# Biological Integrity of Key Species and Habitats Summary

Last Updated: December 23, 2022

## Overview

Thank you to everyone who joined us early on October 6, 2022, to explore the *Biological Integrity of Key Species and Habitats*. The discussion built on the prior workshop to consider biological integrity and:

> *How do we evaluate water quality with the tools that we have relative to the needs of key species, food webs, and habitats?*

Dr. Jacob Carstensen of the Baltic Nest Institute, Denmark, shared what can be learned from managing oxygen problems in the Baltic Sea, including:

- Modern hypoxia in the Baltic Sea is driven by increased nutrient inputs and is more intense and widespread than observed in the geological past. Without nutrient reductions, the extent of hypoxia in the Baltic Sea would likely have been twice as large
- Additionally, seasonal hypoxia will become more frequent and hypoxia will expand in a warmer climate without nutrient reductions. The $4^{o}$ C increase expected due to climate change is anticipated to double the hypoxic area in the Baltic Sea. Warming also intensifies the multiple impacts on key species
- Periods of enhanced saltwater inflows modulate hypoxia in the Baltic Sea giving short-term relief, but enhancing stratification and hypoxia in the long term
- Hypoxia alters the biogeochemical cycling of nutrients (which is a redox-dependent process), enhancing the recycling of N and P that further sustain eutrophication in the system
- Non-motile benthic species are naturally more tolerant to low oxygen concentrations, but also more susceptible to extended periods of hypoxia, which alters the composition of benthic fauna

Then Dr. Tim Essington of the University of Washington highlighted research on species and food web responses to low dissolved oxygen in the Salish Sea.

- It is important to consider the joint effects of temperature and oxygen and key species, for example using pCrit or the metabolic index can help quantify this combined impact on species. Tim is currently working on a species distribution approach to predict oxygen sensitivities where lab experiments are lacking
- Mobile species appear to exhibit distributional shifts from the monitored areas with seasonal hypoxia to those without low dissolved oxygen. Sessile species lack this adaptive capacity, so are not present in areas with seasonal exposure to low oxygen (< 2 mg/l)
- Tim's study revealed unexpected food web effects to low dissolved oxygen, which speaks to the limitation of applying lab-based pCrit studies *in situ* and the role of physiological acclimation
- This is a classic risk management issue. How far are we from thresholds? What is the probability of exceeding biological thresholds? For how long?
    - Fortunately, oxygen operates in a threshold-like manner, so we have the potential to quantify these thresholds and quantify our confidence in a) those thresholds and b) where we are relative to those thresholds

Building on the robust discussion, Dr. Tessa Francis shared a proposal to:

- Describe potential risk to Puget Sound species (starting primarily with fish) of low oxygen levels in marine waters, using existing modeling output and literature sources as the first phase of analysis

## Materials

Here are direct links to the materials for the *Sediment Exchange* workshop:

- Slides
- Full video
- Highlight video
- Chat

A recap for each workshop in The Science of Puget Sound Water Quality workshop series is available on our website. The recaps include a summary, highlight video, full recording, chat, and slides. The videos from the workshop series are also available directly via this YouTube playlist.

## Highlights

**Note:** for the full presentation slides and resulting discussion please see the links above. Below are some highlights from the presentations, followed by questions and key discussion points.

### What can be Learned from Managing Oxygen Problems in the Baltic Sea?

Dr. Jacob Carstensen, Aarhus University, Denmark

Many coastal systems globally have perennial, seasonal, or episodic hypoxia due to their hydromorphology and excessive nutrient input. Some of the well-studied areas include the Gulf of Mexico, Chesapeake Bay in the USA, Changjiang (Yangtze) and Zhujiang (Pearl) river estuaries in China, the Black Sea, and the Baltic Sea in Eurasia. Throughout his career, Jacob has been involved in the study and management of eutrophication in the Baltic Sea and provided a review of this system and challenges as a case study.

#### The Baltic Sea is naturally prone to hypoxia due to its restricted exchange with the oceans

*The papers referenced in the slides are summarized below in the Resources section.*

- Hypoxia manifests in distinct ways in different Baltic systems
  - **Perennial:** The Baltic Sea has always experienced hypoxia to some degree but the tenfold expansion during the 20th century was caused by enhanced anthropogenic inputs of nutrients from land and the atmosphere
  - **Seasonal:** The entrance to the Baltic Sea (Danish Straits) is a permanently stratified area with estuarine characteristics. It experiences seasonal hypoxia associated with the advective transport in the bottom waters bringing in low nutrient and Dissolved Oxygen (DO) waters coinciding with high oxygen demand from organic matter respiration
  - **Episodic:** Coastal areas
    - Wind can import hypoxia from deeper waters, which occasionally leads to fish kills because the fish get trapped against the coastline without being able to move to higher oxygen waters
    - Low resilience to low DO events due to thin bottom layer and high oxygen demand
      - Thin layer of bottom water (1-2 meters) with high sediment respiration, can deplete the oxygen in just a few days
- In iterating on the models in the Baltic, it was discovered that particle shuttling of terrestrial origin organic matter from shallow to deep waters was a missing and important contribution to oxygen demand in these deep basins
- Temperature enhances respiration and by extension increases oxygen demand

- Modern hypoxia in the Baltic Sea is driven by increased nutrient inputs and is more intense and widespread than observed in the geological past
- Saltwater inflows modulate hypoxia in the Baltic Sea, which gives short-term relief but enhances stratification and hypoxia in the long term. Saltwater intrusion also happens with variable frequency and intensity
- Without considering nutrient reductions, hindcast predictions of the extent of hypoxia were estimated to be twice as large
- Seasonal hypoxia will become more frequent and hypoxia will expand in the warmer climate expected from climate change, independent of changes to nutrient loading
- There are multiple synergistic and negative effects of climate change
    - With an anticipated $4^{o}$ C increase because of climate change, an estimated doubling in the hypoxic area is due to reduced solubility and increasing oxygen demand by enhancing respiration
- Different policies apply to different parts of the Baltic Sea
    - The Baltic Sea Action Plan (2021) shifted from reduction targets to a net nutrient input ceiling for each country to avoid the complexity of agreeing on a baseline condition, given the perverse incentive to define a more favorable baseline
    - When considering policy and management actions, it is important to remember that the total residence time of the Baltic is about 30 years, so it will take decades, maybe centuries for the system to respond to nutrient reductions
- Consequences of hypoxia on benthic fauna and biogeochemical cycles
    - Hypoxia alters the biogeochemical cycling of nutrients (redox-dependent processes), enhancing recycling of N and P that sustain eutrophication
    - Non-motile benthic species are naturally more tolerant to low oxygen concentrations, but also more susceptible to extended periods of hypoxia, which alters the composition of benthic fauna by loosing these perennial engineering species first that cannot avoid these hypoxic events
    - Deoxygenation increase energy flow to microorganisms
    - Fish are further affected through habitat losses (benthic and pelagic), making them more vulnerable to predation (including fishing)
        - For example, lower cod reproduction in the central Baltic Sea because of changes in salinity and expanded hypoxia
    - Warming enhances the effects of hypoxia and therefore nutrient reductions will be even more critical in the future

## Species and Food Web Responses to Low Dissolved Oxygen in the Salish Sea

### Dr. Tim Essington, University of Washington

- Organisms have behavioral and physiological coping mechanisms to temperature and oxygen that vary across taxa that we can understand in a risk-based framework
    - Indirect effects stemming from coping mechanisms are likely but hard to predict (e.g., changes in predator/prey overlap)
- If an organism is exposed to low, dissolved oxygen we would expect:
    - Behavioral adaptation potential (e.g., distributional shifts as species move elsewhere)
    - Physiological acclimation potential (e.g., change the gills surface area, circulation rate, etc.)
    - Threshold responses (e.g., resort to core metabolic demands while foregoing a lot of activity or reproduction on a short-term basis)

Field evidence

1. Responses to seasonal hypoxia: acute vs. chronic effects (Hood Canal) | Essington & Paulsen (2010)
   - Mobile species appeared to exhibit distributional shifts from the monitored areas with seasonal hypoxia to those without low dissolved oxygen
   - Sessile species lack this adaptive capacity, so are not present in areas with repeated (i.e. seasonal) exposure to low oxygen (< 2 mg/l)
   - This pattern was also present nearshore; monitored from 30 m – 120 m
   - Geoducks are non-motile and can live 130 years. Therefore, they are very rare in the South Sound even in locations where habitat conditions are otherwise ideal. This is because one extremely low dissolved oxygen event can lead to mortality and they cannot escape
2. Unexpected food web effects to low dissolved oxygen | Moriarty et al. (2020)
   - Researched trophic connection between a pelagic fish (i.e., hake and herring) and their main zooplankton food source (i.e., krill) for 2 years. Based on the extensive field *in situ* and lab studies, the authors expected the following but found these research findings:

| Expected | Research Findings |
|---|---|
| Lower predator-prey overlap | No |
| Reduced feeding rate on zooplankton | A little |
| Increased zooplankton density | No, the opposite |
| Reduced predator density | No, the opposite |

   - Herring were exposed to oxygen concentrations that are lethal in lab studies and expressed Hypoxia Inducible Factor, which means they were modifying their tissue demand, but they were still thriving
   - None of their expectations were borne out. This speaks to the limitation of applying lab-based pCrit studies *in situ*, and the role of physiological acclimation
3. Estimating species tolerances and forecasting | Essington et al. (2022)
   - As the environment gets warmer, metabolism increases, and species need more oxygen, so it is really hard to think about temperature and oxygen requirements separately because they act jointly
   - Species distribution modeling of sablefish on the coast reveals pO2 thresholds
   - The metabolic index is useful, but gets incredibly confused by the oxygen minimum zone (e.g., at 750 meters); it seems like sablefish do not like being in really deep waters. When the data was truncated to 800 meters up, the metabolic index outperformed using pO2 alone.
   - Future and ongoing research focuses on whether we can predict oxygen sensitivities via the metabolic index when lab experiments are lacking
     - A hierarchical modeling approach across taxonomic groups did not work
     - Working on a species distribution approach is proposed

Classic risk-management issue

- Vulnerability analysis
  - **Exposure** overlap between the area of “bad” oxygen level (or metabolic index) and species (by life stage)
  - **Consequence** at the species level in terms of key demographic rates like mortality, development, and growth

- Not all changes in oxygen are harmful. It depends on baseline levels and is highly species-specific
- Fortunately, oxygen operates in a threshold-like manner, so we have the potential to quantify these thresholds and quantify our confidence in a) those thresholds and b) where we are relative to those thresholds

## Biological Impacts of Low Oxygen Levels on Puget Sound Species

Dr. Tessa Francis, University of Washington Puget Sound Institute

- Looking for feedback and collaboration on a project to describe the potential risk to Puget Sound species (mostly fish) of low oxygen levels in marine waters, using existing modeling output and literature sources
- Risk assessment framework
    - Risk = Exposure + Sensitivity
    - Can consider vulnerability, by modifying exposure and sensitivity based on the adaptive capacity of the species or habitat
    - Potentially use the framework from Jameal Samhouri's paper, *Linking Land- and sea-based activities to risk in coastal ecosystems.*
        - Start by developing qualitative criteria to describe exposure and the severity of impact, taking into consideration both the individual and population's sensitivity. This categorical approach helps to incorporate some of the uncertainty given data gaps
        - Then use quantitative data to overlap the spatial distribution of the pressures and species
    - A risk assessment framework can help consider nutrient impacts more broadly beyond just low dissolved oxygen, including indirect effects like nutrients' impact on eelgrass, which salmon rely on heavily
- Tools
    - Atlantis Ecosystem Model: Describe exposure in terms of species distribution and abundance
    - Salish Sea Model: Describe oxygen patterns temporally and spatially, including by depth and in embayments where low dissolved oxygen is more often a challenge
    - Literature review: Basic metabolic needs for specific species like Pcrit and metabolic index

## Discussion

- Tim agreed that it would be valuable to explore the ecological consequences of DO, temperature, and pH in embayments where we are predicting low dissolved oxygen. For example, the key species and depths vary in comparison to Hood Canal
- In the face of climate change:
    - Tim suggested taking a risk-based approach to identify and maintain adaptive capacity (e.g., protect herring that are genetically predisposed to tolerate low oxygen). Follow adaptive pathways that do not lead to profound shifts that cross a threshold. Consider cumulative impacts, like warming waters and low dissolved oxygen
    - Jacob advised considering negative feedback in nutrient cycling to avoid crossing critical thresholds where you suddenly have the collapse of an ecosystem

- Tim responded that reductions in dissolved oxygen are highly contextual. It depends on where you are starting, what organisms are present in an area, and how the change relates to critical thresholds for those species
- Jacob reflected that there is been limited research into the potential impact of sea level rise and increased storm surges on hypoxia. The impact would likely be very site dependent and largely influenced by the fate of the organic matter and how much of it will actually end up in deep areas where low dissolved oxygen is a challenge
- Jacob clarified that the deep-water formation in the Arctic Ocean and the formation of sea ice produce a brine of water that is the engine of the thermal cline circulation of the oceans. Wind primarily drives the exchange between the North Sea and the Baltic Sea, but it is unclear how winds are going to change with climate change
- Tim shared that while salmon like cold water and relatively high dissolved oxygen, salmon are typically not exposed to low dissolved oxygen in the Salish Sea, so the potential impacts are more indirect
- Jacob replied that all the major wastewater treatment plants in the Baltic Sea have been upgraded to tertiary treatment. Efforts to regulate agriculture haven't been as effective though
    - Denmark has encouraged the use of cover crops, regulated the amount of livestock per hectare, and until a few years ago limited crop growth to 90% of the optimal yield in terms of nutrients. Looser regulations on fertilizer application may be why conditions have been getting worse recently. 80% of nutrients in Denmark come from manure because there is a lot of pig farming. Overall, Denmark is still aiming to reduce nutrients by 20-30% more to achieve their ecological goals

# Resources

## Additionally shared


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## Engaging in the workshop series

Our region is navigating complex and challenging decisions on how best to manage nitrogen, dissolved oxygen, and the potential impacts on the key habitats and species of the Salish Sea. The University of Washington Puget Sound Institute is supporting a series of scientific workshops to help address technical uncertainties, advance modeling, and refine monitoring to improve our understanding of nutrients and broader water quality in the Salish Sea. Learn more about upcoming workshops or review the recordings and presentation materials from previous workshops.

### Continue the discussion

- If you have not already, please join the listserv to receive periodic updates about Puget Sound Institute’s program to foster regional water quality science, including information about upcoming workshops
- Join us for the follow-up workshops to dig into these technical uncertainties
- Reach out to Stefano Mazzilli (mazzilli@uw.edu) and Marielle Larson (marlars@uw.edu) if you:
    - Are interested in contributing or helping with one of the upcoming workshops or modeling and monitoring analyses
    - Want to recommend another expert, program, or study for us to connect with to help advance the research
    - Have additional ideas or questions