ÖSTERSJÖSTIFTELSEN
THE FOUNDATION FOR BALTIC AND EAST EUROPEAN STUDIES

SCIENTIFIC FINAL REPORT
Two- and three-year projects and postdoctoral projects

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Project manager: Mats Grahn

Project title: Health hazard in the Baltic Sea: the effects of fluorinated substances on Baltic Sea organisms

1. The three most important results of the project and what conclusions can be drawn from them

1. **PFAS distribution and site-specific profiles**. Distinct differences in PFAS profiles and concentration ranges were observed between Swedish and Polish sewage treatment plants, with generally low concentrations that were nonetheless higher in Sweden. In Poland, no clear concentration gradient was detected near WWTPs, whereas in Sweden, water samples showed elevated PFAS levels close to the plants, with the opposite trend found in sediments. These patterns indicate that PFAS contamination in the Baltic Sea is widespread, varies across sites, species, and environmental matrices, and is likely influenced by multiple and diffuse sources rather than proximity to large sewage treatment plants alone.
2. **Matrix-specific accumulation**. PFAS composition and concentrations varied markedly between environmental matrices such as water, sediment, and biota, with sediment and biota as the strongest accumulators. Among sampled biota, sediment-dwelling crustaceans such as *Monoporeia affinis* contained the highest PFAS concentrations, followed by *Macoma balthica*, while filter-feeding mussels (*Mytilus edulis* × *trossulus*) had lower concentrations, and lower number of different substances. These differences largely reflect the organisms' ecological niches, feeding habits, and exposure pathways.
3. **Toxicological effects at environmentally relevant levels.** Experimental exposures demonstrated that both short- and long-chain PFAS at low concentrations can cause sublethal effects in key Baltic species. PFBA, alone or in combination with copper, induced stress responses in *Lemna minor*, with synergistic toxicity observed when combined with copper. PFTeDA exposure in blue mussels caused concentration-related histological changes in gill, digestive, and reproductive tissues, while PFBA exposure in amphipods (Gammarus sp.) reduced food intake. Environmentally relevant PFAS concentrations can induce measurable sublethal effects in aquatic organisms, and combined exposures with other pollutants may increase toxicity. These results highlight the need for biomarker-based monitoring and risk assessment in Baltic Sea ecosystems.

2. The project's contribution to the international research frontline

This project advances the global understanding of PFAS occurrence, environmental fate, and biological effects in several important ways:

1. **Insights into PFAS distribution in the Baltic Sea region**. By comparing PFAS profiles, concentrations, and transport patterns between Sweden and Poland across multiple environmental matrices (water, sludge, sediment, and biota), the project

provides insights into PFAS distribution in the Baltic Sea region. The findings highlights the role of multiple and diffuse sources.

2. **Detailed species- and matrix-specific accumulation data**. The project delivers high-resolution data on PFAS accumulation patterns across species with different ecological niches, from filter feeders to sediment-dwelling crustaceans. This adds critical evidence to the international literature on how feeding strategies, habitat type, and life history influence PFAS exposure and bioaccumulation, supporting more targeted ecological risk assessments.
3. **Evidence of sublethal effects at environmentally relevant concentrations**. Through controlled exposure experiments, the project shows that both short- and long-chain PFAS can induce measurable sublethal effects in key Baltic species, even at concentrations commonly found in the environment. The observed toxicity of PFBA in duckweed and reduced feeding in amphipods together with histological damage from PFTeDA in mussels provide important mechanistic insights. These results can contribute to new biomarkers for PFAS monitoring, directly informing environmental health assessments and regulatory frameworks.

Overall, the project strengthens the scientific basis for international PFAS management by combining field-based distribution studies with experimental evidence of ecological effects, offering tools and data relevant to marine pollution monitoring, policy development, and cross-border environmental cooperation.

In addition, the project has contributed to capacity building by involving students and early-career researchers at multiple levels. This includes 6 master's students (3 at Södertörn University and 3 at the University of Gdańsk) and 8 bachelor's students at Södertörn University. Furthermore, an international PhD candidate from Hong Kong, engaged in collaboration with Örebro University, has also been actively involved in the project's research activities.

3. The contribution of the research to the knowledge of the Baltic Sea Region and Eastern Europe

This study provides new, region-specific insights into PFAS contamination patterns in the Baltic Sea, revealing important differences between subregions with contrasting hydrological and ecological characteristics. By comparing Swedish and Polish sites, we identified marked differences in PFAS levels in sediments and biota, with consistently higher concentrations in Sweden. This pattern contrasts with observations for many other contaminants, where Polish sites often display higher levels, and suggests that PFAS distribution is shaped by a different set of drivers.

One likely explanation lies in hydrodynamic conditions: the long, narrow, and semi-enclosed bay of Himmerfjärden (Sweden) has more restricted and complex water flows, promoting the retention and accumulation of persistent pollutants, whereas the more open and well-flushed Gulf of Gdańsk (Poland) facilitates dilution and dispersal. However, differences in current and historical PFAS use patterns may also play a substantial role. Sweden may have had more extensive applications of PFAS-containing products in firefighting (including AFFF foam), military activities, certain industrial processes, and agricultural practices, leading to higher legacy loads and ongoing diffuse inputs to the marine environment.

These findings highlight that PFAS pollution in the Baltic Sea cannot be assumed to follow the same geographical patterns as other contaminants, and that both hydrodynamic factors and national usage histories must be considered to explain observed concentrations. They also underscore the importance of combining contaminant monitoring with source tracking and historical emissions inventories. The project not only provides crucial context for interpreting PFAS data in the Baltic Sea but also expands the limited knowledge base for Eastern Europe, contributing to a more integrated and transnational understanding of chemical pollution across the region.

4. New research questions that the project has led to

Although the project has given us many answers and insights regarding PFAS in the Baltic Sea, it has also revealed new and important questions that need to be addressed to fully understand the sources, accumulation patterns, and ecological effects of PFAS. Hence the results of this project open up several important avenues for further research:

1. **PFAS transfer to top predators**. Building on our findings in lower trophic levels, there is a need to investigate PFAS bioaccumulation and biomagnification in Baltic Sea food webs leading up to marine mammals and other apex predators, also with a land to sea focus. This will clarify potential risks to species of conservation concern and to human consumers of seafood.
2. **Source identification and transport pathways**. The interesting spatial patterns, including higher PFAS levels in Sweden than in Poland (contrary to trends for many other contaminants), highlight the need for more precise source tracking. Future research should integrate historical usage data, industrial and military records, and advanced hydrodynamic modelling to disentangle the relative contributions of local point sources, diffuse emissions, and long-range transport.
3. **Ecological effects at environmentally relevant concentrations**. While our experimental work identified sublethal effects in several key Baltic species, the long-term population- and ecosystem-level consequences remain poorly understood. Future studies should address chronic exposure scenarios, multi-stressor effects (e.g., PFAS in combination with metals or other pollutants), and long-term impacts on reproduction, growth, and ecosystem functioning.

By addressing these questions, future research can fill critical knowledge gaps on PFAS dynamics, from sources to top predators.

5. Dissemination of the results of the project within and outside the research community

Published articles

1. Banyoi, S. M., Porseryd, T., Larsson, J., Grahn, M., & Dinnétz, P. (2022). The effects of exposure to environmentally relevant PFAS concentrations for aquatic

organisms at different consumer trophic levels: Systematic review and meta-analyses. *Environmental Pollution*, *315*, 120422. https://www.sciencedirect.com/science/article/pii/S0269749122016360

2. Porseryd, T., Larsson, J., Lindman, J., Malmström, E., Smolarz, K., Grahn, M., & Dinnétz, P. (2024). Effects on food intake of Gammarus spp. after exposure to PFBA in very low concentrations. *Marine Pollution Bulletin*, *202*, 116369. https://doi.org/10.1016/j.marpolbul.2024.116369

Submitted articles

3. Porseryd, T., Ek, S., Larsson, J., Smolarz, K., Grahn, M., & Dinnetz, P. (2025, April). Effects of PFBA and copper exposure, alone and in combination, on the health and growth of Lemna minor at environmental concentrations. Manuscript submitted for publication to *Ecotoxicology*.

   Abstract: *PFAS pollution in the environment is currently of global concern, with ever-increasing environmental concentrations surpassing human safety limits and causing unknown effects on species within the ecosystems. The toxicological effects of short-chain PFAS, including PFBA, are of increasing concern as the global market has shifted towards these compounds with the phase out of long-chain PFAS. Our study aims to measure toxicological effects of PFBA in environmentally relevant levels alone and in combination with copper on the aquatic plant bioindicator species Lemna minor, in a controlled experimental system. By comparing the individual and combined effects of each pollutant, we found significant stress responses, including reduced dry weight, increased dead and damaged fronds, and compensatory growth. PFBA alone (10 ng/L and 100 ng/L) stimulates plants to produce more fronds and when PFBA and copper are combined, plants exposed to 10 ng/L PFBA produced larger fronds. However, the plants in the combination exposure also experience more damage and higher mortality. This points to a synergistic toxic effect, where the combination is more harmful than either substance alone.*

4. Smolarz, K., Larsson, J., Dinnetz, P., Obszarski, J., Leprêtre, A., Świeżak, J., Hallman, A., Grahn, M., & Porseryd, T. (2025, June). Exposure to environmentally relevant levels of perfluorotetradecanoic acid (PFTeDA) affects respiratory and reproductive functions of Mytilus trossulus: An experimental study. Manuscript submitted for publication to *Journal of Hazardous Materials*.

   Abstract: *Perfluoroalkyl substances (PFAS) are extensively used worldwide and are now ubiquitous in the environment. PFAS enters marine environments via multiple sources including atmospheric deposition, agricultural and municipal runoffs, and wastewater treatment plant outlets. They are present in different biotic and abiotic environmental congeners at different concentrations, exerting negative effects on marine life. Perfluorotetradecanoic acid (PFTeDA) belongs to long-chained perfluoroalkylcarboxylic acids, has been commonly found in the marine environment and can accumulate in living organisms. Yet, the effects of exposure of marine fauna to PFTeDA are poorly understood. Here, we present the results of an experimental study in which the blue mussel Mytilus trossulus has been exposed to two environmentally relevant doses of PFTeDA, 3ng/L and 30ng/L, over a period of*

seven days. Biomarkers reflecting structure and functionality of respiratory, reproductive and digestive systems were used to evaluate PFTeDA toxicity. In addition, aromatization efficiency and biochemical markers of oxidative stress, neurotoxicity and cellular detoxification were measured in the gill tissue. No clear signs of oxidative stress or neurotoxicity were found. Yet, histological examination highlighted the negative effect of PFTeDA on respiratory, reproductive and digestive systems. In the blue mussels exposed to 3ng/L and 30ng/L, changes such as epithelial loss, oedema and local haemocytic infiltration were commonly found in the gill tissue. Gill oedema, a significant and sublethal effect of PFTeDA exposure, reflects a combination of cellular damage and possible ionoregulation failure. An elevated number of digestive tubules atrophy was also detected in the digestive tubules of exposed mussels. Increased gonadal development was found in mussels treated with PFTeDA highlighting that the compound may affect mussel reproduction. The severity of the histological changes was related to the concentration of PFTeDA. Given the persistent and bioaccumulative nature of the compound, endpoints such as gill oedema and reproductive changes should be considered key biomarkers for environmental PFAS monitoring in both laboratory studies and field assessments.

Articles in preparation

5. Tentative title: PFAS distribution and trophic transfer in Baltic Sea food webs from Sweden and Poland.
   Abstract: *PFAS concentrations and stable isotopes were measured in organisms across all trophic levels from two Baltic Sea food webs in Sweden and Poland, to investigate the distribution and trophic transfer of PFAS within these ecosystems.*

6. Tentative title: PFAS dynamics from wastewater treatment plants: Comparative analysis and modelling in two Baltic Sea catchments

   Abstract: *We investigated PFAS occurrence, distribution, and transport from sewage treatment plants in Sweden and Poland by analyzing multiple environmental matrices, including water, sludge, sediment, and biota. Flow modelling was applied to assess temporal and spatial patterns of PFAS transport. We observed distinct, site-specific PFAS profiles and concentration ranges between Swedish and Polish sewage treatment plants, with generally low concentrations that were higher in Sweden. While no clear concentration gradient was seen near Polish WWTPs, Swedish water samples showed elevated PFAS levels close to the plants, accompanied by an opposite trend in sediments. The highest PFAS concentrations were found in crustaceans.*

7. Tentative title: PFAS in sediment and biota in small harbors and marinas along the Swedish coast. In collaboration with the project ClimScape we have analysed two commonly used groups, perfluorocarboxylic (PFCA) and perfluorosulfonate acids (PFSA), of which one group, PFCA, showed a statistically significant result, with greater concentrations in harbor sediment than in sediment collected at reference sites.

Conference presentations

SETAC Europe 33rd annual meeting, 30 april-4 may 2023, Dublin, Ireland

1. PFAS in the marine environments: does perfluorotetradecanoic acid (PFTeDA) affects marine invertebrates? Poster, presenting; Katarzyna Smolarz
2. Heath hazard in the Baltic Sea: the presence of total fluorinated substances in various matrices. Poster, presenting: Tove Porseryd and Josefine Larsson

Baltic Sea city accelerator club, 16-18 april, 2024 Katrineholm, Sweden.

1. PFAS in the Baltic Sea. Oral, presenting: Mats Grahn

Baltic Sea Science congress, 26-30 may 2025, Sopot, Poland

1. PFAS Contamination in the Baltic Sea: Wastewater Treatment Plants as a Source of Pollution. Poster, presenting: Tove Porseryd
2. Exposure to perfluorotetradecanoic acid (PFTeDA) affects the respiratory, reproductive and digestive systems of the blue mussel Mytilus trossulus: an experimental study. Poster, presenting: Katarzyna Smolarz

Popular science presentations

A key focus of the project has been outreaching and dialogue beyond the academic sphere. PFAS as a topic generates significant interest in civil society, attracting attention from decision-makers, local communities, and students of all ages. We have actively contributed to this dialogue through more than 20 presentations, discussions, workshops, and collaborative project activities, covering both PFAS in general and the specific results of our project.

Stakeholders engaged include:

- **Municipal network meetings** (e.g., Baltic Sea Accelerator Club, Kommunnätverk Hanöbukten) with participation from municipal officials and elected politicians.
- **County Administrative Boards** (e.g., Skåne, Blekinge, Stockholm).
- **Regional administrations** (e.g., Region Skåne, Region Blekinge) involving both officials and political representatives.
- **National agencies and authorities** (e.g., the Swedish Agency for Marine and Water Management).
- **Civil society organisations and local associations** (e.g., Kivik Tang, Naturskyddsföreningen Österlen, Kiviks museum, Samverkan för Hanöbukten, Rotary Clubs, Biblioteket Simrishamn and Naturum vattenrike).
- **Educational institutions** – students and teachers at Nova Gymnasiet, Österlen.

Through these activities, the project has contributed to increasing public awareness, facilitating informed decision-making, and strengthening stakeholder collaboration on PFAS issues in the Baltic Sea region.