Biological Integrity of Key Species and Habitats
Biological Integrity of Key Species and Habitats

### Agenda

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:00 AM</td>
<td>Intro</td>
</tr>
<tr>
<td>8:10 AM</td>
<td>What can be learned from managing oxygen problems in the Baltic Sea?</td>
</tr>
<tr>
<td>8:55 AM</td>
<td>Species and food web responses to low dissolved oxygen in the Salish Sea</td>
</tr>
<tr>
<td>9:25 AM</td>
<td>Break</td>
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<tr>
<td>9:30 AM</td>
<td>Q&amp;A</td>
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<tr>
<td>9:45 AM</td>
<td>Biological impacts of low oxygen levels on Puget Sound species</td>
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<tr>
<td>10:00 AM</td>
<td>Discussion</td>
</tr>
<tr>
<td>10:25 AM</td>
<td>Wrap-up</td>
</tr>
</tbody>
</table>

### Navigating the Workshop

Welcome! While we wait, please:
- Update your name to include your pronouns and organization
- Message Marielle with any access needs
- Introduce yourself in the chat. We’ve muted participants and turned off your videos to minimize technical issues, so we encourage you to use the chat to say hello instead

Questions or Comments?
- Add them to the chat
- Raise your hand and we’ll unmute you

The slides, recording, and summary will be available on Puget Sound Institute’s website
University of Washington Puget Sound Institute’s Role

Puget Sound Partnerships’ Marine Water Quality Implementation Strategy

Technical Uncertainties

Help address technical uncertainties and advance modeling tools to assist decision-making.

- Facilitate scientific workshops and regional collaboration
- Convene Model Evaluation Group
- Lead complementary model runs
- Expand access to models, outputs, tools, and scientific knowledge

Research, Modeling, and Monitoring to Reduce Uncertainties

Nutrient Science Community in Puget Sound

Refine Research Actions

Targeted Technical Uncertainties

- Improve confidence in modeling of the Salish Sea and share findings
- Kickoff (7/26)
- Tools to Evaluate Water Quality (9/29)
- Biological integrity of key habitats and species (10/6)

Upcoming Workshops

- Sediment exchange (10/17)
- Phytoplankton and primary production (11/2)
- Change in interannual variability of rivers and ocean impact (week of 11/14)
- Improve watershed modeling to evaluate source reduction strategies to adaptively manage strategies (week of 12/12)

Improved Confidence in Actions
Driving Scientific Question

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

Build common knowledge around the science to inform a range of recovery efforts.
WHAT CAN BE LEARNED FROM MANAGING OXYGEN PROBLEMS IN THE BALTIC SEA?

Jacob Carstensen, Aarhus University
If you can’t breathe, nothing else matters
Hypoxia is a growing global problem

Breitburg et al., 2018, Science
Well-studied areas: Gulf of Mexico

- Receives excess nutrients from the Mississippi River watershed, stimulating production and creates stratified conditions along the coastal margin
- On average 14000 km² affected by hypoxia (<2 mg/L)
- June-August

Pitcher et al. (2021) Prog.Oceanogr.
Well-studied areas: Chesapeake Bay

› The largest estuary in the US
› Receives freshwater from several large rivers, although Susquehanna is the dominant (>80%)
› Seasonal hypoxia of about 10 km$^3$ (volume!)
Well-studied areas: Changjiang and Zhujiang estuaries

- **Changjiang Estuary:**
  - Seasonal hypoxia—typically August for (around 10-15,000 km²) at depths of 20-50 m

- **Zhujiang Estuary:**
  - Seasonal hypoxia (~1000 km²) in wet season (lower part) at depths of 10-30 m and dry season (upper part)

Pitcher et al. (2021) Prog.Oceanogr.
Well-studied areas: Black Sea

› Natural hypoxia due to the restricted ventilation of bottom waters
› Waters are sulfidic from about 100 m and below
› The Black Sea was a lake until ca. 8000 years ago
› The northwestern shelf has also experienced seasonal hypoxia

Pitcher et al. (2021)
Prog.Oceanogr.
Outline of talk

› Different types of how hypoxia manifests itself in different Baltic systems and the mechanisms behind
  › Central open basin (perennial)
  › Entrance area/Danish Straits (seasonal)
  › Coastal areas (episodic)

› Future trajectories of hypoxia in response to management and climate change
  › Current policy frameworks
  › The multiple synergistic and negative effects of warming

› Consequences of hypoxia
  › Fauna
  › Biogeochemical cycles
Below the surface – it’s a different world

Photo: Nanna Rask
A century expansion of perennial hypoxia in the Baltic Sea

Updated from Carstensen et al. (2014) PNAS
Seasonal hypoxia in the western Baltic Sea

- **Area (km²)**
  - 2-4 mg L\(^{-1}\)
  - <2 mg L\(^{-1}\)

- Kørslet Østvand (0-2 mg/l)

**12. - 22. September 2022**
- Littsvind (0-2 mg/l)
- Hol (4-6 mg/l)

**Medio September**
- Area (km²)
  - 2002
  - 1989-2009
  - 1997

**Min Max Ave**
Widespread coastal hypoxia

Source: Conley et al. (2011) ES&T
Baltic Sea hypoxia takes many shapes and sizes

- Perennial hypoxia
- Seasonal hypoxia
- Episodic hypoxia

WHY IS HYPOXIA SUCH A BIG PROBLEM IN THE BALTIC SEA?
MECHANISMS GOVERNING THE OXYGEN SUPPLY
The Baltic Sea is naturally prone to hypoxia.
The ventilation of the bottom waters is driven by events of saltwater intrusions of variable density and mixing across the halocline.
The ventilation of the bottom waters is driven by events of saltwater intrusions of variable density and mixing across the halocline. Dark blue = denser water (Major inflows).

Saltwater intrusions happen at variable frequency and intensity

Recent expansion of perennial hypoxia in the Baltic Sea

Updated from Carstensen et al. (2014) PNAS
Recent expansion of perennial hypoxia in the Baltic Sea

Updated from Carstensen et al. (2014) PNAS
Oxygen supply decreases with temperature.

Typical range for inflows:

- Sali=15
- Sali=17
- Sali=19
- Sali=21
- Sali=23
- Sali=25

Temperature Jan-Dec (°C)

\[ \Delta T \approx 1.5 \, ^\circ C \]

\[ -\Delta O_2 \approx 0.3-0.4 \, \text{mg L}^{-1} \]
MECHANISMS GOVERNING THE OXYGEN CONSUMPTION
Nutrient enrichment of the Baltic Sea

Updated from Gustafsson et al. (2012) Ambio
Source: Carstensen et al. (2014) PNAS
Particle shuttling contributes to oxygen demand in the deep basins.

Source: Nielsson et al. (2021) MarChem
Temperature enhances respiration

Updated from Carstensen et al. (2014) PNAS
SEASONAL HYPOXIA
IN THE WESTERN BALTIC SEA
Imbalance between oxygen supply and consumption on a seasonal scale

Source: Hansen et al. (2016) DCE report
Imbalance between oxygen supply and consumption on a seasonal scale

Source: Hansen et al. (2016) DCE report
EPISODIC HYPOXIA
Imported hypoxia from deeper waters
Low resilience from thin bottom layer and high oxygen demand

Sediment respiration

Little wind mixing

Ca. 1940
Hypoxia comes and goes
Hypoxia comes and goes
Hypoxia comes and goes

Week 25 - 2008

Områder ramt af
Iltsvind
Kraftigt iltsvind
Målestationer
Hypoxia comes and goes
Hypoxia comes and goes

Week 28 - 2008

Hansholm
Thisted
Nykøbing
Mors
Løgstør
Nørre Sundby
Aalborg
Lemvig
Struer
Skive
Viborg

Områder ramt af
Iltsvind
Kræftig iltsvind
Målestationer
Hypoxia comes and goes
Hypoxia comes and goes

Week 30-2008
Hypoxia comes and goes
Hypoxia comes and goes
Hypoxia comes and goes
Hypoxia comes and goes
Hypoxia comes and goes
Hypoxia comes and goes
Hypoxia comes and goes
Hypoxia comes and goes

Week 38 - 2008

Hansholm
Thisted
Nykøbing
Mors
Løgstør
Nørre Sundby
Aalborg
Lemvig
Struer
Skive
Viborg

Områder ramt af
Iltsvind
Kraftigt iltsvind
Målestationer
HYPOXIA IN THE FUTURE
DIFFERENT POLICIES APPLY TO DIFFERENT PARTS OF THE BALTIC SEA

Coastal zone

National implementation by EU member states

Focus on ecological status, secondary supporting elements (incl. oxygen)

Offshore waters

HELCOM BSAP

EU Marine Strategy Framework Directive
BALTIC SEA ACTION PLAN (2021)

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**Eutrophication goal**

- 2.4. By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and productivity, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality.

- 6.3. By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally.

- 6.5. By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate.

- 14.1. By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution.

Further information on connection to other treaties related to eutrophication can be found on page 26.

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**SDG targets addressed**

- Cross-reference with other segments

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**Pressures addressed**

**Activities addressed**

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**Table 2a. Nutrient input ceiling (NIC) of nitrogen for the HELCOM countries, non-HELCOM countries in the Baltic Sea catchment area, other countries with airborne input, Baltic Sea shipping and North Sea shipping (in tonnes/year).**

<table>
<thead>
<tr>
<th>Country</th>
<th>Bohuslan Bay</th>
<th>Bohuslan Sea</th>
<th>Baltic Proper</th>
<th>Gulf of Finland</th>
<th>Gulf of Riga</th>
<th>Danish Straits</th>
<th>Kattegat</th>
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<tr>
<td>Germany</td>
<td>947</td>
<td>3,920</td>
<td>34,677</td>
<td>1,645</td>
<td>1,747</td>
<td>23,947</td>
<td>4,601</td>
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<tr>
<td>Denmark</td>
<td>230</td>
<td>1,146</td>
<td>9,625</td>
<td>421</td>
<td>462</td>
<td>26,067</td>
<td>28,538</td>
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<tr>
<td>Estonia</td>
<td>113</td>
<td>404</td>
<td>1,478</td>
<td>11,334</td>
<td>13,099</td>
<td>72</td>
<td>24</td>
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<tr>
<td>Finland</td>
<td>35,087</td>
<td>28,700</td>
<td>1,827</td>
<td>20,457</td>
<td>295</td>
<td>76</td>
<td>89</td>
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<tr>
<td>Lithuania</td>
<td>108</td>
<td>495</td>
<td>25,878</td>
<td>305</td>
<td>8,820</td>
<td>65</td>
<td>80</td>
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<td>Latvia</td>
<td>73</td>
<td>330</td>
<td>6,457</td>
<td>246</td>
<td>43,074</td>
<td>51</td>
<td>54</td>
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<tr>
<td>Poland</td>
<td>668</td>
<td>3,125</td>
<td>151,997</td>
<td>1,407</td>
<td>1,596</td>
<td>1,480</td>
<td>1,449</td>
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<tr>
<td>Russia</td>
<td>839</td>
<td>1,993</td>
<td>10,517</td>
<td>61,503</td>
<td>5,296</td>
<td>238</td>
<td>245</td>
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<tr>
<td>Sweden</td>
<td>17,718</td>
<td>32,633</td>
<td>30,690</td>
<td>626</td>
<td>525</td>
<td>6,056</td>
<td>32,799</td>
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<tr>
<td>Other countries</td>
<td>1,375</td>
<td>5,908</td>
<td>26,947</td>
<td>2,886</td>
<td>2,188</td>
<td>4,933</td>
<td>4,502</td>
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<tr>
<td>Belarus</td>
<td>-</td>
<td>-</td>
<td>13,456</td>
<td>-</td>
<td>12,820</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Czech Republic</td>
<td>-</td>
<td>-</td>
<td>3,551</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ukraine</td>
<td>-</td>
<td>-</td>
<td>1,653</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Baltic Sea shipping</td>
<td>284</td>
<td>1,141</td>
<td>5,180</td>
<td>675</td>
<td>346</td>
<td>651</td>
<td>701</td>
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<tr>
<td>North Sea shipping</td>
<td>131</td>
<td>475</td>
<td>2,427</td>
<td>196</td>
<td>150</td>
<td>739</td>
<td>846</td>
</tr>
</tbody>
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https://helcom.fi/baltic-sea-action-plan/
Outlook for the Baltic Sea

No quick recovery from hypoxia

Outlook for the Danish Straits

A 4 °C temperature will double the hypoxic area

Source: Conley et al. (2009) Hydrobiol
Effect of management

What if nutrient inputs had not been reduced?

Source: Andersen & Carstensen (2011) Politiken
SUMMARY: DRIVERS OF HYPOXIA

› The Baltic Sea is naturally prone to hypoxia due to its restricted exchange with the oceans
› Modern hypoxia in the Baltic Sea is driven by increased nutrient input and is more intense and widespread than observed in the geological past
› Saltwater inflows modulate hypoxia in the Baltic Sea giving a short-term relief, but enhances stratification and hypoxia in the long term
› Seasonal hypoxia will become more frequent and hypoxia will expand in a warmer climate without nutrient reductions
WHAT ARE THE CONSEQUENCES OF HYPOXIA?
Oxygen affects everything.
Effect on benthic fauna and their bioengineering

Pearson & Rosenberg (1978)

Meadows & Tait (1989)
Deoxygenation increases energy flow to microbes

Wright 2012
The entire benthic community changes

Biological Traits important for carbon and nutrient turnover and retention

- large
- long-lived
- slow-growing
- perennials
- deep-dwelling bioturbators
- high energy and CNP content per individual

- small
- short-lived
- annuals
- fast-growing
- surface-modifiers
- low energy and CNP content per individual

Carstensen et al. (2020)
AMBIO
Assessing the loss of benthic fauna – catastrophic year

Estimated 300,000 tons of benthic biomass was lost by comparing before and after situation.

This corresponds roughly to the weight of the Danish population.

Hansen et al. (2003)
Assessing the loss of benthic fauna – Baltic Sea

Estimated 3 mio. tons of benthic biomass is missing due to hypoxia

Karlson et al. (2002)
... and occasionally fish get caught in hypoxic waters
Cod reproductive volume in the Baltic Sea

Hatching conditions:
S > 11
O₂ > 2.8 mg/L
Hypoxia reduces sediment denitrification and creates N feedback

Source: Jeremy Testa
Hypoxia enhances P release from sediments

Phosphorus is bound to Fe(OH)₃ under oxic conditions and released by Fe-reduction under anoxic conditions.
The "vicious" circle

Hypoxia

P-release

N-fixation

Source: Vahtera et al. (2007) Ambio
SUMMARY: CONSEQUENCES OF HYPOXIA

› 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 by loosing perennial engineering species first

› Fish are affected through habitat losses (benthic and pelagic), making them more vulnerable to predation (including fishing)

› Warming enhances the effects of hypoxia and therefore nutrient reductions will be even more critical in the future
TAKE HOME MESSAGES FOR PUGET SOUND

› The terminal inlets are naturally prone to low oxygen conditions due to the relatively shallow thickness of the bottom layer and reduced ventilation (seasonally) – similar to the mechanisms some areas of the Danish Straits

› The supply of oxygen is primarily governed by the physics, but the risk of oxygen demand outpacing oxygen supply increases with eutrophication (enhanced supply of OM to the bottom)

› Efforts to improve oxygen conditions can be counteracted by climate change, e.g. from oxygen-poorer waters entering PS, but this does not mean that these efforts have been in vain
Species and Food Web Responses to low dissolved oxygen in the Salish Sea

Tim Essington
University of Washington
School of Aquatic and Fishery Sciences
Collaborators

• Sean Anderson
• Lewis Barnett
• Anne Beaudreau
• Halle Berger
• Halley Froehlich
• John Horne
• Emma Hodgson
• Shannon Hennessey
• Phil Levin
• Lingbo Li

• Julie Keister
• P. Sean McDonald
• Pamela Moriarty
• Jan Newton
• Caroline Paulsen
• Sandy Parker-Stetter
• Samantha Sleidlecki
• Mei Sato
• Eric Ward
Main take home points

• Organisms have behavioral and physiological coping mechanisms that vary across taxa
• Indirect effects stemming from coping mechanisms are likely but hard to predict
• We have core biological knowledge to understand the types of organismal responses in a risk-based framework
Gas physiology 101

Environment

Pressure gradient

Surface Area
Gas solubility
Circulation rate

Tissue Demand

Organism
Coping with low dissolved oxygen?

- Environment
  - Pressure gradient
  - Surface Area
  - Gas solubility
  - Circulation rate
- Organism
  - Tissue Demand
Coping with low dissolved oxygen?

Environment

Pressure gradient

Surface Area
Gas solubility
Circulation rate

Tissue Demand

Organism
Coping with low dissolved oxygen?

- Surface Area
- Gas solubility
- Circulation rate

Tissue Demand

Pressure gradient

Environment

Organism
Responses to seasonal hypoxia: acute vs. chronic effects
Intensity of Seasonal Hypoxia: South Hood Canal

Data from HCDOP Citizens Monitoring Program
BACI – Type Design

1 Impact site “Hoodsport”
3 Reference sites
   Account for basin or other effects related to bathymetric profiles
General Results

Oxygen high everywhere

Oxygen low at Hoodsport
Main Findings

Absent all of the Time

Absent during low dissolved oxygen events
What about nearshore habitats?

Fig. 3. Proportions of total relative density of taxa (at the level of Order) from the north and south sites at 10, 20, and 30 m depths.
Gas physiology 101

- Environment
  - Pressure gradient
    - Surface Area
      - Gas solubility
      - Circulation rate
    - Tissue Demand
  - Organism
An Aside on Geoducks

Geoducks are rare at all depths in southern region

Cannot be explained by substrate availability
Unexpected Food Web Effects to low Dissolved Oxygen
Consequences of Distributional Shifts?

Moderate Tolerance

High tolerance
Consequences of Distributional Shifts?

Moderate oxygen depletion = refuge
Consequences of Distributional Shifts?

Severe oxygen depletion

Dissolved oxygen
Sampling Design
Seasonal dynamics of $O_2$ by Site
Expectations

• Lower predator-prey overlap
• Reduced feeding rate on zooplankton
• Increased zooplankton density
• Reduced predator density
Reality

- Lower predator-prey overlap NOPE
- Reduced feeding rate on zooplankton A LITTLE
- Increased zooplankton density NOPE, the OPPOSITE
- Reduced predator density NOPE, THE OPPOSITE
Herring were exposed to $[O_2]$ that were lethal in lab studies, and expressed Hypoxia Inducible Factor
Estimating species tolerances and forecasting
Moving forward: predicting effects in a changing climate

• Metabolic index: ratio of metabolic supply vs. demand
  • Incorporates joint effects of temperature and oxygen
• Estimating these in the lab
Sablefish Distributions in the California Current
Can we identify oxygen thresholds?
Does metabolic index improve predictions?
Yes! Threshold effects are estimated!
No! Metabolic Index gets confused ....
Ongoing Activities

• Can we predict oxygen sensitivities via metabolic index when lab experiments are lacking?
  • Hierarchical modeling approach
    • Nope
  • Species Distribution Approach
    • Working on it
Moving forward in Puget Sound: A focus on Risk
Vulnerability Analysis

• Exposure – overlap between area of “bad” oxygen level (or metabolic index) and species (by life stage)

• Consequence at species level
  • Mortality
  • Development
  • Growth
Vulnerability Assessment: Dungeness Crab in the California Current

Pay attention to Dungeness Crab
Focus on Thresholds and Risk
Thank you to funders

- National Science Foundation
- Washington Sea Grant
- Hood Canal Dissolved Oxygen Program
- NOAA Fisheries
Questions for the Region

- How do we build on the current focus on dissolved oxygen and nutrients to include multiple stressors?
- How do we balance a species, key indicator, and ecosystem approach across different efforts?
- How do we incorporate ideas of adaptation and resilience in the face of climate change?
Questions?
Biological impacts of low oxygen levels on Puget Sound species
Biological impacts of low oxygen levels to Puget Sound species

Objective:

- Describe potential risk to Puget Sound species (mostly fish) of low oxygen levels in marine waters, using existing modeling output and literature sources.
A risk assessment framework

Risk = Exposure + Sensitivity
A risk assessment framework

Risk = Exposure + Sensitivity

Species distribution
Oxygen patterns

Physiological effects
Exposure - I

- Species distribution
  Atlantis Ecosystem Model

---

Courtesy of Hem Nalini Morzaria-Luna
Exposure - II

- Oxygen patterns
  Salish Sea Model

Ahmed et al. (2019)
2006 maximum dissolved oxygen depletions below the water quality standard due to all anthropogenic sources
Sensitivity

- Literature review
Sensitivity

- Behavior
- Lethal vs sublethal effects
- Life stage
Exposure

Qualitative criteria

• Spatial overlap
• Temporal overlap
• Exploitation
• Etc.

Quantitative data

Pressure
Species
Exposure

Other criteria?
Sensitivity

Qualitative criteria

• Severity of impact
  • Population
  • Individual
• Current status
• Intrinsic recovery factors
  • Replenishment rate
  • Connectivity

Severity of impact (pop.)

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
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<tbody>
<tr>
<td>&lt;10% loss</td>
<td>10-50% loss</td>
<td>&gt;50% loss</td>
<td></td>
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</tbody>
</table>

Other criteria?
Linking land- and sea-based activities to risk in coastal ecosystems

Jameal F. Samhouri*, Phillip S. Levin

Conservation Biology Division, Northeast Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration,
3750 New Jersey Ave., SE, Silver Spring, MD 20910, USA.
• Use an understanding of risk to prioritize action

- Take a multi-stressor approach
Thank you!

- tessa@uw.edu
Wrap up

• We’ll share the presentation materials, recording, and a summary of the discussion

• Subscribe for updates at http://eepurl.com/h5nxsr

• Share any people, programs, or studies we should connect with

• Continue the discussion
  • Email Stefano Mazzilli (mazzilli@uw.edu) and Marielle Larson (marlars@uw.edu) to connect directly
  • Join the upcoming workshops to dig in further

Upcoming Workshops

Sediment exchange (10/17)

Phytoplankton and primary production (11/2)

Change in interannual variability of rivers and ocean impact (week of 11/14)

Improve watershed modeling to evaluate source reduction strategies to adaptively manage strategies (week of 12/12)
Appendix
Combines $pO_2$ with temperature-dependent biological responses to oxygen in order to define “aerobically available habitat”

Presentation by Martha Sutula at The Science of Puget Sound Water Quality workshop on July 26, 2022
Modeling Capacity and Interpretation

Streamlined analyses to existing parameters (e.g., dissolved oxygen, temperature, net primary production rates, etc.):

- Across time, depth, and location, including:
  - Annually, seasonally, or daily
  - By basin and embayment
- From a range of perspectives (e.g., absolute values, non-compliance days, % volume days, etc.)
- Under scenarios with different loading inputs at each wastewater treatment plant and river

![Graphs showing nitrate + ammonia and dissolved oxygen concentrations over time.](image-url)
Supporting Line of Evidence: DO Variability

Annually, seasonally or daily:
- Minimum dissolved oxygen
- Dissolved oxygen variability
- Rate of dissolved oxygen change
- Number of hypoxia exposures
- Hypoxia exposure duration (hours)
- Hypoxia return time (hours)

* e.g., Low et al. (2021)