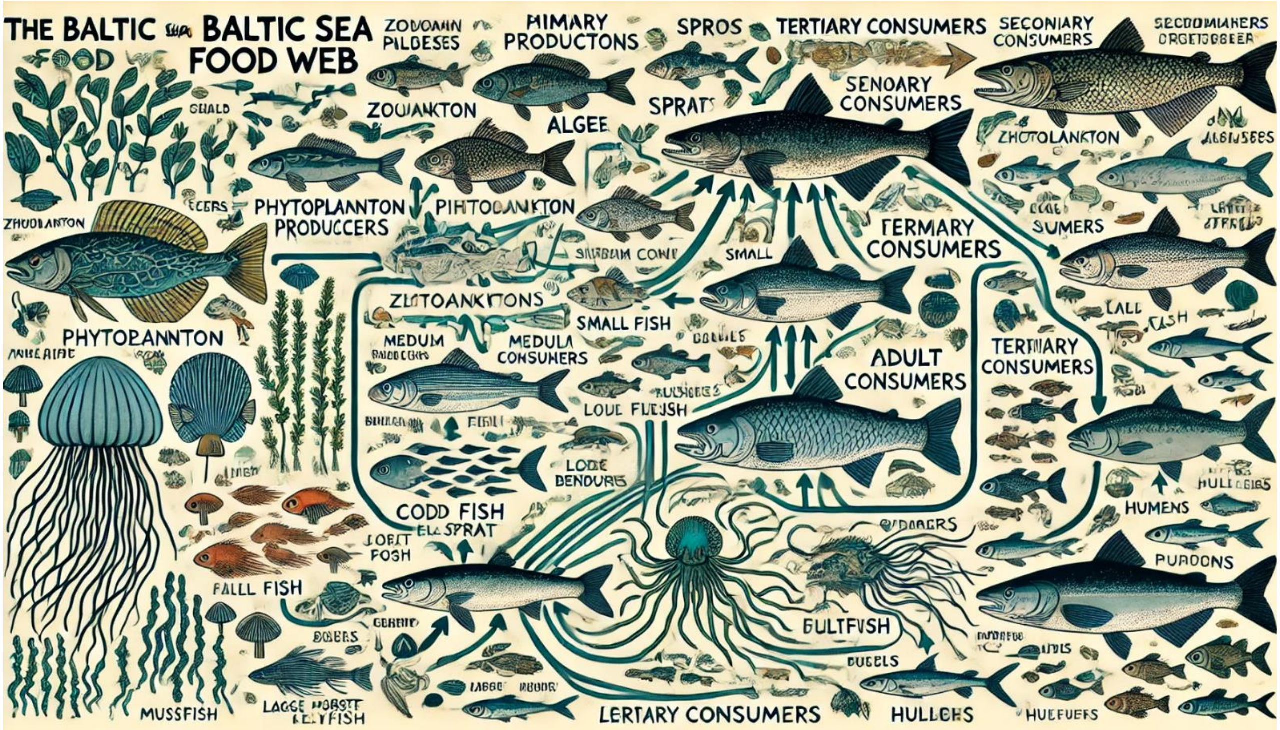
Integrated assessments of the state and the structure of the Baltic Sea ecosystems.



Dr. Maciej T. Tomczak

Self-presentation

1. Name and surname.

Maciej Tomasz Tomczak

2. Diplomas and academic degrees held - including the entity awarding the degree, the year of obtaining them and the title of the doctoral dissertation.

June 29th, 2007 – **Ph.D in Oceanology**, Faculty of Biology, Geography and Oceanology, University of Gdańsk. Doctoral dissertation entitled "*An evaluation of management practices for central Baltic herring (Clupea harengus membras L.) stock"*; Supervised by Prof. Jan Horbowy, Sea Fisheries Institute in Gdynia.

June 21st, 2003 - Postgraduate degree in Ecological Auditing and Environmental Management, Faculty of Management, University of Gdańsk.

September 12th, 2001 – **Master of Science in Oceanography i**n Marine Biology, Faculty of Biology, Geography, and Oceanology, University of Gdańsk.;

3. Information about current employment in scientific units.

August 22nd, 2022 – present. **SLU-Aqua, Swedish University of Agricultural Sciences.** Uppsala, Drottningholm Lab, Ekerö, Stockholm, Sweden. Researcher.

October 1st, 2014 – June 8th, 2023 **Baltic Sea Centre, Stockholm University,** Sweden Researcher.

October 1st, 2009 – September 30th, 2014: **Baltic NEST Institute, Stockholm Resilience Centre, Stockholm University**, Kräftriket, 104 05 Stockholm**,** Sweden, Researcher.

October 1st, 2007 – September 30, 2009: **Danish Technical University, Institute of Aquatic Resources,** Researcher.

January 1st, 2005 – September 30th, 2008: **Sea Fisheries Institute – National Research Institute,** Department of Fisheries Oceanography and Marine Ecology. Senior specialist.

4. Discussion of the achievements referred to in Art. 219 section 1 point 2 of the Act.

a) Title of the scientific archivment

Integrated assessments of the state and structure of the Baltic Sea ecosystems.

This scientific achievement consists of a series of six publications in internationally recognized scientific journals indexed by the Philadelphia Institute of Scientific Information (Philadelphia List), in which I am both the first and corresponding author.

b) List of publications constituting scientific achievement

1.**Tomczak, M. T.,** Niiranen, S., Hjerne, O., & Blenckner, T. (2012). Ecosystem flow dynamics in the Baltic Proper—Using a multi-trophic dataset as a basis for food–web modelling. **Ecological Modelling**, 230, 123-147.

Contribution: Formulating the research hypothesis and idea, data collection and synthesis, model construction and calibration, results interpretation, figure preparation, manuscript writing, and table preparation. Estimated contribution: 80%.

2.**Tomczak, M. T.,** Heymans, J. J., Yletyinen, J., Niiranen, S., Otto, S. A., & Blenckner, T. (2013). Ecological network indicators of ecosystem status and change in the Baltic Sea. **PloS one**, 8(10), e75439. B

Contribution: Formulating the research hypothesis and idea, model interpretation, figure preparation, manuscript writing, and table preparation. Estimated contribution: 85%.

3. **Tomczak, M.T**., Müller-Karulis, B., Blenckner, T., Ehrnsten, E., Eero, M., Gustafsson, B., ... & Humborg, C. (2022). Reference state, structure, regime shifts, and regulatory drivers in a coastal sea over the last century: The Central Baltic Sea case. **Limnology and Oceanography**, 67, S266-S284.

Contribution: Formulating the research hypothesis, data synthesis, results interpretation, figure preparation, manuscript writing, and table preparation. Estimated contribution: 80%.

4.**Tomczak, M.T**., Müller-Karulis, B., Järv, L., Kotta, J., Martin, G., Minde, A., Põllumäe, A., Razinkovas, A., Strake, S., Bucas, M. and Blenckner, T., 2009. Analysis of trophic networks and carbon flows in south-eastern Baltic coastal ecosystems. **Progress in Oceanography**, 81(1), pp.111-131.

Contribution: Formulating the research hypothesis and idea, model construction, research procedure, results synthesis and interpretation, figure preparation, manuscript writing, and table preparation. Estimated contribution: 70%.

5.**Tomczak, Maciej T.,** Grete E. Dinesen, Erik Hoffmann, Marie Maar, and Josianne G. Støttrup. "Integrated trend assessment of ecosystem changes in the Limfjord (Denmark): Evidence of a recent regime shift?" **Estuarine, Coastal and Shelf Science** 117 (2013): 178-187.

Contribution: Formulating the research hypothesis and idea, data synthesis, results interpretation, figure preparation, manuscript writing, and table preparation. Estimated contribution: 70%.

6.**Tomczak, M.T**., Szymanek, L., Pastuszak, M., Grygiel, W., Zalewski, M., Gromisz, S., ... & Margoński, P. (2016). Evaluation of Trends and Changes in the Gulf of Gdańsk Ecosystem—an Integrated Approach**. Estuaries and Coasts**, 1-12.

Contribution: Formulating the research hypothesis and idea, data synthesis, results interpretation, manuscript writing, and table preparation. Estimated contribution: 70%.

Bibliometric summary:

Publication number, abbreviated name of the publisher, year of publication	**Citations**					
	WoK	**Scopus**	**Google Scholar**	**IF**	**IF5**	**Points of the Ministry of Science and Higher Education**
1. Ecological Modelling, 2012	74	75	113	2.069	2.524	100
2.PloS one, 2013	63	68	97	3.534	4.244	100
3. Limnology and Oceanography, 2022	24	23	34	4.579	5.826	140
4. Progress in Oceanography, 2009	49	54	84	2.916	3.1	140
5. Estuarine, Coastal and Shelf Science, 2013	18	21	29	2.252	2.687	140
6. Estuaries and Coasts, 2016	10	10	15	2.559	2.872	100
Sum:	238	251	371	17.909	21.253	720

Number of citations based on the Web of Knowledge (WoK) and Scopus databases as of August 30, 2024. Impact factor (IF) and five-year IF (IF5) values are given for the year of publication. (Points of the Ministry of Science and Higher Education) are provided according to the current list based on the Annex Points of the Ministry of Science and Higher Education to the announcement of January 5, 2024.

c) Discussion of the scientific purpose of the work mentioned above and results achieved, along with a discussion of their possible use

Integrated Assessments of the State and Structure of the Baltic Sea Ecosystems

When discussing ecosystems, it is crucial to define what we mean by the concept of an ecosystem. According to Odum and Barrett (1971), *"An ecosystem is a functional unit in ecology that encompasses both organisms (biocenosis) and their abiotic environment, interacting to allow energy and matter to flow through the system"*. An ecosystem comprises the following key elements: i) Living organisms (biocenosis)- All living entities within a specified area, including plants, animals, fungi, and microorganisms, ii) Abiotic environment- The non-living components of the environment, such as soil, water, air, minerals, and other physical and chemical factors, iii) Interactions - The relationships between organisms and their environment that create a coherent system, iv) Flows of energy and matter - Processes including photosynthesis, respiration, decomposition, and biogeochemical cycles that facilitate the movement of energy and materials through the ecosystem.

Furthermore, Ulanowicz (2001) emphasizes the dynamics of food webs, energy flows, and information transfers, along with ecosystems' complexity and adaptive capacity to evolve and adjust to environmental changes. His methodology utilizes tools from information and systems theory to better understand and quantify these processes.

Complex systems such as marine ecosystems require a holistic approach known as Integrated Ecosystem Analysis (IEA) (Levin et al., 2009). This method integrates biological, physical, chemical, and social aspects to assess the ecosystem's state and understand the interdependencies between its components, as well as to predict the impact of environmental and anthropogenic factors. This form of assessment is crucial for scientific advice and effective marine environment management, requiring robust methods and tools, including: i) **Data monitoring, collection, and synthesis** - Systematic gathering of data from diverse sources, including satellites, ocean sensors, field surveys, and historical databases, ii) **Ecosystem modelling** - Use of mathematical models and computer simulations to understand the dynamics of ecosystems, the interactions and energy flows between components, iii) **Multivariate analysis** - Application of statistical methods to analyze complex data sets to identify dependencies and factors influencing the ecosystem.

The Baltic Sea can be described as an ecosystem with low biodiversity, highly sensitive to eutrophication, and influenced by external factors such as climate and anthropogenic activities. Its unique hydrology, characterized by salinity gradients and vertical stratification, significantly impacts its functionality. However, when considering different regions and scales—ranging from entire Baltic Sea basins to individual bays or estuaries—it becomes necessary to differentiate ecosystems based on specific ecological and economic attributes that require targeted assessments.

Möllmann et al. (2009) studied regime shifts in the central Baltic ecosystem, focusing on changes in hydrographic conditions, species composition, and trophic interactions during the late 1980s and early 1990s. This research identified substantial modifications in the ecosystem's structure, leading to a transition from a cod-dominated state to one dominated by sprat. This shift involved significant alterations in interspecies interactions and trophic flows, driven predominantly by climatic and anthropogenic factors, fundamentally changing our understanding of food web dynamics in the Baltic Sea ecosystems.

This habilitation thesis is based on a series of six scientific publications that appeared in internationally recognized journals listed on the so-called Philadelphia List. **The primary goal was to evaluate the condition, structure, and transformation mechanisms of ecosystems influenced by natural environmental changes such as climate variation and human activities.**

The research questions addressed included:

- How has the structure of food webs and the flows of mass and energy changed?
- What factors have influenced the ecosystem?
- How do the dynamics of ecosystem function respond to changing environmental conditions?

To answer these questions, I analyzed multidisciplinary, multi-year environmental data from the brackish waters of the Baltic Sea. This study not only provided new insights into the functioning of its ecosystems but also highlighted the roles played by various organisms and functional groups within food webs. The studies employed modern methods of data analysis and synthesis and were interdisciplinary, incorporating aspects of ecology, modeling, and multidimensional statistical analyses.

These studies were part of several international and national projects, including:

- EU 7th Framework Program MEECE - Marine Ecosystem Evolution in a Changing Environment (grant agreement 212085),
- Baltic Sea Regional Project (BSRP) - GEF ID 922, IBRD ID48795,
- FORMAS project "Regime Shifts in the Baltic Sea Ecosystem - Modelling Complex Adaptive Ecosystems and Governance Implications",
- Strategic marine environmental research funds from Stockholm University through the Baltic Ecosystem Adaptive Management Program,
- KnowSeas - Knowledge-based Sustainable Management for Europe's Seas, FP7/2007-2013 European Community's Seventh Framework Programme under grant agreement no. 226675,
- BONUS-BLUEWEBS project funded by BONUS (Art 185),
- Danish national collaborative project "Regime Shift in the Limfjord" funded by the DFFE (contract No. 304-FVFP-060671-01),
- EU 6th Framework Program ELME (European Lifestyles and Marine Ecosystems), Grant agreement ID: 505576.

During my tenure at DTU-Aqua, in cooperation with Baltic NEST at Stockholm University, I conducted research on food webs in the Baltic Sea, which was published as the first article by the discussed scientific institution. In this research, I presented an in-depth analysis of the Baltic Proper ecosystem, focusing on interactions within the food web and the dynamics of energy flows (Fig.1)

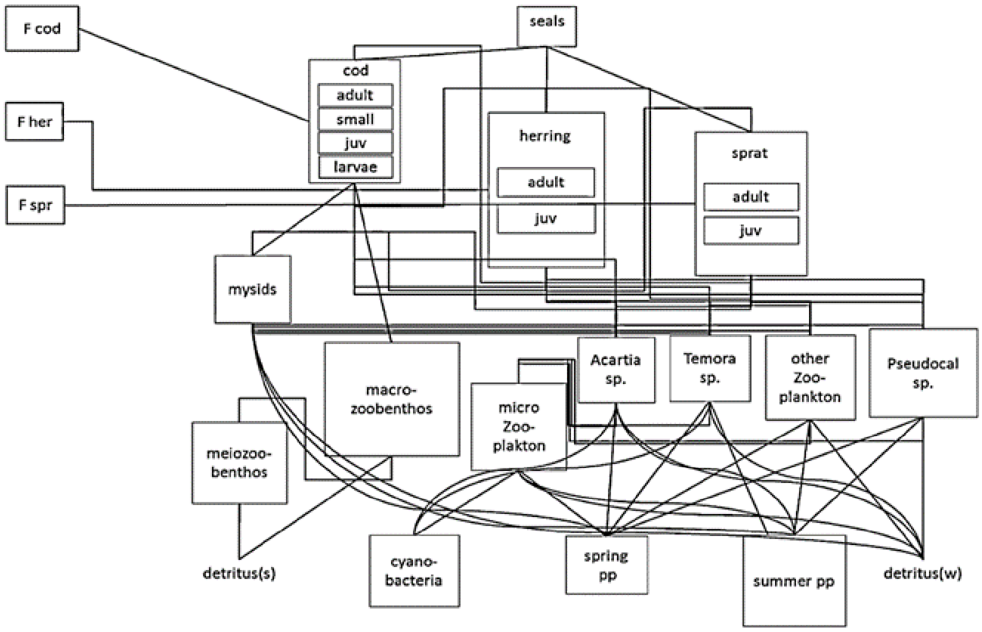


Figure 1. Structure of the Ecopath with Ecosim (EwE) Model for the Baltic Proper. Where 'F' represents individual fisheries, 'pp' denotes primary producers, and 'juv' indicates the juvenile stage of a given fish species. The detritus pool is divided into two groups: detritus on the sediment (detritus (s)) and detritus in the water column (detritus (w)). (Adapted from Tomczak et al., 2012).

The analyses range from 1974 to 2006, during which I simulated observed ecological processes, including the significant regime shift described by Möllmann et al. (2009). This work successfully simulated and described the mechanisms of reorganization that occurred in the late 1980s and early 1990s, mainly due to changes in fishing practices and climate. Forcing functions representing fisheries, eutrophication, hypoxia, and temperature were successfully integrated into the model, reflecting the non-linear relationships within the ecosystem. To analyze the dynamics, state and structure, I developed a dynamic food web model based on Ecopath with Ecosim (Christensen and Walters 2004). This model includes 22 functional groups, representing various components of the food web from primary producers to top predators and fisheries. The model was calibrated using extensive long-term monitoring data (Tomczak et al., 2012), and it explained as much as 51% of the variability in observed biomass and catch across trophic levels, effectively reorganizing the Baltic Sea food web. Before the state change, trophic flows through the detrital chain and benthic organisms dominated, with macrozoobenthos playing a crucial role in transferring energy from lower trophic levels to top predators. After the regime shift, pelagic trophic flows became dominant.

The model accurately reproduced the biomass and catch time series for most functional groups, although some overestimations were noted, particularly for adult sprat and juvenile herring. Significant changes were identified in predator-prey dynamics, particularly between cod and sprat. Cod predation on macrozoobenthos decreased, while sprat predation on zooplankton increased. The regime shift also included changes in zooplankton structure and fish populations, influenced by climatic factors and fishing pressure. The replacement of *Pseudocalanus spp*. by *Temora spp*. and *Acartia spp*. as the dominant species affected fish populations and their interactions, particularly in terms of food competition between cod larvae and the sprat population.

This work underscores the importance of understanding energy and matter flows within an ecosystem for effective management and prediction of changes. Methodological issues such as model performance were also discussed, and improvements to the calibration process were proposed. Calibration involved fitting the model to observed data (time series) and adjusting parameters for better accuracy, which significantly enhanced model performance. Despite some discrepancies in simulating specific groups, the model successfully captured the observed changes in state and reorganization in trophic flows and structure, highlighting its value as an ecosystem assessment tool. Uncertainties and limitations, such as challenges related to the accuracy of simulating specific functional groups and the need for more comprehensive data to assess error probabilities, were also considered.

The implications for ecosystem management are significant, as the model's ability to simulate interactions between different trophic levels and the impacts of human activities is crucial for informing fisheries management. By simulating the effects of predatory and natural mortality and environmental changes, the model provides valuable information for developing sustainable fishing practices and supporting an ecosystem-based approach to fisheries management (EBFM) (Link & Browman, 2017). The paper suggests that future research should focus on improving the model by incorporating additional environmental factors and using indicators to assess the state of the ecosystem, which will further enhance our understanding and support scientific advice for Baltic Sea management.

Further research on the food web and indicators was conducted while working at Baltic NEST at the University of Stockholm. The results were published in a second paper, part of this scientific achievement. This study examined ecological changes in the Baltic Sea between 1974 and 2006, including a regime shift in the late 1980s. The study employed the food web model described in the first paper. It used Ecological Network Analysis (ENA) to calculate indicators that assess changes in the ecosystem, enabling an assessment of the state according to criteria by Odum (Odum & Barrett, 1971) and Ulanowicz (2001). ENA was used to analyse ecosystem resilience and trophodynamic properties, employing indicators such as Total System Throughput (TST), Ascendency, Overhead, Redundancy, Average Mutual Information (AMI), Finn Cycling Index (FCI), System Omnivory Index (SOI), Connectivity Index (CI), and Development Capacity (DC).

The results revealed significant transformations in the ecosystem in the late 1980s, with further developments in the 1990s and early 2000s. To examine the changes suggested by the model, methods such as Integrated Trend Analysis (ITA), as employed by Möllmann et al. (2009), and approaches by the ICES Working Group for Integrated Assessment of the Baltic Sea (ICES 2008) were used. These methods included sequential t-tests on time series (STARS), principal components analysis (PCA), and chronological clustering (CC). The ENA analyses demonstrated two distinct states of the ecosystem, highlighting non-linear changes in accordance with hysteresis theory (Scheffer et al., 2001) (Fig.2).

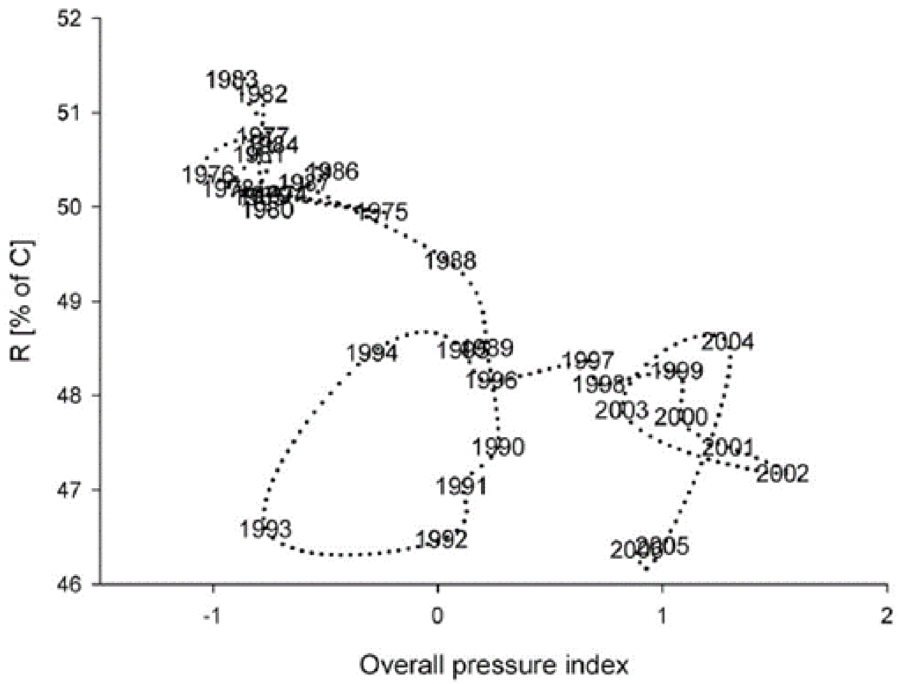


Figure 2. Redundancy – as an Indicator of Resilience (R) in Relation to the Overall Pressure Index. (Figure blacked out from Tomczak et al., 2013).

Before the reorganization, the Baltic Sea exhibited a complex, web-line structure supporting diverse energy flows and nutrient recycling. After the shift, the ecosystem became more linear and stressed, with fewer groups involved in energy transfer and reduced nutrient recycling. The conclusions of the paper emphasize that understanding the dynamics of regime change is crucial for effective ecosystem management. The sudden transformation of the Baltic Sea reduced its resilience, making it more vulnerable to further disruptions and potential sudden state changes. The study highlights the need for integrated, holistic approaches to ecosystem management that consider both anthropogenic and environmental pressures. Strengthening the resilience of marine ecosystems requires adaptive management strategies that can respond to current and future changes. The research described above underlines the utility of ecosystem indicators in capturing the dynamics of the food web system, providing valuable information about the dynamics of the Baltic Sea (Longo et al., 2015). The study indicates the necessity for continued monitoring, tool improvement, and research to develop effective ecosystem management strategies that maintain ecosystem resilience and functionality in the face of numerous pressures.

Another study that addresses the research questions posed by the scientific achievements, but on a broader timescale, is the third article. This paper presents an extensive analysis of the dynamics of the Baltic Sea ecosystem over the last century. The aim was to identify and understand the reference ecosystem state, structural changes, regime shifts, and regulatory factors that influenced these changes. The study is based on an integrated approach using long-term data series, ecosystem network analysis, and various statistical methods (ITA and General Additive Modeling - GAM) to assess the state of the ecosystem and its changes.

The occurrence of regime shift in marine ecosystems has significant implications for environmental legislation, including, for example, the Marine Strategy Framework Directive, which requires the setting of reference levels and the designation of the ecosystem state as a target state. The Baltic Sea ecosystem underwent major changes in the 20th century, related to anthropogenic pressures and climate variability, which resulted in a reorganization of the ecosystem. In this work, historical information was collected and reconstructed, and changes in the ecosystem were identified using multivariate statistics and modeling with 31 biotic and abiotic variables from 1925 to 2005 relating to the central part of the Baltic Sea. A series of changes in the state of the ecosystem were identified and described, occurring in the 1930s and 1970s, and again in the late 1980s and early 1990s (Fig.3).

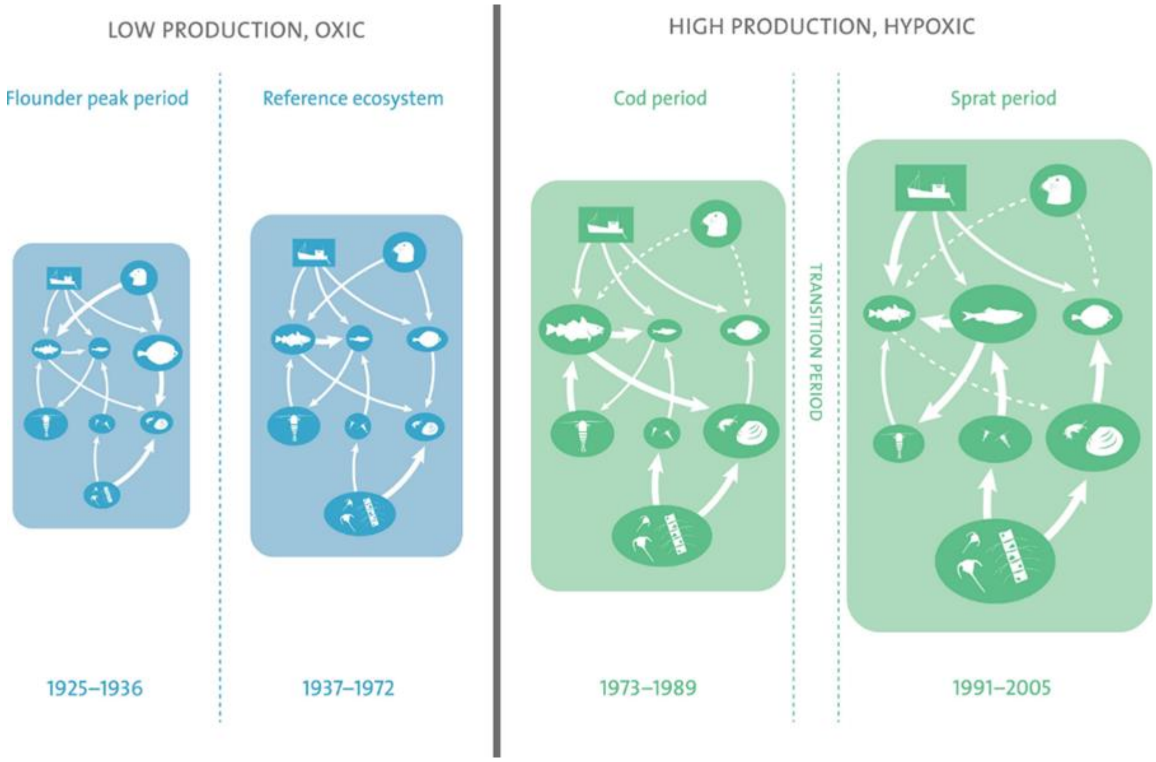


Figure 3. Conceptual Diagram Illustrating Changes in the Baltic Sea Ecosystem between 1925 and 2005, Indicating Potential Ecosystem Transformation. Blue and green rectangles represent systems with low and high productivity, respectively. Arrows indicate the direction and strength of control. The width of the arrows denotes the intensity of the interactions. Dashed lines signify weakening or loss of trophic control. Circles and ellipsoids represent natural elements of the food web; squares depict fisheries. (Adapted from Tomczak et al., 2022).

This research confirmed and described the phenomenon of regime shift in the trophic state of the Baltic Sea ecosystem in the 1970s, transitioning from a phase of low primary production in the years 1925–1972 to a phase of high primary production and high eutrophication starting in the latter half of the 1970s. Importantly, the study analyzed and described the changes and consequences associated with this phenomenon and its long-term effects. This is one of the first, if not the only, works that quantifies changes in the ecosystem over a long timescale, i.e., since the 1920s, and illustrates how the ecosystem has evolved. During the period of flounder dominance (*Platichthys flesus*) from 1920 to 1936, the early 20th-century Baltic Sea ecosystem was characterized by low biomass of cod, herring, sprat, and benthic fauna, but high biomass of flounder. Flounder biomass peaked in the 1920s and early 1930s before crashing. This peak coincided with a period of hydrographic stagnation, characterized by the absence of significant inflows from the North Sea, leading to lower salinity in the deeper water layers. This environment was unfavorable for cod recruitment but sufficient for the more euryhaline flounder. High fishing pressure and the expansion of trawling initially increased flounder biomass through compensatory growth, but eventually led to a collapse due to overfishing. From 1937 to 1972, after the collapse of the flounder stock in the early 1940s, the Baltic Sea ecosystem entered a period known as the "reference ecosystem." This period, lasting until the early 1970s, was marked by relatively stable conditions without extreme changes in the biomass of key groups. There were high salinities and good oxygen conditions, with frequent inflows of saltwater, which contributed to environmental stability. Cod biomass increased during this period due to improved reproductive conditions and reduced competition from flounder. This period was also characterized by increasing primary production, marking the beginning of eutrophication. The early 1970s marked a significant regime change in the Baltic Sea ecosystem, transitioning to a phase of high production. This change was characterized by an accelerated increase in primary production and biomass across almost all trophic levels. Cod became the dominant species during this period (1973–1989) thanks to favorable reproductive conditions and increasing primary production. The interaction between cod and its prey became the dominant pattern in the food web. The biomass of cod as the main predator was supported by two trophic pathways: benthic and pelagic. Eutrophication began to significantly impact the ecosystem, leading to increased nutrient levels and productivity. In the late 1980s and early 1990s, another regime shift occurred after 1989, shifting from cod to sprat dominance, consistent with the results of Möllmann et al. (2009). Over the long term, the Baltic Sea underwent a transition from being dominated by benthic trophic flows to pelagic flows. Historically, benthic components played a significant role in trophic transfer, whereas in a more modern productive system, the pelagic-benthic link was weak, and pelagic components predominated. The analysis shows that throughout the period under study, productivity, climate, and hydrography primarily influenced the functioning of the food web, while fishing became important only recently. An important conclusion is that eutrophication had far-reaching direct and indirect effects from a long-term perspective, affecting not only the productivity status of the system but also impacting higher trophic levels. The study also suggests, in the long term, a shift in the main factors regulating the state of the ecosystem from salinity to oxygen content. The "reference ecosystem" identified in the analysis can provide the basis for establishing baseline ecosystem states and threshold values for indicators of the ecosystem state of the central Baltic Sea.

Another paper presented as part of the scientific achievements (number four), the food web and energy flows in five coastal ecosystems of the Baltic Sea were analyzed: the Bay of Puck, the Curonian Lagoon, the Lithuanian coast, the coast of the Gulf of Riga, and the Gulf of Pärnu (Fig.4).

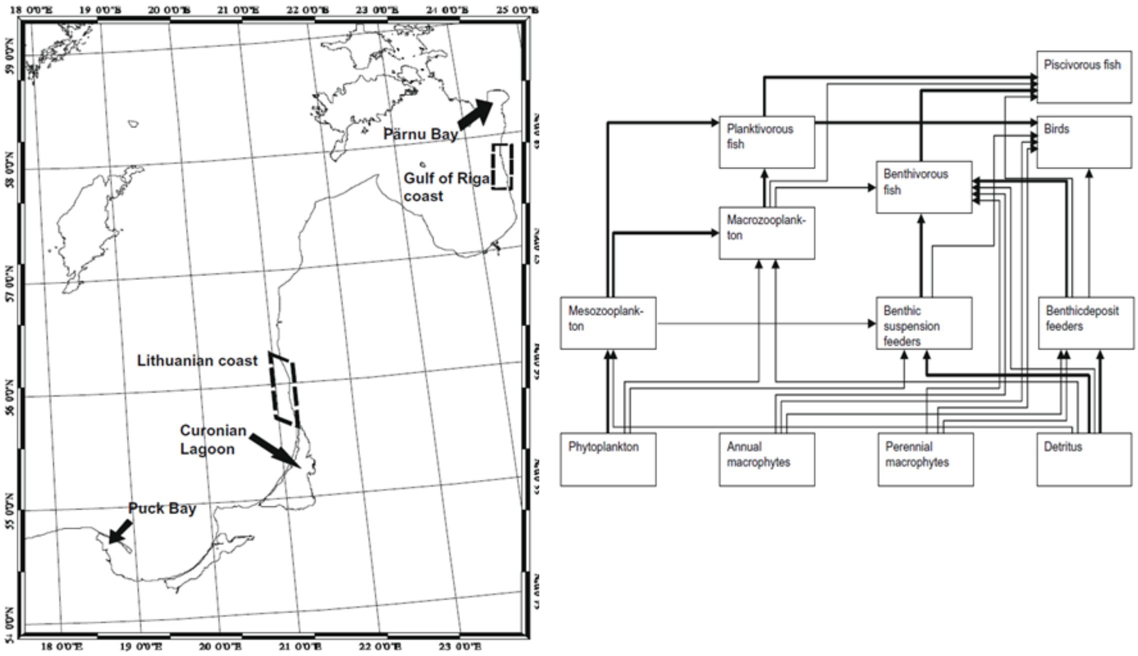


Figure 4. Left Panel: Southeastern part of the Baltic Sea showing the locations of the studied areas – from south to north: Bay of Puck, Curonian Lagoon, Lithuanian coast, Gulf of Riga coast, and Pärnu Bay. Right Panel: Trophic network structure of ECOPATH models. (Adapted from Tomczak et al., 2009).

These studies were presented in the broader perspective of comparative ecology as proposed by Magrey (Baird and Ulanowicz 1993; Megrey et al., 2009). Using ECOPATH models (Christensen and Walters 2004), the structure and functioning of these ecosystems were examined, identifying 12 common functional groups. The ecosystems studied varied in trophic status, from the hypertrophic Curonian Lagoon to the mesotrophic coast of the Gulf of Riga. A key finding was that much of the macrophyte biomass in these ecosystems was not consumed by herbivores but entered the detritus food chain. Fishing was found to have a significant impact on economically valuable species and a broad impact on food web flows, often leading to cascading effects. For example, changes in predatory fish biomass due to fishing activities influenced benthic fish and macrozoobenthos populations, demonstrating interconnectedness in these ecosystems and a potential top-down control mechanism. These results highlight the importance of considering ecosystem-specific responses when using benthic invertebrates as indicators of productivity and eutrophication. The study demonstrates the usefulness of ecosystem models such as ECOPATH in integrating diverse ecological data to provide a comprehensive understanding of ecosystem dynamics and support sustainable management.

Article number five, presented as part of the scientific achievement, examines the Limfjord ecosystem during the period from 1984 to 2008 to identify significant changes in its structure and the potential drivers of these changes. These were the first studies using the ITA method in these waters.

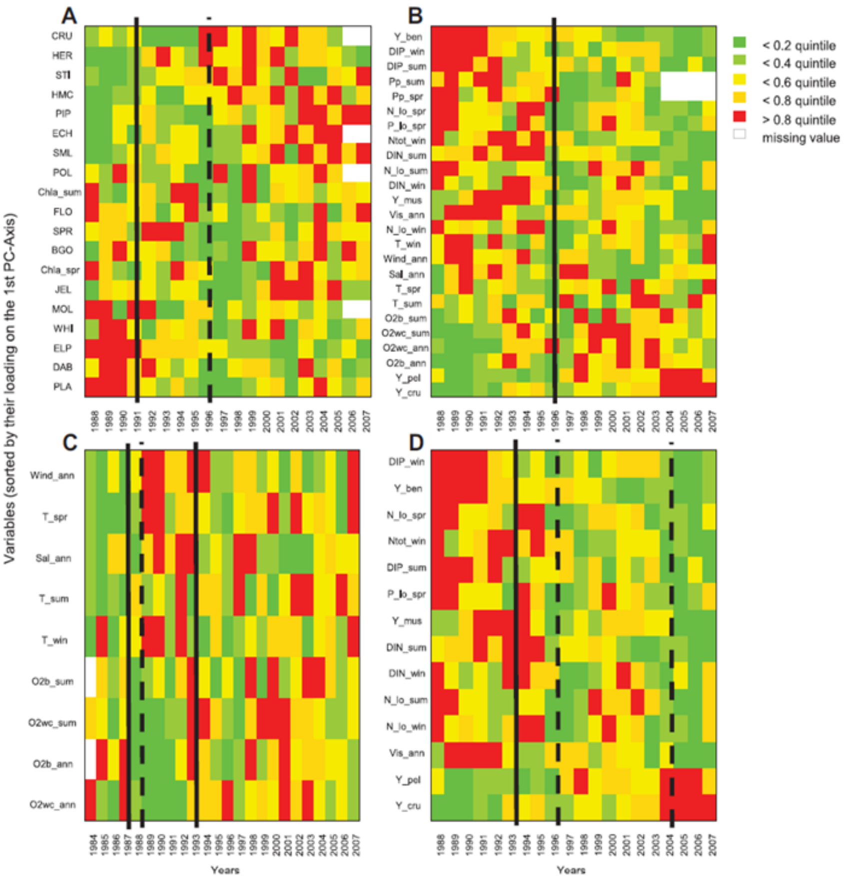


Figure 5. Traffic Light Plots Showing the Development of the Limfjord System. Time series data have been transformed into quartiles and ordered by PC1 axis values: (A) biota; (B) abiotic variables; (C) climatic impact; and (D) anthropogenic pressure. Solid lines represent regime changes detected through Chronological Clustering, while dashed lines indicate major changes identified using the PC1 index. Changes from red to green represent transitions from high to low values. (Adapted from Tomczak et al., 2013).

The entire research was conducted within the framework of ongoing activities at DTU-Aqua, aimed at supporting the resource management of blue mussel (*Mytilus edulis* L.) and their commercial use. This study employed an Integrated Trend Assessment (ITA) approach using time series data covering biological, fisheries, and abiotic variables. These data were carefully selected for their ecological significance and completeness. The results indicated several periods of significant changes in the Limfjord ecosystem, particularly in 1991-1994, 1997-1998, and 2003-2007, with a landmark year in 1995. Analysis of biological data revealed a shift from dominance by bottom fish species such as eel, whiting, and plaice to pelagic fish species such as sprat and herring, as well as small fish, jellyfish, crabs, starfish, and mussels. This suggests a nonlinear regime shift driven by a combination of anthropogenic pressure and climate disturbance (Fig.5). Restoring the ecosystem to its original state would likely require significant changes in the pressures exerted on the ecosystem. This article also contextualizes the changing ecosystem state in the Limfjord within a broader perspective of regional change, noting that similar dynamics were observed in adjacent marine systems such as the North Sea and the Baltic Sea. The timing of these changes is consistent with the change in condition in the Limfjord, highlighting the potential impact of widespread climate anomalies in the late 1980s. The study underscores the need to understand these changes for effective ecosystem management, particularly in the context of communicating changes to the public, stakeholders, and decisionmakers. Overall, the article provides solid evidence that the state of the Limfjord ecosystem is changing, although not necessarily in a detrimental economic way. The results highlight the need for adaptive management strategies to cope with the ongoing conditions in the ecosystem and the economy based on it. The complexity of the ecosystem and the numerous variables involved underscore the importance of integrated resource management approaches that take into account both socioeconomic and ecological perspectives.

Following article analyzing the coastal ecosystem (number six in the scientific achievement) covers the integrated assessment of ecosystem trends in the Gulf of Gdańsk (GoG) during the period from 1994 to 2010.

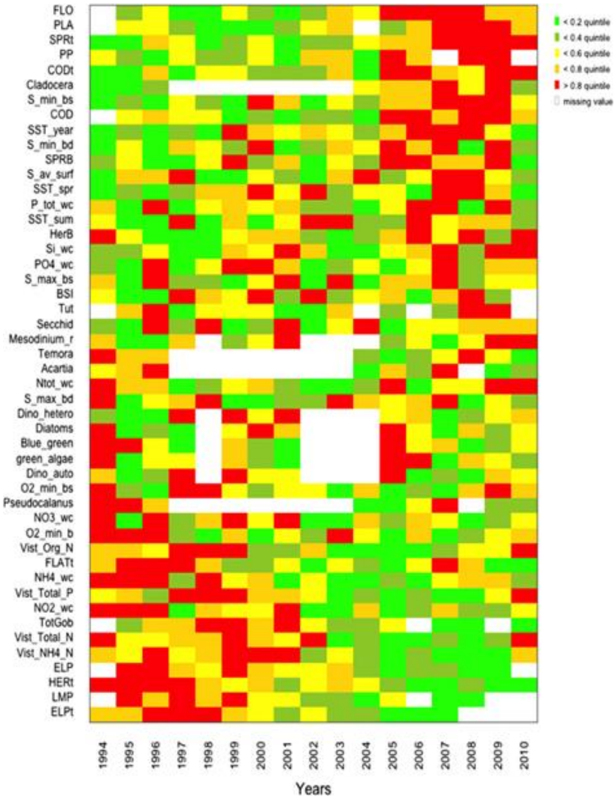


Figure 6. Visualization of Changes in the Gulf of Gdańsk Ecosystem. Changes from red to green represent transitions from high to low values. (Adapted from Tomczak et al., 2016).

The study focused on identifying significant changes in the ecosystem and understanding the factors behind them, using a combination of biotic and abiotic data. In this work, statistical ITA methods, described in earlier works, were employed. The results indicated significant changes in the ecosystem of the Gulf of Gdańsk between 1994 and 2010. There was an increase in open sea species such as flatfish, sprats, and cod, and a decline in typical coastal species such as eel and strongyloidiasis. Primary production also increased during this period. This work identified two main periods of change in the ecosystem: 1996-1997 and 2002-2003. These changes were related to various anthropogenic pressures, such as high fishing pressures on flatfish and eels and high nitrogen loads from rivers. Additionally, surface temperature and salinity played significant roles as environmental factors. The analysis also showed a major disturbance in 2007, characterized by exceptionally high temperatures and salinity, combined with low oxygen conditions. In this work, I emphasized the complexity of the ecosystem of the Gulf of Gdańsk. The food web of the Gulf of Gdańsk showed a change from a system dominated by coastal species to a system more influenced by open sea species (Fig.6). Despite reduced nutrient loads, high eutrophication remains a problem. This was the first integrated analysis for the Gulf of Gdańsk. In my work, I emphasized the need to have long-term data to fully capture the dynamics of changes, as it is difficult to confirm changes in the state of the ecosystem at this time. The work identified gaps in data and knowledge and made suggestions that future research should focus on collecting more comprehensive datasets, including data on coastal zoobenthos, to provide a more complete picture.

The results of interdisciplinary research presented in this habilitation thesis, mostly conducted in international teams, were among the first to include a holistic assessment of the Baltic Sea ecosystems, encompassing both the open sea and coastal zone ecosystems, and taking into account long-term changes in structure and functioning. To summarize the research issues based on the works collected in the scientific achievement, it should be emphasized that the structure of food webs and mass and energy flows have undergone significant changes in response to various external factors, such as eutrophication, fishing, and climate change. For the open Baltic Sea ecosystem, the shift in dominance from benthic fish, from cod to pelagic sprat, influenced the main energy flow pathways from benthic to pelagic. However, in coastal ecosystems, it is significant changes between the detrital and pelagic chains, which indicates changes in the use of resources and recycling of matter in ecosystems. Also important in coastal ecosystems (where this change was observed) was the transition from the dominance of relatively large, specialized organisms with a K- reproduction strategy to small, more opportunistic organisms with an R-strategy.

As mentioned earlier, eutrophication, fishing, and climate change are factors determining the shape and functioning of the Baltic Sea ecosystem. Locally, various factors play a leading role, but regionally and throughout the Baltic Sea, in the long term, it is eutrophication caused by inflows of biogenic salts that come to the fore, bringing far-reaching direct and indirect effects. The model studies mentioned aimed to propose innovative practical applications in the management of marine ecosystems. They can form the basis for plans to manage anthropogenic pressure and create plans for the protection, conservation and restoration of ecosystems. Models and analyses presented in the habilitation thesis enabled working groups within HELCOM to use them as tools for future condition assessments of the Baltic Sea. Indices based on trophic models were also proposed as holistic indicators of ecosystem status for OSPAR FW9, and they will be considered in condition assessments of ecosystems by OSPAR for the development of management plans in the EU, such as the Marine Strategy Framework Directive, the Biodiversity Framework Directive, and the Common Fisheries Policy. In the management of marine ecosystems worldwide, methods using IEA help manage fishing, protect biodiversity, and are considered as one of the main tools in advisory processes, taking into account socio-economic needs and impacts. An example is the IEA program conducted by NOAA (www.integratedecosystemassessment.noaa.gov) and the use of trophic models as advisory tools in ICES, called Feco, for the Irish Sea cod stock (Howell et al., 2021). Based on the works included in the habilitation dissertation and my scientific achievements, I am currently working on applying Feco approaches to Baltic Sea fish stocks and integrating them into operational approaches in ICES advice (ICES 2023).

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5. Information about significant scientific activity carried out at more than one university or scientific institution, especially a foreign one.

My involvement with the ecology of organisms in the Baltic Sea commenced during the third year of my Master's studies at the **Faculty of Biology, Geography, and Oceanology of the University of Gdańsk**. It was then that I initiated scientific collaboration with Dr. Mariusz Sapota, who supervised my Master's thesis titled "Fecundity and Gonadal Development Cycle of the Round Goby (Neogobius melanostomus, Pallas 1811) from the Gulf of Gdańsk." The findings from this thesis were published in "Oceanological and Hydrobiological Studies" (Tomczak and Sapota 2006). In my fifth year of Master's studies, I was granted a prestigious scholarship by the Kingdom of Denmark for the **Denmark International Study (DIS)** program, focusing on marine biology and ecology. After completing my Master's degree, I enrolled in the doctoral program at the **Institute of Oceanology of the Polish Academy of Sciences (IO PAS)** in Sopot and the **Sea Fisheries Institute in Gdynia**. As a doctoral candidate, I engaged in various activities at the MIR, including ichthyological and environmental analyses, participating in research cruises and expeditions. I also became actively involved in the work of study groups within the **International Council for the Exploration of the Sea (ICES)**, which related to the subject of my Ph.D. thesis - "An evaluation on management practices for the central Baltic herring (*Clupea harengus membras* L.) stocks" and a broad assessment of fish resource state using an ecosystem approach.

During this period, I attended numerous courses organized by ICES and NMFRI in resource assessment methodologies and ecological modeling. One significant issue in Baltic Sea herring resources is determining the biological basis for dividing the population into stocks with different dynamics (Jørgensen et al., 2005). This issue was extensively discussed in ICES study groups on the assessment of herring stock states, in which I participated in 2002 and 2003 (ICES 2002, 2003). This aspect formed the core assumpcion of my doctoral thesis.

As part of my work at the Department of Fisheries Resources Assessment, I initiated collaboration with Prof. Draganik and researchers from the Königsberg district (AtlantNIRO, Russia) to assess the stock of Baltic flounder in ICES subarea SD26, which had not been assessed by ICES previously. This was the first assessment of the status of this stock, resulting in the publication (Draganik et al., 2007). In 2005 and 2006, I participated in two internships abroad at **CEFAS - the Center of Environmental, Fisheries and Aquaculture Science in Lowestoft, UK,** where I worked with Dr. Andy Payne and Professor John Pinnagar to learn how to construct and develop food web models. This collaboration led to the creation of the first trophic model of the Bay of Puck, which quantified trophic flows, identified key functional groups, and determined the predatory mortality rate for the round goby (*Neogobius melanostomus* L.). It was the first integrated analysis of the Bay of Puck ecosystem and its role in the early development of the round goby population. These studies served as the foundation for international cooperation within the Baltic Sea Regional Project (BSRP- 2002-2007, Baltic Sea Regional Project: Environmentally Sustainable Development of the Baltic Sea. World Bank, Global Environment Facility (GEF), and the International Baltic Sea Fishery Commission (IBSFC)). Together with Dr. Barbel Muller-Karulis, we organized several meetings within the BSRP, where, with my assistance, models for other coastal ecosystems of the Baltic Sea were constructed, leading to a paper (Tomczak et al., 2009) and presentations at international scientific conferences, including the ICES Annual Science Conference 2008. This work enabled the completion of my dissertation and was discussed in sections 2.

After defending my PhD, I was employed at the **Sea Fisheries Institute in Gdynia (currently the - National Marine Fisheries Research Institute: NMFRI)**, as a senior specialist at the Department of Fisheries Oceanology and Marine Ecology. As part of the IN_ExFish project, I engaged in modeling the dependence of cod, herring, and sprat stock-recruitment on climatic factors using innovative statistical methods. The results of this research were presented at scientific conferences and ICES working groups. This research highlighted the most significant environmental factors for key Baltic Sea fish species and indicated that temperature (in August at a depth of 60 m) for sprat, surface salinity for central Baltic herring, and RV (reproductive volume - oxygen and salinity concentrations) for Baltic Sea cod were the main environmental factors influencing recruitment to the stock. These results were presented at the ICES Baltic Fisheries Assessment Working Group and tested as one of the bases for ICES scientific advice at that time. In cooperation with Professor Sture Hanssen from the University of Stockholm, this work was published in the journal Progress in Oceanography (Margoński et al., 2010).

In 2007, I began work at the leading scientific center - **DIFRES (Danish Institute for Fisheries Research, currently the Danish Technical University, Institute of Aquatic Resources - DTU-Aqua)**. My main task, in cooperation with **DMU (National Environmental Research Institute, currently Aarhus University**) and the **Baltic NEST Institute, Resilience Centre at Stockholm University,** was to refine and develop the Baltic Sea trophic model (Harvey et al., 2003) and apply it to the NEST system (www.nest.org), which integrates various types of models into an environmental decision support system. It was used to study the assumptions of the Baltic Sea Action Plan (HELCOM 2007). The trophic network model and its results were published in Ecological Modeling (Tomczak et al., 2012) and contributed to scientific achievements in section 2. This work quantifies trophic flows in the Baltic Proper and illustrates changes in the structure of the Baltic Sea, taking into account regime shift occurring in trophic networks and influencing factors.

During my employment at DTU-Aqua, I participated in several projects i.e:

- IN EX FISH - Incorporating extrinsic drivers into fisheries management FP6- 022710,
- KnowSeas (Knowledge-based Sustainable Management for Europe's Seas): An EU-funded project (FP7-ENV-2008-1-226675, 2009-2013),
- ECOSUPPORT (Advanced tool for scenarios of the Baltic ECOsystem to SUPPORT decision making in the Limfjord project), EU's Seventh Framework Programme (FP7, grant no. 217246),

I focused on an integrated assessment of the marine environment and its modeling, and an ecosystem approach to fisheries management. Continued research on recruitment processes, taking into account climate and ecosystem factors in the InExFish project, led to article "*Recruitment of lesser sandeel Ammodytes marinus in relation to density dependence and zooplankton composition"* describing dependence of sandeel recruitment from the North Sea, on composition and availability of zooplankton in early developmental stages (Van Deur et al., 2009). The results of this work were presented at international and sectoral conferences (e.g., 15

Danske Havforskemöte 2009). It is worth noting that the results of this work were implemented during these years to provide scientific advice to ICES regarding fishing yields.

Working at DTU-Aqua, I collaborated with Professor Josianne G Støttrup and Dr. Erik Hoffmann, synthesizing and developing available historical data on the Limfjord ecosystem. These research were conducted as part of a national project on resource management and fisheries of the Limfjord (a project mainly focused on scientific advice regarding the operation of the blue mussel *Mytilus edulis*). The results of these tests allowed for an integrated evaluation of ecosystem dynamics, showed drastic and non-linear changes in the structure of the ecosystem, and identified factors influencing the condition of this reservoir, and consequently, its impact on blue mussel exploitation and the economy of the population dependent on this activity. The most significant factor was eutrophication and anoxic episodes, which altered the ecosystem's condition. The result of work in the project was the publication (Tomczak et al., 2013) and the inclusion of results as a basis for resource management of blue mussels. In cooperation with Professor Rasmussen Nilssen and Dr. Martin My Lindgren from DTU-Aqua, I started work on a spatial-dynamic ecosystem model, which accurately simulates the distribiution of trophic groups and biomass changes in the ecosystem over 50 years. The results of the model were later used by ICES WGINOSE (Working Group on the Integrated Assessment of the Marine Ecosystem of the Northern) and published in the ICES Journal of Marine Science (Olsen et al., 2023).

In October 2009, I was employed at the **Baltic NEST Institute at Stockholm University**, headed by Professor Frederick Wulff. In the team of Professor Thorsen Blenkner, I continued the research conducted at DTU-Aqua. This area of research was further explored by me in the FORMAS project "Regime Changes in the Baltic Sea Ecosystem – Modelling Complex Adaptive Ecosystems and Implications for Management". The project aimed to explore the interactions between gradual and abrupt changes (regime shifts) in the Baltic Sea and to develop the governance structures necessary to implement an ecosystem management approach. This project allowed me to deeply understand the phenomenon of changes in the condition and structure of the Baltic Sea ecosystem in light of Odum's ecological theories, Ulanowicz, or Pimm (Odum and Barrett 1971; Baird and Ulanowicz 1993; Pimm 1984), defining linearity, resistance to disturbances (resistance), and adaptability (resilience). This was described in article number two of the scientific achievement. This work is pioneering in connecting food web modeling, multivariate statistical methodology (Integrated Trend Analysis - ITA), and indicators based on ENA. Another paper, titled "*Role of Trophic Models and Indicators in Current Marine Fisheries Management*" (Long et al., 2015), which I co-authored, was published as part of the mentioned project, showing that ENA-based indicators can be used to support environmental decision-making process and fisheries management, although at the time of writing, neither scientific advice nor the administrative and legal apparatus was ready for this. In perspective, our work showed that it is possible and is currently happening (Howell et al., 2021).

Another co-authorship paper shows the perspective in which to examine and evaluate ecosystems in an integrated way using tools such as *"Modeling social—ecological scenarios in marine systems"* (Österblom et al., 2013), which provided the theoretical basis for further model works.

Based on earlier cooperation and the KnowSeas project, together with Dr. Johanna

Heymans from the **Scottish Association of Marine Science**, we conducted research based on trophic models for the ecosystems of northern Bengal and the western shelf of Scotland (Heymans and Tomczak 2016; Alexander et al., 2014) published in the ICES Journal of Marine Science and Ecological Modeling. The work on the Northen Benguela ecosystem uses the methodology I proposed in the paper number two, combining food web modeling, ITA, and indicators based on ENA. These works allowed us to understand the mechanisms of changes in the state and structure of food webs and evaluate the state of ecosystems according to the aforementioned theories of Odum and Ulanowicz. It shows that ENA-based indicators can be used to support environmental decision-making. The work regarding the West Scottish shelf allowed us to evaluate the influence of environmental and anthropogenic factors on cod fish stocks, which has significant economic importance.

Another interesting approach to integrated ecosystem assessment, in which I participated and used the food web model of the Baltic Sea (Tomczak et al., 2012), was the BalticSTERN project. The acronym STERN in BalticSTERN stands for Ecological and Economic Evaluation and is inspired by the report "The Economics of Climate Change - The Stern Report" (2007), which examined the costs and benefits of mitigating the effects of climate change. The report *"FishSTERN: a first attempt at an ecological-economic evaluation of fishery management scenarios in the Baltic Sea region"* (Blenckner et al., 2011) provides cost-benefit analyses of fishing problems in the Baltic Sea, taking into account changes in the ecosystem, climate, and socio-economic factors. The FishSTERN report contributed to a better understanding of the benefits of improved fishing management in the Baltic, integrating ecology with economics.

My research was conducted in two pathways: i) focusing on ecological modelling of ecosystems/trophic networks as methods for integrated state assessment and integrated analyses of ecosystem data such as ITA, ii) and using the results for ecosystem management of fishing/fisheries and more broadly, for ecosystem management in the context of scientific advice from **ICES, HELCOM**, and **OSPAR**.

Modeling of trophic networks started at NMFRI and continued at DTU-Aqua and Stockholm University, leading to results, publications, and presentations exploiting the trophic model of the Baltic Sea Proper, which were used for scenarios based on climate shifts and anthropogenic pressure. My publications in journals (i.e Global Change Biology) and presentations at international conferences show potential changes in the Baltic Sea ecosystem due to changes in climate productivity and fishing pressure according to IPCC and HELCOM scenarios for the future (Niiranen et al., 2013; MacKenzie et al., 2012).

I continued studies of food webs at the **Baltic Sea Center at Stockholm University,** where within the strategic project **Baltic Eye**, financed in partnership with the BalticSea2020 foundation, I was responsible for research on higher trophic levels, fishing, and specific activities in the field of communicating scientific results at the intersection of science and politics. Participation in meetings, including the **Baltic Advisory Council**, allowed for practical knowledge of mechanisms in fisheries management from the perspective of stakeholders (industry, politicians, and non-governmental organizations).

At this time, as a co-aplicant and partner in research applications, I obtained a number of grants in which I was PI at Stockholm University and the main contractor:

- MAREFRAME Co-creating Ecosystem-based Fisheries Management Solutions, FP7 (EU 7th Framework Programme for Research and Technological Development), KBBE.2013.1.2-08: Innovative insights and tools to integrate the ecosystem-based approach into fisheries advice,
- BLUEWEBS Blue Growth Boundaries in Novel Baltic Food Webs. This project, funded under the BONUS program, BONUS call 2015-122,
- BALTICAPP Wellbeing from the Baltic Sea – applications combining natural science and economics BONUS call 2015-73. (https://blogs.helsinki.fi/balticapp/),
- FutureMares - Climate Change and Future Marine Ecosystem Services and Biodiversity, European Union's Horizon 2020 research and innovation programme under grant agreement No 869300,
- DEMO - DEMOnstration exercise for Integrated Ecosystem Assessment and Advice of Baltic Sea was funded by Granholm Stiftelse,
- BalticCAT – Baltic Cumulative Assessment Tool, by Swedish Environmental Protection Agency (https://www.su.se/english/research/research-projects/balticcat-cumulative-effect-assessment-tools-for-the-baltic-sea),

They allowed for the continuation of research and further development of the model, creation of a scientific team (employment of Dr. Barbara Bauer and Dr. Natalia Kaultska as postdocs), and cooperation with world-class scientists.

I participated and cooperated scientifically also in projects such as:

- XWEBS - Food web Knowledge Synthesis for the Baltic Sea. BONUS (Art. 185),
- BIOC3 - Biodiversity changes - causes, consequences, and management implications, BONUS (Art. 185),
- MUNIMAP - BSR INTERREG Project #C056 Marine Munition Remediation Roadmap,

Further work on models in the mentioned projects resulted in creating two new spatio-dynamic models of the Baltic Sea ecosystems – Central Baltic Sea ICES SD 25-29;32 and Kattegat. The purpose of the new model for the central ecosystem of the Baltic Sea was to analyse and understand the dynamics of trophic networks in its current state of sprat domination (2004-2015) and to identify factors conditioning the spatial arrangement of the main functional groups from primary producers to seals, including fishing fleets (divided by tool and size classes). The spatial resolution of the model is 0.25 × 0.25 degrees and is adapted from the analysis of fisheries data by ICES, STECF, and EC JRC (Fig.7). An accurate description and confirmation of the quality of the model (key-run) were done and published in the Report of the ICES Working Group on Multi-species Assessments Methods (WGSAM) (ICES 2017).

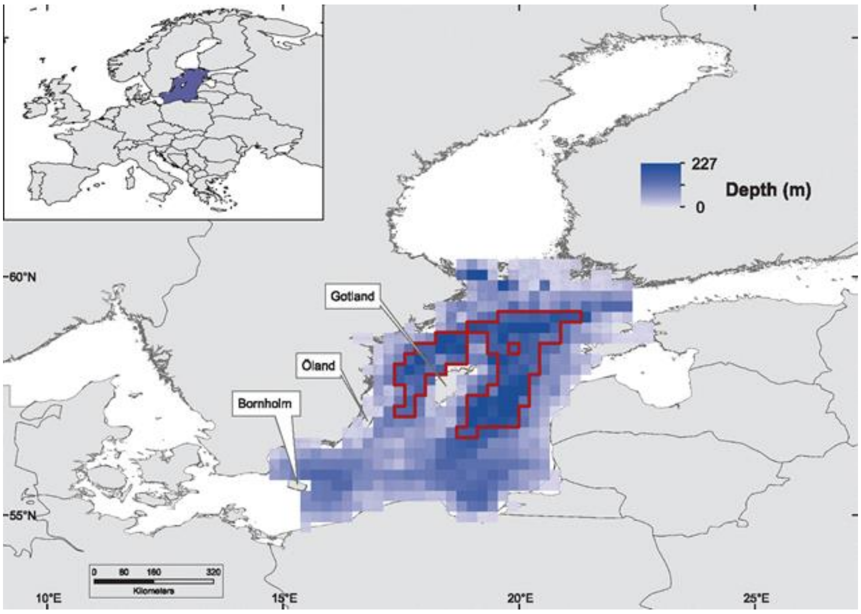

Figure 7. Model area. Shades show the average depth of the spatial cells used in the Ecopath with Ecosim model (resolution: 0.25 × 0.25 degrees). The red thick lines show the extent of hypoxia (bottom oxygen concentration <2 ml/l) according to the results of the coupled physical-biogeochemical model RCO-SCOBI, see Bauer et al. 2018.

The creation of a spatial and dynamic ecosystem model, including interdisciplinary data from ecology, economics, and fisheries sciences, is a way to integrated assessments, but also a method for understanding dependencies and actions of systems with socio-economic elements. Based on this tool, in the article *"Reducing eutrophication increases the spatial extent of communities supporting commercial fisheries: a model case study"* (Bauer et al., 2018), we showed that rising nutrient levels lead to the concentration of fish in smaller areas, potentially increasing the risk of overexploitation and environmental degradation and that effective policies to prevent excessive eutrophication, such as the Baltic Sea Action Plan, can increase the spatial availability of productive fisheries, thereby supporting more sustainable fishing. So far, actions related to the reduction of nitrogen and phosphorus loads into the marine environment have also been researched in cooperation with the **Joint Research Center in Ispra** in the context of the "Marine Strategy Framework Directive," assessing the impact of nutrient management on marine ecosystems across Europe. The effect of this work is *"Effects of Nutrient Management Scenarios on Marine Food Webs: A Pan-European Assessment in Support of the Marine Strategy Framework Directive"* (Piroddi et al., 2021). The results showed that although nutrient reductions generally led to declines in primary production and biomass of small pelagic fish, the overall impact on the structure and function of marine ecosystems was moderate. In particular, some regions, such as the Baltic Sea, showed little improvement in species diversity as a result of nutrient reductions, while others, such as the northeastern Adriatic and the Black Sea, showed declines. We emphasize the importance of regionalization and the further improvement of ecological models to better predict the outcomes of management interventions. In the context of the Marine Strategy Framework Directive, a tool based on the use of Bayesian network models was also created to support decisions regarding the management of the marine environment. In the BlueWeb project, such a tool was created to support decisions regarding the management of the marine environment in the Baltic Sea region – *"Integrating diverse model results into decision support for good environmental status and blue growth"* (Uusitalo et al., 2022). This network integrates results from various fields such as climatology, biogeochemistry, marine ecology, and economics to assess the likelihood of achieving both good environmental status (Good Environmental Status - GES) and sustainable development "blue growth." In the study, we took into account uncertainties associated with forecasts, which allows for the assessment of risks associated with different management scenarios.

In order to ensure that tests based on ecological models and scenarios were grounded in reality more broadly, we examined the conditions and pressures interacting with the Baltic Sea. In the work *"Shared socio-economic pathways extended for the Baltic Sea: exploring long-term environmental"* problems (Zandersen et al., 2019), We focused on the impact of different sectors such as agriculture, wastewater management, fisheries, shipping, and atmospheric deposition on the Baltic Sea ecosystem where we created global socio-economic development pathways (SSPs) adapted to regional conditions to assess possible future scenarios and conservation challenges of the marine environment. We named them respectively: SSP1: Sustainability, SSP2: Middle of the Road, SSP3: Regional Rivalry, SSP4: Inequality, SSP5: Fossil-fueled Development). Shared Socio-Ecological Pathways were (SSP) base for quantifiable research, which as co-author I presented at several conferences and published in articles: *"Food web and fisheries in the future Baltic Sea"* (Bauer et al., 2019), "*The necessity of a holistic approach when managing marine mammal–fisheries interactions: Environment and fisheries impact are stronger than seal predation"* (Costalago et al., 2019), *"Provision of aquatic ecosystem services as a consequence of societal changes: The case of the Baltic Sea"* (Hyytiäinen et al., 2021). The conclusions from these research projects show that climate change, nutrient loads, and fisheries management have a key impact on the future of marine ecosystems and fisheries in the Baltic Sea. Models and scenarios of future changes show that actions to reduce greenhouse gas emissions and sustainably manage fisheries can lead to higher biodiversity and an increase in fish stocks. In turn, scenarios that assume further increases in emissions and the lack of appropriate environmental policies lead to habitat degradation, a decline in biodiversity, and a lower economic value of fishing. It follows that management is essential for the long-term health of the Baltic ecosystem based on an integrated approach that takes into account both broad ecological and socio-economic aspects. Also, the methodological aspect of these works, which connects with various model approaches in one chain from climate changes to dynamics of higher trophic levels and fishing fleets (IPCC atmospheric models (Moss et al., 2010), to biogeochemical models e.g., RCO-SCOBI (Saraiva et al., 2019) to Baltic EwE (Bauer et al., 2019) creating a holistic tool (end-to-end) for simulating changes in the Baltic Sea ecosystem.

The development of methods and models also allows for showing how uncertainty and model precision affect scientific advice. Conclusions from the article *"Model uncertainty and simulated multispecies fisheries management advice in the Baltic Sea"* published with (Bauer et al., 2019b) show that despite model uncertainty, the differences between various models used should not significantly impede their use for strategic advice on fisheries management in the Baltic Sea. These models, together, can be useful for developing a way of advising that goes beyond traditional maximum sustainable yield (MSY) goals.

Connecting trophic network models with other model approaches or developing other methods, which I was developing within the international framework of cooperation, have borne fruit in works and presentations such as: "Food-web modeling in the maritime spatial planning challenge simulation platform: results from the Baltic Sea region" (Goncalves et al., 2021), *"Two-way coupling between Ecosim (EwE-F) and a biogeochemical model of the Baltic Sea"* (Akoğlu et al., 2019), where the trophic network model is connected with spatial analysis of marine protected areas or iteratively with the BALTSEM biogeochemical model (Gustafsson et al., 2012). Both of these jobs are pioneering work and will be further developed. A very interesting and innovative approach to integrated assessments of the Baltic Sea is the method used and published in Ecological Informatics together with Prof. Laura Uusitalo and Prof. Allan Tucker under the title *"Hidden variables in a Dynamic Bayesian Network identify ecosystem level change"* (Uusitalo et al., 2018). We show there that dynamic Bayesian networks with hidden variables show potential in analyzing complex ecological interactions and early detection of changes in ecosystems. We emphasize that despite the limited availability of data, such models can be useful for identifying patterns of change that may be crucial for the sustainable management of ecosystems.

I participated in an analysis focusing on models that can help overcome gaps between indicators and policy needs. We published the article *"Food web assessments in the Baltic Sea: Models bridging the gap between indicators and policy needs"* (Korpinen et al., 2022). This article reviews the current state of food web indicators and assesses the potential of models to fill gaps in these indicators. Together with co-authors, we showed that food web models have great potential in assessing the state of the marine environment where other indicators and methods fail. In particular, models such as EwE (Ecopath with Ecosim) and Atlantis can be useful in defining goals and thresholds for indicators of Good Environmental Status (GES) and filling data gaps. However, for these models to be effectively implemented, further work is required to synchronize them with spatial and temporal monitoring data.

Alien species in ecosystems are an increasingly observed phenomenon, in this case, in the Baltic Sea. Their appearance affects the structure and trophic flows in ecosystems and may significantly change the quantity of energy and mass reaching higher trophic levels, and consequently, may translate into changes in biodiversity or biomass, e.g., of fish, birds, or mammals, and even affect fishing. This issue I addressed in two works: *"How to determine the likely indirect food-web consequences of a newly introduced non-native species: a worked example"* (Pinnegar et al., 2014) in Ecological Modeling and Changes in the *"Baltic Sea coastal food web: A case study on the invasion of Round goby Neogobius melanostomus"* (Pallas, 1814) (Morkūnė et al., 2024) in Estuarine, Coastal and Shelf Science. In both of these works, using a trophic model for the given region, we showed how alien species such as *Fistularia commersonii* or *Neogobius mellanostomus* influence the trophic network.

Lately, an important element of my scientific activities has been bioaccumulation and biomagnification studies of pollution in the Baltic Sea and Kattegat food webs. In the renowned magazine Science of the Total Environment, together with scientists from the **Institute of Oceanology, Polish Academy of Sciences in Sopot**, we published simulation results of the transport of pollution - arsenic derivatives Clark I, released from dumped chemical weapons in the Baltic Sea - *"Effects of climate and anthropogenic pressures on chemical warfare agent transfer in the Baltic Sea food web"* (Czub et al., 2024) (Fig.8).

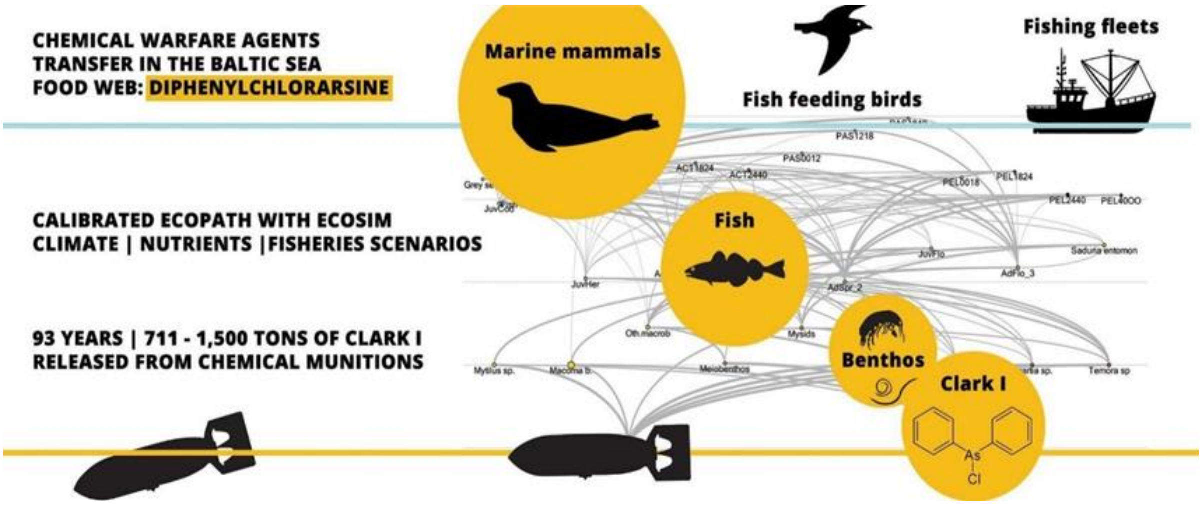

Figure 8. Concept of the impact of climate change and anthropogenic pressure on the transfer of chemical warfare agents in the Baltic Sea food web.

The results confirm that Clark I bioaccumulates mainly based on the detritus food web. Intensive fishing and climate change have the greatest impact on the accumulation rate and transfer of pollutants in the food web. The study suggests that removing chemical weapons from the seabed should be considered as part of the integrated management of the Baltic Sea to reduce potential risks to the ecosystem and seafood consumers. Similar studies I conducted with the Swedish Nuclear Agency simulating the bioaccumulation of coal C14 in the Kattegat ecosystem. The results of these simulations are in the process of publication.

The trophic network models I developed in cooperation with scientists from DTU-Aqua and Stockholm University consist of 29 trophic groups and eight fishing fleets, describing temporally and spatial changes in the ecosystem from 1982-2008 and is calibrated to time series of commercial fishing data, biomass from fishing research, and environmental monitoring (Fig.9).

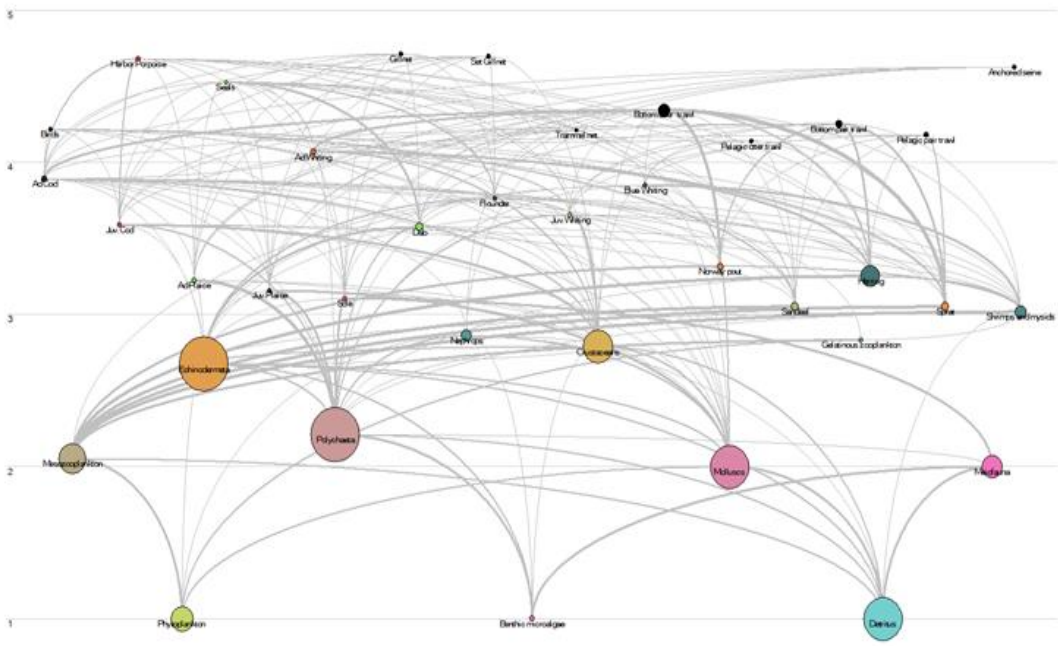

Figure 9. EwE food web diagram for Kattegat.

This model was used in the article *"Testing management scenarios for the North Sea ecosystem using qualitative and quantitative models published In ICES Journal of Marine Science"* (Olsen et al., 2023). In this work, we analyze different management scenarios for the North Sea ecosystem, using both qualitative and quantitative models. The main objective was to assess how different modeling approaches can support ecosystem-based management, taking into account the complexity of ecological interactions and the impact of human activities on marine ecosystems. The results suggest that qualitative models such as Fuzzy Cognitive Mapping (FCM) can be used effectively in conjunction with quantitative models ecosystems, such as Ecopath with Ecosim (EwE), to evaluate different management scenarios. Despite some differences in results, the two approaches can complement each other, which could lead to better strategies for managing the North Sea ecosystem. In particular, integrating both types of models can help identify and manage key ecosystem processes, supporting more sustainable management decisions.

From the beginning of my scientific activity to a considerable extent, I have been involved in sixteen ICES and HELCOM expert groups and recurrent workshops (**see point II.10. Information on scientific or artistic activity**):

Participation in working groups and workshops of ICES, and particularly directing them, allowed for the development of research towards ecosystem approaches to fisheries management and broad international cooperation. Working within ICES allowed for the publication of many reports, in which I am the main author (as group chair) and publications, based on group work and workshops.

My involvement with the **ICES/HELCOM Working Group on Integrated Assessment of the Baltic Sea (WGIAB)** has been a key platform for developing integrated ecosystem assessments and advancing methodological approaches. As the chair of WGIAB, I directed the group's focus toward coastal ecosystem assessments, which culminated in a co-authored publication, "*Temporal Development of Coastal Ecosystems in the Baltic Sea over the Past Two Decades"* in the ICES Journal of Marine Science (Olsson et al., 2015). In this article, we analyzed the temporal changes in 13 coastal ecosystems across the Baltic Sea, factoring in various biological components and the influence of key drivers such as climate, eutrophication, hydrology, and fishing pressure. Using multivariate analyses, we identified significant structural shifts, particularly linked to nutrient levels, which were emphasized as a major driver of change across most areas.

Building upon the work of WGIAB, I initiated, organized, and chaired the **ICES Workshop on Developing Integrated Advice for Baltic Sea Ecosystem-based Fisheries Management (**WKDEICE) workshops under the **DEMO** project. These workshops identified challenges and barriers to applying ecosystem approaches in ICES advice for the Baltic Sea and proposed a series of solutions. This work, together with previous WGIAB chairmen, resulted in the publication of the article *"A Demonstration of an Integrated Ecosystem Assessment and Advice for Baltic Sea Fish Stocks"* (Möllmann et al., 2014). The paper highlights the challenges in applying ecosystem-based approaches, such as incorporating environmental and economic factors into ICES scientific advice for the Baltic Sea. It also discusses approaches like "ecologically constrained Maximum Economic Yield" (eMEY) to improve management beyond the traditional focus on maximizing fishing yield (MSY). The eMEY approach, discussed in

"Ecological-Economic Fisheries Management Advice—Quantification of Potential Benefits for the Case of the Eastern Baltic COD Fishery" (Voss et al., 2017), considers both ecological and economic sustainability, balancing fish biomass maintenance and short- to medium-term economic costs.

My involvement in WGIAB also facilitated my participation in a number of multidisciplinary and methodological studies, such as: *"Biological Ensemble Modelling to Improve Marine Science and Ecosystem-Based Management Advice"* (Gårdmark et al., 2011), where we demonstrated the usefulness of multi-model approaches in ecological research, particularly in managing marine resources amid uncertainties from climate change and human activities. *"Integrated Ecological-Economic Fisheries Models—Evaluation, Review, and Challenges for Implementation"* (Nielsen et al., 2018), in which my trophic model was included. The review of 35 models outlined the challenges related to model complexity and usability, highlighting the need for better integration in decision-making processes.

Furthermore, I have contributed to discussions about indicators and decision-making processes during workshops such as WKCLIMAD (**Workshop on Pathways to Climate-Aware Advice**, Baudron et al., 2023), which laid the foundation for publications like Increasing the Uptake of Multispecies Models in Fisheries Management (Karp et al., 2023), where we recommended actions to implement multispecies and ecosystem models in scientific advice for fisheries.

Through my leadership and participation in ICES workshops and expert groups, I have contributed to several highly cited publications (Belgrano et al., 2021 Eero et al., 2015; Horbowy and Tomczak, 2017; Lassalle et al., 2013; Otto et al., 2020; Tam et al., 2017) and reports (see point 4 II. Information on scientific or artistic activity). These works are part of the advice process for bodies such as the European Commission (e.g., Ecosystem Overviews or TAC Fishing Opportunities). The ongoing integration of ecosystem approaches within ICES requires activities that bring together ecological, fisheries, and social knowledge, a focus that was emphasized during the **ICES Workshop on the operational use of Food Web indicators and information** (WKFoodWeb) workshop. There, we proposed innovative structures and methods for inclusive, integrated ecosystem assessments in ICES scientific advice, with these efforts still ongoing.

Throughout my scientific career, I have served as a reviewer for a number of scientific journals, including: *ICES Journal of Marine Science, PloS ONE, Ecological Modelling, Marine Ecosystem Progress Series, Progress in Oceanography, Fish and Fisheries, Canadian Journal of Fisheries Science, Ambio, Shelf, Oceanological and Hydrobiological Studies, Estuarine, Coastal and Shelf Science, and Frontiers in Marine Science*. Additionally, I have acted as an expert reviewer for the National Science Center's OPUS and PRELUDIUM programs. I have also chaired sessions at international conferences, such as PICES 2014 in Korea and the ICES Annual Science Conference.

6. Review of Teaching Achievements, Public Engagement and Popularization of Science

Although my teaching opportunities have been limited due to my employment in research institutes that do not engage in formal teaching, I have taught classes whenever possible. For instance, I lectured and conducted tutorials for four years at Stockholm University, focusing on the **Baltic Sea Ecology and Management course.**

In my work related to scientific advisory for fisheries and the marine environment, I frequently participated in meetings and discussions with stakeholders, such as fishing organizations and environmental NGOs. As the chair of ICES Working Groups and Workshops, I actively organized and coordinated these events.

In addition to my academic and scientific endeavors, I have also engaged in public outreach and science communication. In 2017, I published an article on the **POLITYKA** portal titled "*One Hundred Years of Fishing in the Baltic Sea – From the Point of View of a Fish Fry Customer"*, and I have worked with the Pro-Science organization to improve the visibility of marine science in Polish national media.

7. Other Career Information

With extensive experience in fish resource assessments, population dynamics, and stock management methods across Europe and other parts of the world, I have also worked as an independent auditor in **Marine Stewardship Council (MSC)** certification processes. This experience provides me with a comprehensive perspective on the status of fisheries, fishing challenges, and business operations, which I have applied to certification processes.

8. Summary

My scientific contributions include **44** original scientific publications in English (**42** of which were published after earning my PhD), indexed in the Philadelphia Institute of Scientific Information. Most of these works are the result of international collaboration. I am the **first author of 7 publications (8 as a corresponding author)**. The total impact factor of my **44** publications is **157,** according to the Journal Citation Reports, and **173.6** when considering 5-year impact factors. The total points awarded for my publications, based on the Ministry of Science and Higher Education's list as of January 5, 2024, is **4890**. My work has been cited **1456** times (**1365** without self-citations) in the Web of Knowledge database, **1542** times (**1444** without self-citations) in Scopus, and **2306** times in Google Scholar (as of September 9, 2024). My Hirsch index is **23** (Scopus) and **27** (Google Scholar). I have presented my research at numerous international scientific conferences, managed six scientific projects, and participated as a contractor in another **12**. I have **chaired five** and remain a member of **sexteen** ICES and HELCOM expert groups and the JRC.

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