quality of the environment but also involve natural environmental factors such as predation and overall climate change. Conversely, if the main changes in coastal fish communities were linked to rising temperatures, it would expect a similar pattern over time in both indicators, but the catches of Piscivores and Cyprinids were generally not correlated, implying that some different factors were influencing each indicator more significantly at the current scale of the study (Paper **IV)**.

A possible shift in population trend development in the eastern Gotland basin region of the Baltic Sea for Piscivores and Cyprinids is observed in 2008 (Figures 7 and 8) exactly matching the same time when the round goby invasion accelerated in this region (Rakauskas et al., 2008). During an overall piscivore decrease in the Baltic Sea (Figure 6) an increase in station

JUR after 2008 was observed (Figure 7) that overlaps with the round goby invasion spread direction area (Puntila et al., 2018) and increasing commercial fishing activity location of the species (Annex 6). But the only significant (p<0.05) increase of piscivores was observed in the next south Lithuanian station MBU (Paper **IV**) which was affected by the invasion in the earlier years (Rakauskas et al., 2013).

In the shallow water coastal areas sampled with beach seine, across the whole period, the total biomass of coastal fish did not change significantly. Following the arrival of the round goby, there was a noticeable decline in the abundance of juvenile turbot, while no obvious change was observed in the abundance of juvenile flounders. The inquiry pertains to the fluctuations in the productivity of turbot and it addresses whether unproductive generations of turbot persist or if the species has undergone adaptations in response to the altered state of the ecosystem (Paper **III**). When comparing demersal fish biomass trends in the Gulf of Riga offshore (Figure 9) with the appearance period of the round goby, the declines of the native demersal fish biomass could be explained by various environmental factors not directly related to the invasion. Anthropogenic factors that encompass eutrophication, fishing intensity, habitat loss, and changes in habitat quality and natural factors that involve predation and climate change, should both be assessed as factors that may act individually or in a synergy to impact those demersal fish communities. By combining this knowledge with when shifts in trends happened and on how many taxonomical and trophic levels it coexists it is possible to discuss if the regime shift happened in the Baltic Sea. For example, the shifting of the dominance of large predators to the small three-spined sticklebacks in the shallow bays of the Swedish coastline in the 2000s (Eklöf et al., 2020). Climate change and temperature increase cause an overall coldwater marine demersal fish species decline meanwhile accelerating the spread of invasive species like the round goby due to its high thermal resilience (Christensen et al., 2021) as well as decrease the overall species richness the coastal fish community (Bowser et al., 2022).

4.3 The impact on local fish communities' food web

The ecological role of the round goby in the Baltic Sea is both as a mesopredator and a prey for higher trophic-level organisms. It is widely characterized in various research reports and peer-reviewed publications in the Baltic region that are summarized in paper **I** after (Nurkse et al., 2016), (Almqvist et al., 2010), (Oesterwind et al. 2017) etc. Additionally, mentioning the role of round goby in the trophic transfer of accumulated microplastics through eating mussels (D'Avignon et al., 2023). When analysing the changes in the diet composition of juvenile flounders and turbots in the eastern Baltic Sea area before and after the establishment of the invasive round goby, it was found that after the round goby invasion, the diet overlaps increased of both flatfish juveniles with other species and their feeding success decreased (paper **III)**. The diet of juvenile turbot shifted from mysids to common shrimp, likely due to a decrease in mysids and an increase in common shrimp abundance in the habitat (Table 1). Nevertheless, a decrease in amphipods (including *Bathiporeia*) in the stomachs of flounders (Figure 11) was observed coinciding with a decrease in the Gulf of Riga (Figure 12) in the same period. A significant decrease in turbot recruitment was observed in the second observation period as well (Paper **III**). Juvenile flounder, which had the widest food spectrum of the studied species, increased their intake of zooplankton when the availability of their primary food item, *Bathyporeia pilosa*, decreased. Although, the recruitment estimates of flounder and turbot showed increasing co-variation after the round goby invasion, suggesting that the recruitment of the two species may be regulated by processes in the common nursery habitat in shallow (<2m) waters. Or implementing pressure on the overall living space of flounders during the round goby spawning season with a presence in very high numbers. As it was found that for adult flounder's depth distribution was shifted to deeper areas from 3-7m to 10-13m during round goby spawning time, but when round goby abundance was low, as in July, flounders were found at all depths of the sampling area (Karlson et al., 2007). The juvenile turbots, whose dominant food item before the round goby invasion was mysids, shifted their diet towards the common shrimp, indicating a potential shift in food availability. As for the turbot as species, it is known that the juveniles compete over food, but the adults successfully feed on the round goby (D.Ustups unpublished data) so developing a situation of unclear interspecific relations in terms of nutrition estimates and energetic circulations within trophic levels. Round goby, in addition to benthic invertebrates, preys also on several different fish species juveniles or eggs of ecological and commercial importance. Thus, there is potential for predator-prey reversal and negative effects of the invasive round goby on large, predatory fishes (Wallin Kihlberg et al., 2023). Within the length groups above 7cm fish start to appear in the diet of round goby (Figure 10) whether in the form of fish eggs or juveniles (E. Kruze unpublished data based on Paper **III** study) including round goby, eelpout, and three-spined sticklebacks in the Gulf of Riga offshore samples (L. Rozenfelde unpublished data 2018-2022). Changes in abiotic factors, specifically the temperature increases during certain periods, were associated with variations in the overall structure of the ecosystem, marked by decreases in detritivorous organisms and increases in phyto- and zoo planktivorous taxon groups (Paper **II**). Conversely, in the last observation period of the study (2009-2014) the effects of a new contributor on the food web, like the appearance of the new round goby should be considered and attention drawn if there are some indications of an overall temporal shift in the functioning observable in the ecosystem.

4.4 Recommendations for further monitoring

Characterizing entire fish populations in an open water environment using a sparse network of samples across a vast area poses significant challenges. However, this approach provides the closest approximation to reality given the absence of any other observations during the specified period and location. Relatively the comparison of round goby catch volumes between passive coastal gillnet monitoring and active offshore scientific trawling results elucidates much higher catchability in the coastal waters, especially during spawning migration in spring–early summer (Paper **I**). While active sampling gears provide better quantitative data on fish abundance per area unit this method faces limitations on rocky ground types, shallow waters as well as generally higher expenses (Franco et al., 2022). However round goby seasonally migrates between ecological niches in the coastal areas and offshore areas (Behrens et al., 2022b), (Andres et al. 2020) so coastal sampling could also indicate effects on nearby deepwater biotopes where the use of active sampling gears is challenging. So far according to the HELCOM guidelines fisheries independent coastal fish monitoring is conducted in late summer (Neuman et al., 1999) when round goby activity is little and its catchability with passive gears is low (Figure 13). Catches of round goby observed in May were approximately 10 times higher than those recorded in late summer and autumn. Therefore, monitoring of round goby in coastal areas should be focused on the period between late April and early June, as the catches between years may vary to some extent (Paper **I**). “Nordic Coastal Multi-mesh” nets provide a wider range of round goby length groups, especially the smaller ones with lower total catch volume of the middle-sized fish (12-20cm) making the measurements more efficient and less laborious on the field. When recalculating “Nordic Coastal Multi-mesh” nets data to historic “Coastal net series” values (Annex 1), it is suggested that cautious use of the correction values in individuals smaller than 9cm or larger than 22cm due to the scarcity of the available data. The method is well developed and described to be used for different fish species where the quantity is sufficient (Paper **I**). Another aspect of the application of the “Nordic Coastal Multi-mesh” nets sampling method is the possible faster attainment of the maximum catchability of the gears-specific mesh size panel in high fish concentrations. To limit the possibility of this feature and achieve representative CPUE values, repetitions with different soak times could be performed to reduce this risk (Rotherdam, et al. 2006). Nevertheless, small fish species and juveniles (below 5cm) usually were not representatively sampled by the "Nordic Coastal Multi-mesh" nets (Figure 15), and a combination of methods (active and passive fishing gears) should be used to cover the whole size spectrum of the targeted fish community.

In an open sea environment with internationally shared borders, besides mutually applied monitoring strategies, it is essential to incorporate also comparable national-level observations on coastal fish especially migrating fish species to ensure comprehensive data collection and analysis. Especially if there is an aim to reduce the spread of non-indigenous fish species and a specialized fishery sector is established it is crucial to embed an advantageous knowledge basis at the beginning of the industry's development. The fishery should be improved within seasonal terms and gear technical restrictions to exclude undersize valuable, protected, and endangered fish bycatch species and damage to the environment. Also, observer-based surveillance of bycatch in specialized fishing is obligatory. On the other hand, the fishing industry is exploring potentially profitable market avenues, and as illustrated by the Latvian scenario, these opportunities are primarily situated beyond the borders of the European Union. (Behrens et al., 2022a). So, the promotion of the round goby commercial fishing sector and advanced showcase production of high-value products for local markets would be supportable. Anyway, the future role of the round goby on the environment and fisheries is unclear and therefore, developing a pioneering stock assessment for the round goby in the Baltic Sea is crucial.

In the Baltic Sea region, there is a lack of coastal necto-zoobenthos observations performed and developed monitoring programs that are crucial for characterizing coastal and demersal fish community's role in the coastal food webs, involving also freshwater fish that do feeding migrations to coastal waters. Such data could provide reliable background data on food availability in the ecosystem as well as an insight into this unexplored segment.

The development of a new round goby ecological indicator should be considered in the Baltic Sea region (Olsson et al., 2018; MARMONI 2014) with so far unknown preferable target values because of its unclear role in the ecosystem and the bioeconomic paradox of an invasive fish species being commercially valuable.

5 Conclusions

1. The round goby established a stable population in the coastal areas by 2009 that rapidly increased and spread offshore until 2017 and after that, an remarkable decrease in the scientific population assessments was observed that is attributed to targeted round goby fishing management actions (Paper **I**).

2. A significant increase in cyprinid populations that are linked to eutrophication was registered but indirect shifts in cyprinid and piscivore population trends were observed after 2009 in the central Baltic Sea (Paper **IV**). A significant decrease in turbot recruitment was observed after the invasion of round goby (Paper **III**). The biomass of benthic fish species decreased in the Gulf of Riga after 2010 (Paper **II**).

3. The competition over mysids influences the food selection strategy of turbot juveniles after the invasion (Paper **III**). A decrease in the amphipod *Monoporeia affinis* and *Pontoporeia femorata* biomass was observed after 2009 in the Gulf of Riga (Paper **II**).

4. For round goby population trend assessment coastal fish monitoring should be conducted in May-June during the pre-spawning migration of round goby by using “Nordic multi-mesh gillnets” preferably applying experiments with different soak times (Paper **I**).

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ANNEXES

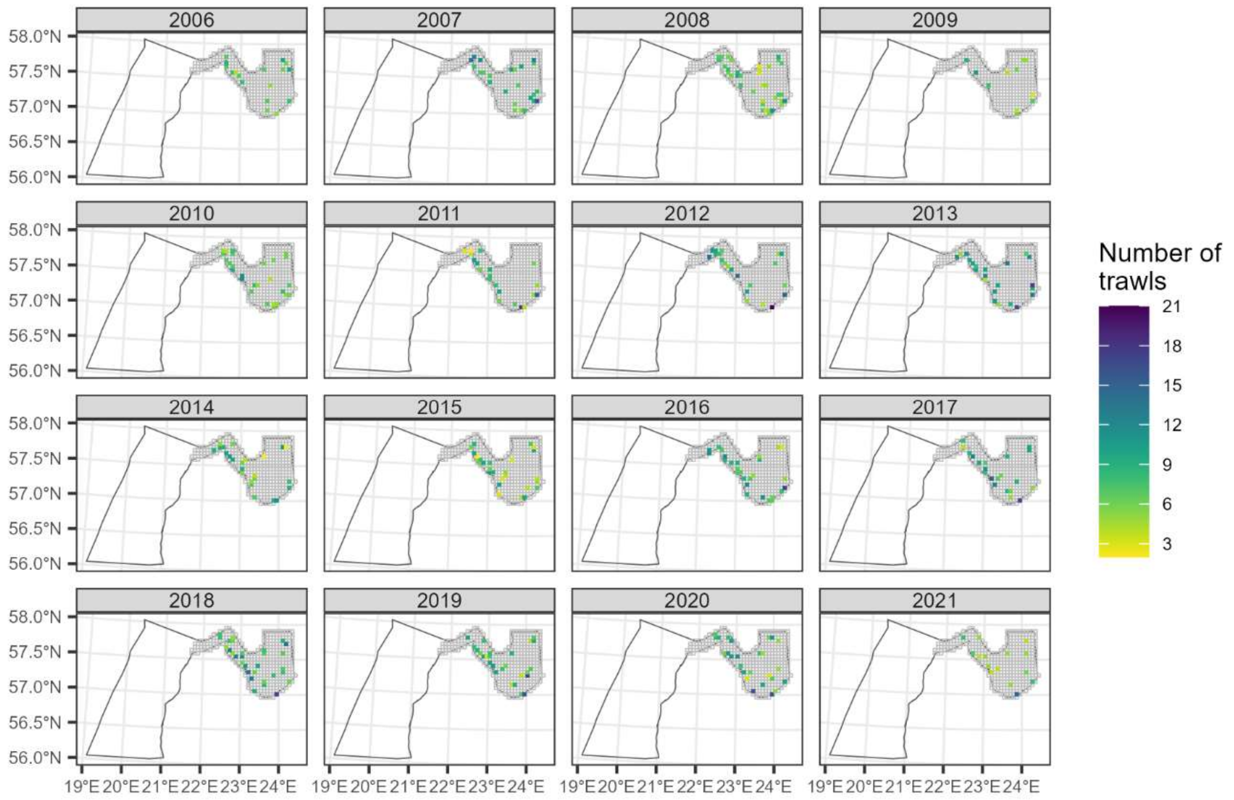
Annex 1

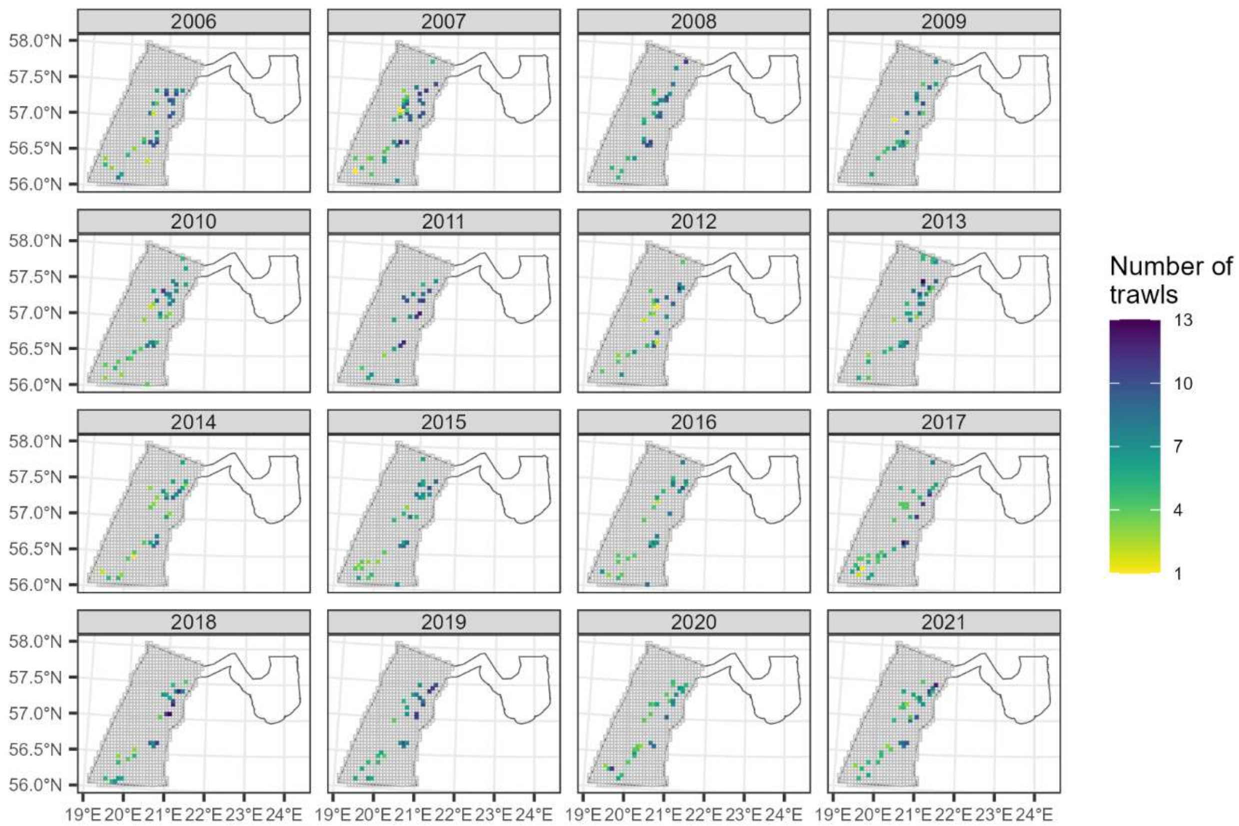
Recalculation (from “Nordic Coastal Multi-mesh” nets to “Coastal net series”) coefficients and their 95% confidence intervals (Paper **I**)

Length (cm)	Proportion in “Coastal”	Proportion in “Coastal” (95%CI)		Multiplicator for “Nordic” (to Obtain Values at “Coastal”)	Multiplicator (95%CI)	
5	0.0002	0.0001	0.0006	0.0002	0.0001	0.0006
6	0.0009	0.0003	0.0027	0.0009	0.0003	0.0027
7	0.0048	0.0020	0.0116	0.0048	0.0020	0.0118
8	0.0242	0.0115	0.0503	0.0248	0.0116	0.0529
9	0.1127	0.0617	0.1968	0.1270	0.0658	0.2451
10	0.3901	0.2597	0.5385	0.6397	0.3508	1.1666
11	0.7121	0.5783	0.8169	2.4734	1.3713	4.4612
12	0.8391	0.7437	0.9036	5.2138	2.9012	9.3699
13	0.8582	0.7713	0.9156	6.0506	3.3725	10.8554
14	0.8428	0.7483	0.9063	5.3620	2.9729	9.6712
15	0.8347	0.7370	0.9010	5.0503	2.8022	9.1022
16	0.8460	0.7525	0.9085	5.4953	3.0405	9.9319
17	0.8576	0.7687	0.9161	6.0249	3.3236	10.9215
18	0.8534	0.7630	0.9132	5.8203	3.2201	10.5201
19	0.8361	0.7373	0.9027	5.1028	2.8069	9.2769
20	0.8234	0.7191	0.8946	4.6618	2.5599	8.4897
21	0.8267	0.7200	0.8985	4.7711	2.5718	8.8514
22	0.8374	0.7170	0.9128	5.1491	2.5334	10.4654
23	0.8478	0.7022	0.9294	5.5724	2.3583	13.1670
24	0.8578	0.6797	0.9449	6.0304	2.1223	17.1355
25	0.8671	0.6521	0.9579	6.5261	1.8741	22.7255
26	0.8760	0.6208	0.9682	7.0626	1.6368	30.4736

Annex 2

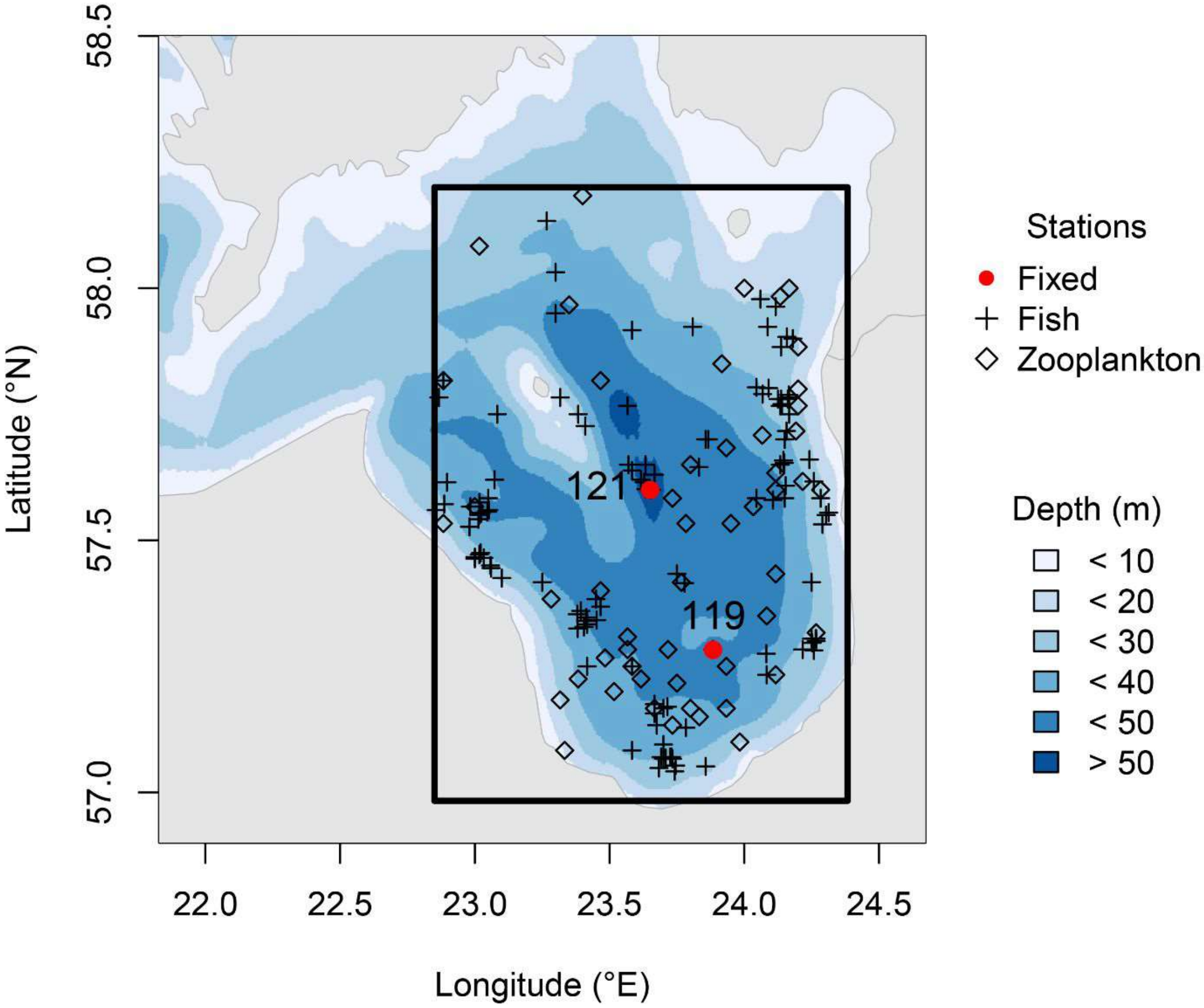
Spatiotemoral distribution of trawls in the gulf of Riga and the open sea (Paper **I**)





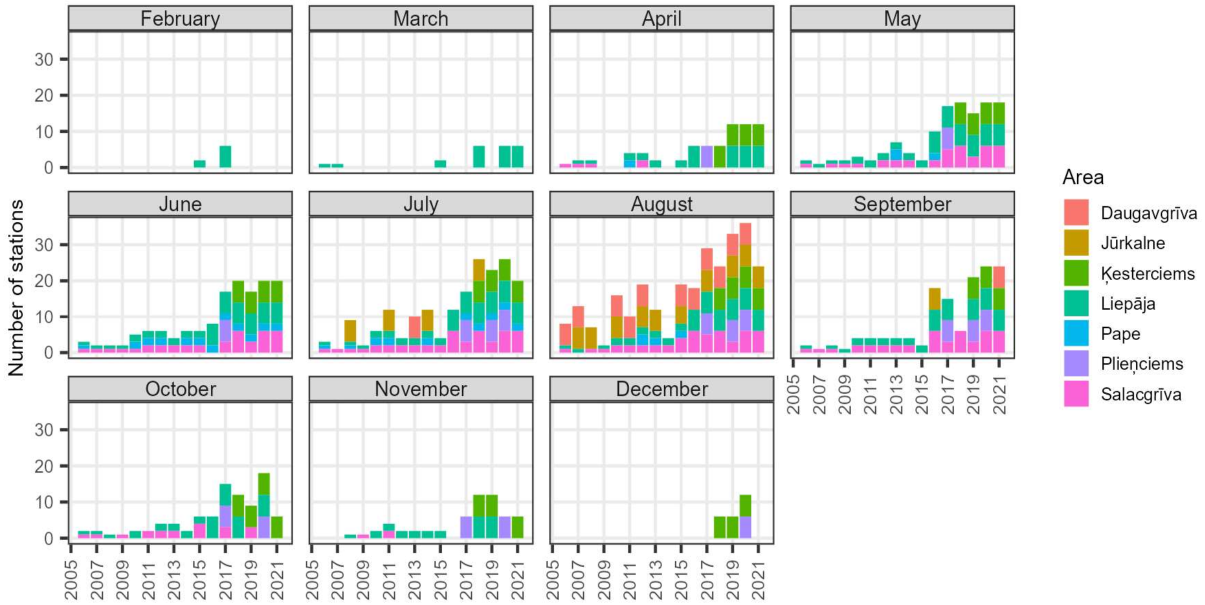
Annex 3

Map of sampling stations for phytoplankton, zooplankton, benthos and fish within the Gulf of Riga. All samples were taken from sampling stations deeper than 20m within the area marked with the black rectangle, representing offshore species communities. The permanent (i.e. fixed) stations for benthos (station 119) and phytoplankton (119 and 121) samples are marked with red dots in the figure. (Paper **II**)



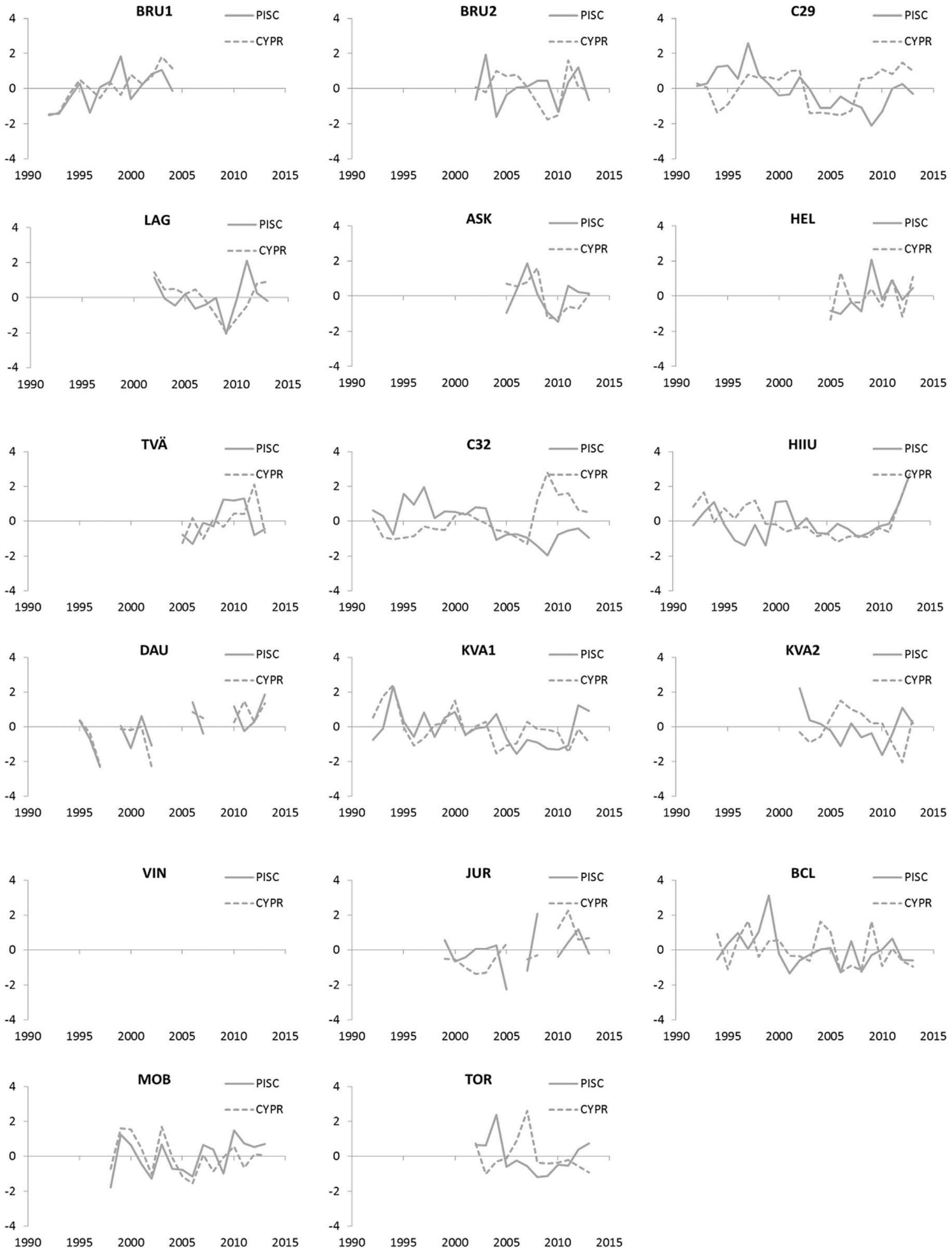
Annex 4

Spatiotemporal distribution of the number of coastal fish monitoring stations (Paper **I**)



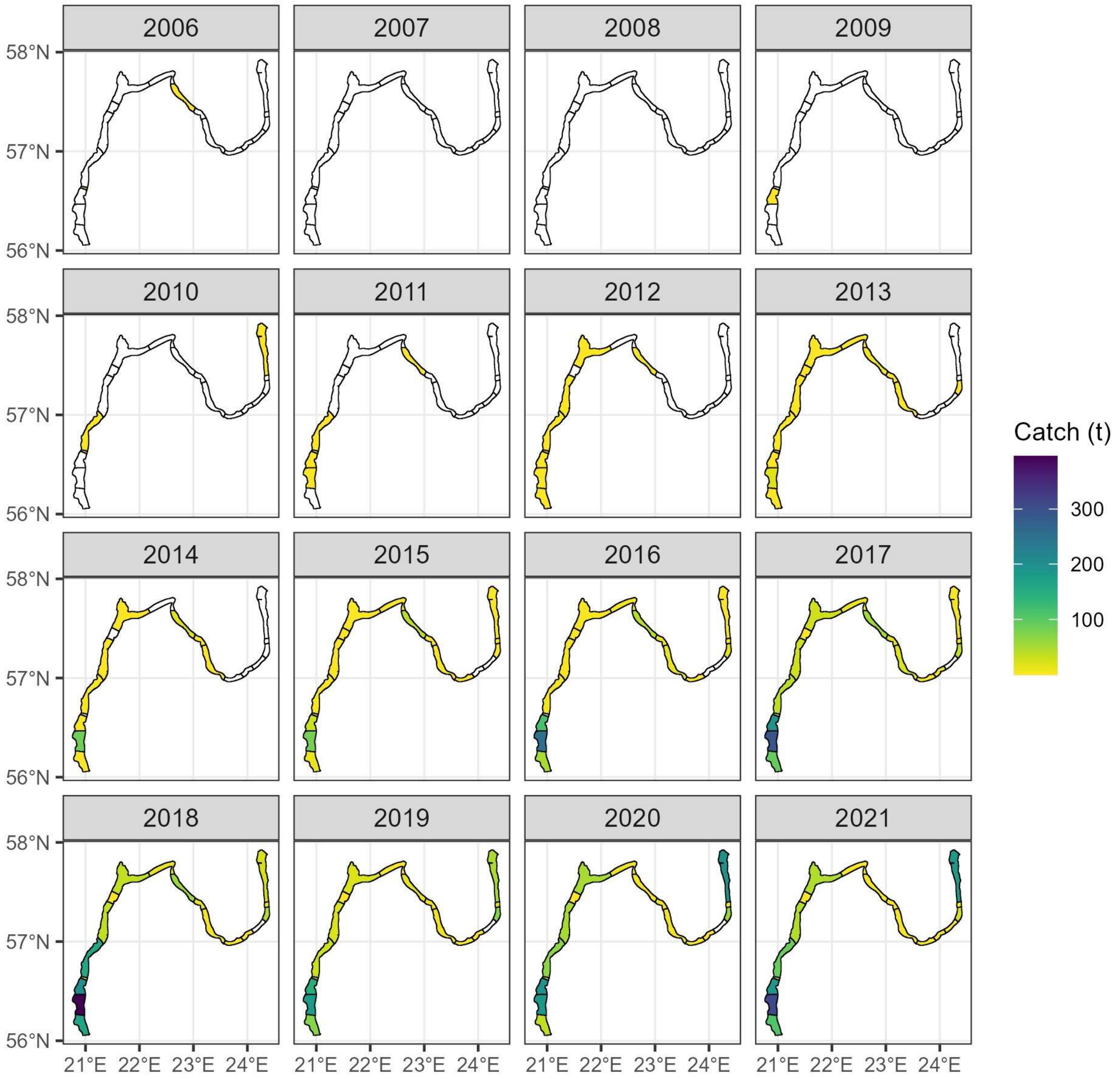
Annex 5

Temporal development in Piscivores and Cyprinids in the assessed data series, DAU and JUR corresponds to the Latvian EEZ stations. Lines show relative changes in abundance (CPUE), quantified as anomalies from the mean (z-scores).
(Paper **IV**)



Annex 6

Spatial distribution of the commercial landings of round goby in Latvian coastal waters (Paper I)



PUBLICATIONS

I

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II

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III

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IV

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