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Draft Methodology for Assessing Ocean Acidification and Hypoxia Impacts in Oregon

Technical Support Document

For development of the Water Quality Status Report and List of Impaired Waters

DEQ

This document was prepared by
Oregon Department of Environmental Quality
Water Quality Division
700 NE Multnomah Street, Portland Oregon, 97232

Contact: Kaegan Scully-Engelmeyer
Phone: 503-575-5224
Or
Contact: Lesley Merrick
Phone: 971-323-7228

Visit DEQ's Assessment web page

State of Oregon
DEQ Department of Environmental Quality

Executive Summary

The Federal Clean Water Act requires Oregon to report on the quality of its surface waters every two years. Oregon surface waters are assessed to determine if they contain parameters at levels that exceed protective water quality standards. The result of these analyses and conclusions is called the "Integrated Report" because it combines the requirements of Clean Water Act section 305(b) to develop a status report and the section 303(d) requirement to develop a list of impaired waters.

State of Oregon
Department of Environmental Quality

U.S. Environmental Protection Agency regulations require states to describe the methodology, data and information used to identify and list segments of water bodies that are considered "water quality limited" -- or impaired -- and require cleanup plans known as Total Maximum Daily Loads. This Assessment Methodology contains the "decision rules" DEQ will use to compare data and information to existing water quality standards for the development of Oregon's 2024 Integrated Report.

For the three past assessment cycles, DEQ has received data and information on the impacts of changing ocean conditions on fish and aquatics life in response to ocean acidification and hypoxia. These submissions included requests for DEQ to define parameters and data requirements needed to conduct a scientifically defensible assessment. Acknowledging the scientific rigor needed to differentiate environmental stressor response from natural background conditions in Oregon's dynamic marine ecosystem and the lack of existing methodologies to use as reference, DEQ has been working with a scientific technical workgroup. The focus of the workgroup was to assist in the interpretation of the existing state of science in this field into a policy framework. The results of these efforts and the rationale for decisions made are presented in this technical support document. The accompanying draft methodologies for assessing the impacts of ocean acidification and low marine dissolved oxygen in Oregon's territorial waters for use in the 2024 Integrated report can be found here.

For many of the policy related decisions, DEQ relied on precedent established in the existing draft Assessment Methodology for Oregon's 2024 which is a culmination of over 20 years of water quality assessment. In some cases, data requirements or approaches used to define background conditions may be more stringent than for other parameters. This is reflective of balancing the state of the science on this topic and the level of certainty DEQ needs to classify waters as impaired. As new indicators and methods for evaluating impacts become more widely used, DEQ may revise these methodologies.

Acknowledgements

DEQ would like to acknowledge the valuable contributions of DEQ’s 2022 Ocean Acidification and Hypoxia Technical Workgroup to the development of the draft methodologies outlined in this document. Recommendations and assistance offered during the workgroup process provided critical scientific and technical elements in the development of procedures for assessing impacts of ocean acidification and hypoxia in Oregon’s territorial waters. A workgroup overview document that summarizes the workgroup activities, meetings, and engagement process can be found here.

Glossary of Terms

Anthropogenic - When used to describe “sources” or “warming,” means that which results from human activity.[1]

Anthropogenic carbon (C_{anth}) – Global oceanic uptake of carbon dioxide emitted through human activity.

Aragonite Saturation State ($\Omega_{aragonite}$; Ω_{ar}) – A measure of the thermodynamic tendency for the mineral calcium carbonate to form or to dissolve. The symbol Ω (omega) is often used as shorthand for "calcium carbonate saturation state". By convention, Ω is usually expressed with respect to aragonite, one of the two most abundant forms of calcium carbonate in the ocean. An aragonite saturation state (Ω_{ar}) greater than 1.0 indicates supersaturation, while values less than 1.0 indicate undersaturation with instability favoring dissolution. Levels below 1.0 are considered corrosive.[2]

Assessment Methodology – A document that describes the "decision rules" used to compare data and information to existing water quality standards to identify and list water quality limited segments requiring TMDLs.

Biological Criteria (or biocriteria) – Numeric values or narrative descriptions that are established to protect the biological condition of the aquatic life inhabiting waters that have a designated aquatic life use.

Calcifiers - Organisms that synthesize calcium carbonate (from calcium and bicarbonates or carbonates) into shells and other skeletal structures. Carbonate ions are an essential element for marine calcifiers, and their decreased availability in marine ecosystems is a concern.[3]

Clean Water Act (CWA) - The Clean Water Act is an act passed by the U.S. Congress to control water pollution. It was formerly referred to as the Federal Pollution Control Act (Public Law 92-500), as amended (33 U.S.C. 1251 et seq.).

Corrosivity - Conditions in which waters are undersaturated with respect to calcite or aragonite.

Depth Horizon – Depth from the surface to a given threshold separating two layers of water in a stratified water body.

Designated Beneficial Use - The purpose or benefit to be derived from a water body as designated by the Water Resources Department or the Water Resources Commission.[1]

Dissolved Oxygen (DO) - The amount of oxygen dissolved in water.

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[1] Oregon Secretary of State Administrative Rules

[2] http://www.necan.org/lexicon/5

[3] https://edis.ifas.ufl.edu/publication/FA220

Ecological Integrity - The summation of chemical, physical, and biological integrity capable of supporting and maintaining a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of the natural habitat of the region.[1]

Estuary/Estuarian - All mixed fresh and oceanic waters in estuaries or bays from the point of oceanic water intrusion inland to a line connecting the outermost points of the headlands or protective jetties.[1]

Hypoxia – In marine and freshwater environments, hypoxia refers to low or depleted oxygen in a water body.[4]

Marine Waters (Ocean Waters) – All oceanic, offshore waters outside of estuaries or bays and within the territorial limits of the State of Oregon.[1]

Narrative Criteria - Criteria expressed in concise statements, generally in a "free from" format. General statements of attainable or attained conditions of ecological integrity and water quality for a given use designation.

Natural Background Conditions – conditions or circumstances affecting the physical, chemical, or biological integrity of a water of the state that are not influenced by past or present anthropogenic activities. Disturbances from wildfire, floods, earthquakes, volcanic or geothermal activity, wind, insect infestation and diseased vegetation are considered natural conditions.[1]

Numeric Criteria - Criteria expressed as a concentration of chemicals in or properties of water that should protect a designated use.

Ocean Acidification – Increased concentrations of carbon dioxide in sea water causing a measurable increase in acidity (i.e., a reduction in ocean pH).[5]

Pollutant – Any substance introduced into the environment that may adversely affect the usefulness of a resource or the health of humans, animals, or ecosystems. For most environmental media, this term is commonly understood to refer to substances introduced by human activities.[6]

Pollution - Such contamination or other alteration of the physical, chemical, or biological properties of any waters of the state, including change in temperature, taste, color, turbidity, silt, or odor of the waters, or such discharge of any liquid, gaseous, solid, radioactive, or other substance into any water of the state that either by itself or in connection with any other substance present can reasonably be expected to create a public nuisance or render such waters harmful, detrimental, or injurious to public health, safety, or welfare; to domestic,

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[1] https://secure.sos.state.or.us/oard/displayDivisionRules.action?selectedDivision=370

[4] https://oceanservice.noaa.gov/hazards/hypoxia/#:~:text=In%20ocean%20and%20freshwater%20environments,oxygen%20in%20a%20water%20body.

[5] https://www.epa.gov/ocean-acidification#:~:text=Changing%20Ocean%20Chemistry,affecting%20us%20and%20our%20environment.

[6] https://www.epa.gov/report-environment/roe-glossary#p

commercial, industrial, agricultural, recreational, or other legitimate beneficial uses; or to livestock, wildlife, fish, other aquatic life or the habitat thereof.[1]

Reference Conditions - The characteristics of the segments of a waterbody that are least impaired by human activities. For some water bodies, characterization of these conditions may require an evaluation of past conditions.

Resident Biological Community - Aquatic life expected to exist in a particular habitat when water quality standards for a specific ecoregion, basin or water body are met. This must be established by accepted biomonitoring techniques.[1]

Oregon Territorial Sea - as provided in ORS 196.405(5), means the waters and seabed extending three nautical/geographical miles seaward from the coastline in conformance with federal law.[1]

Upwelling – a process in which deep, cold water rises toward the surface of the ocean.[7]

Wastes - sewage, industrial wastes, and all other liquid, gaseous, solid, radioactive, or other substances that may cause or tend to cause pollution of any water of the state.[1]

Water Column - The depth of water in any waterbody measured from the surface to the bottom sediments.

Water Quality - The chemical, biological, and physical integrity of a body of water.

Water Quality Assessment - An evaluation of the condition of a waterbody using existing and readily available data, such as biological surveys, chemical-specific analyses of pollutants in waterbodies, and toxicity tests, to determine if water quality standards are being attained.

Water Quality Criteria - A required element of State water quality standards, expressed as constituent concentrations, levels, or narrative statements, representing a quality of water that protects the designated use. For waters with multiple use designations, the criteria must protect the most sensitive designated use.

Water Quality Standards (WQS) - Provisions of State or Federal law which consist of designated use or uses, criteria necessary to protect those uses, as well as an antidegradation policy.

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[7] https://oceanexplorer.noaa.gov/facts/upwelling.html

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Introduction

Oregon's coastal waters are part of the California Current Ecosystem (CCE), one of the most productive regions of the world ocean. However, the upwelling that fuels this productivity also results in dramatic variability in dissolved oxygen (DO) and pH, which naturally constrains available habitat for marine calcifiers and aerobic animals and has been implicated in major species distribution and abundance shifts on monthly to decadal time scales.

Climate change and local anthropogenic pollution sources are driving ocean acidification and hypoxia (OAH) and warming water temperatures beyond the envelope of natural variability (Chavez et al., 2017). This is causing the CCE to undergo some of the most rapid declines of pH and DO in the world's oceans, raising the potential for major ecosystem disruptions (Chavez et al., 2017; Laruelle et al., 2018; Osborne et al., 2020). Dramatic responses to OAH have been observed in species that form critical links in the food web, including detrimental effects on a variety of ecologically and economically important calcifiers along the U.S. West Coast, such as oysters (Barton et al., 2015, 2012), foraminifera (Osborne et al., 2020, 2016), pteropods (Bednaršek et al., 2014a, 2017b, 2018), echinoderms (Sato et al., 2018, 2017), and crab (Bednaršek et al., 2020).

Under the Clean Water Act, states, territories, and authorized tribes report to the Environmental Protection Agency about the status of designated beneficial uses of their waters and the extent to which water quality impacts are affecting those uses. West Coast states have yet to routinely assess the water quality impacts of OAH on marine designated uses, in part because established OAH water criteria and assessment methodologies to conduct such assessments do not yet exist. Leading up to the 2024 assessment cycle, Oregon DEQ proposed to fill this current methodology gap by convening a workgroup of leading scientific experts to synthesize evidence that could support policy decisions on OAH impairment within Oregon's territorial waters. The purpose of this document is to outline the rationale, process, and approach that DEQ is proposing to use to assess OAH impacts to marine designated uses.

Background

Upwelling and OAH

Oregon's marine territorial waters extend three nautical miles seaward and encompass a range of intertidal and subtidal habitats commonly referred to as the inner continental shelf or nearshore ecoregion.[8,9] Oregon's inner shelf ecosystem is strongly influenced by seasonal upwelling, a process that brings cold, nutrient rich, carbon dioxide (CO_2)-rich, saline, oxygen depleted waters from deeper waters offshore up onto the continental shelf.[10,11] Upwelling in the eastern Pacific coast is driven by seasonal prevailing winds from the north, which, due to the earth's rotation, there is a net transport of surface water offshore, replaced by deeper waters rising toward the surface onshore (Huyer, 1983). The addition of these upwelled waters onto the shelf initiates a cascade of biochemical responses, increasing photic-zone productivity and respiration resulting in a wide range of observed pH and DO concentrations, with higher values generally seen in the winter months, and lower values during the summer upwelling season (Grantham et al., 2004; Hales et al., 2006; Peterson et al., 2013). Additional nutrients in upwelled waters affect eutrophication processes which also contribute to DO and pH changes in these environments.

Recently, there has been the emergence of severely hypoxic (low oxygen, <0.5 ml/l DO) and even anoxic (zero DO) waters observed on the Oregon shelf during summer upwelling, raising concern for impacts to resident biological communities and habitats (Chan et al., 2008). Though Oregon's nearshore environments are characterized by significant inter and intra seasonal variability in DO conditions (Adams et al., 2016, 2013; Peterson et al., 2013; Siedlecki et al., 2015), the frequency, severity, and duration of low DO events appear to be increasing (Chan et al., 2008; Grantham et al., 2004; Pierce et al., 2012).

There are several sources that contribute to the relatively acidified conditions in inner shelf waters of Oregon's territorial sea. First, upwelled deep waters already rich in CO_2 due to respiration of organic matter at depth are upwelled onto the continental shelf, where they combine with the anthropogenic carbon signal from long term accumulation of atmospheric CO_2 (Feely et al., 2016, 2008). The signature of these combined sources results in an onshore gradient of high CO_2 and low pH conditions compared with offshore waters. OA stress in nearshore and estuarine environments is further influenced by freshwater inputs, which affect the corrosivity of the waters through changes in salinity (Harris et al., 2013), and local watershed sources of nutrients which can drive nearshore eutrophication processes, further acidifying coastal waters and depleting DO. These localized processes have an amplifying effect on the global OA signal, making nearshore upwelling-influenced waters some of the most vulnerable to early impacts of changing ocean and climatic conditions (Feely et al., 2008; Harris et al., 2013).

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[8] MarineEcoregionStrategy.pdf (state.or.us)
[9] https://secure.sos.state.or.us/oard/displayDivisionRules.action?selectedDivision=370
[10] https://www.epa.gov/report-environment/roe-glossary#p
[11] https://oceanexplorer.noaa.gov/facts/upwelling.html

Distinguishing changing ocean conditions from natural background

Advances in monitoring and modeling technologies offer new ways for researchers and scientists to understand and characterize the dynamic and variable conditions found in Oregon's coastal ecosystems. It has become clear in recent years that nearshore ocean conditions are changing across a range of spatial and temporal scales (Arroyo et al., 2022; Harris et al., 2013), and it is of critical importance that scientists and managers work together to understand and anticipate the impacts these changes may have on coastal ecosystems and species (Boehm et al., 2015; Chan et al., 2019, 2017). A strategic approach is needed to assess impacts in these systems in such a way that detrimental changes in marine ecological integrity caused by human activities are differentiated from those due to natural seasonal, annual, or decadal cycles (Boehm et al., 2015).

Significant progress has been made in recent years to synthesize and define biologically relevant carbonate saturation thresholds related to impacts of OA on organismal fitness (Bednaršek et al., 2021a, 2021b, 2019; Waldbusser et al., 2015). Similarly, work has advanced to clarify the thresholds of impacts of suboxic and hypoxia stress on CCE aerobic organisms (Chan et al., 2019; Deutsch et al., 2015; Vaquer-Sunyer and Duarte, 2008).

These thresholds can be applied to water column observations of pH and DO to assess excursions from water quality standards and criteria, but the rate at which the Oregon shelf waters would naturally fall below these thresholds must be considered. This is a critical step in differentiating between naturally occurring biological impacts from those associated with anthropogenic activities. Recently, researchers have advanced methodologies to remove the contribution of the global anthropogenic pCO_2 from changing seawater pH, providing a pre-industrial calculation of natural background variability in carbonate system parameters (pH, pCO_2, and saturation state of calcium and aragonite carbonate mineral solubility ($\Omega_{\text{aragonite(ar)}}$ & Ω_{calcite})). While no such methodology exists for DO, researchers in Oregon use decadal time series observations to calculate the declining trend in DO that is emerging above natural background (Pierce et al., 2012).

Clean Water Act framework

The stated goal of the Clean Water Act is to "restore and maintain the physical, chemical, and biological integrity of the Nation's waters." Under the CWA framework, states, territories, and authorized tribes develop water quality standards, monitor waters, assess data against water quality standards (numeric and narrative criteria), develop restoration plans and implement those plans (**Figure 1**).

Water quality standards are developed to assign designated beneficial uses and include numeric or narrative criteria to protect those uses. Adoption or modification of WQS is an extensive process that includes both state and federal requirements. WQS, including parameter specific and narrative criteria, must be approved by the U.S. EPA, and are codified by Oregon State Administrative Rules.

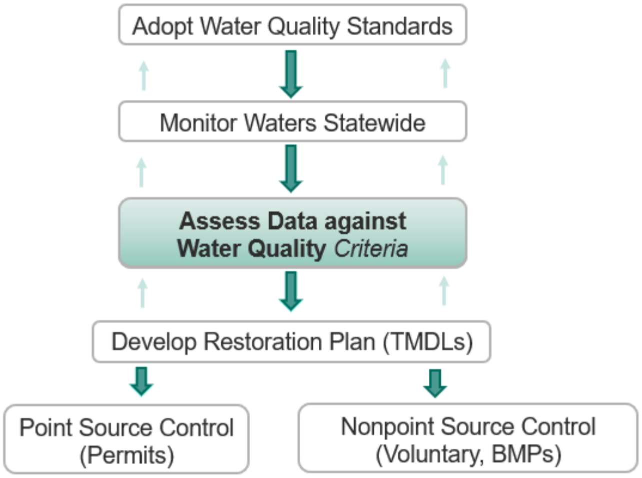

Figure 1. Clean Water Act Framework diagram.

Water quality monitoring data and information provides the foundation for assessing the attainment of WQS and the identification of impaired waters. Oregon uses the Assessment Methodology to document how these decisions will be made for reporting purposes. Specifically, the methodology includes scientifically and technically defensible procedures to assign data quality and quantity requirements, describe how WQS will be interpreted to assess against numeric and narrative criteria (including identifying indicators) and set allowable exceedance frequencies. The result of these assessments is called the "Integrated Report" because it combines the requirements of CWA section 305(b) to report on the status of all state waters and the requirement of section 303(d) to develop a list of impaired waters which must be reported to the U.S. EPA every two years.

In the IR reporting, an assessment category ranking is given to all assessed pollutants or measured parameters in a particular waterbody segment (**Table 1**). DEQ uses data to evaluate the most common beneficial uses, such as aquatic life, drinking water or recreation. A waterbody is listed as impaired (Category 5) if data or information indicate that at least one beneficial use is not being fully supported. This impairment triggers the need for a Total Maximum Daily Load or other plan to address the issue. The impaired waterbody may meet water quality criteria during some years, but data indicate that the beneficial use is not always supported.

Table 1. Assessment categories used in Oregon's Integrated Report.

Category	Description
Category 1	All designated uses are supported. (Oregon does not have sufficient data to assess this category.)
Category 2	Available data and information indicate that assessed designated uses are supported and the water quality standard is attained.
Category 3	Insufficient data to determine whether a designated use is supported.

	Oregon further sub-classifies waters if warranted as: **3B: insufficient data; potential concern:** Insufficient to determine use support but some data indicate non-attainment of a criterion. **3C: insufficient data; non-reference condition:** Biocriteria scores differ from reference condition, but are not classified as impaired.[12] **3D: insufficient data; not technologically feasible to assess:** Insufficient data to determine use support because numeric criteria are less than quantitation limits.
Category 4	Data indicate that at least one designated use is not supported but a TMDL is not needed. This includes:
	4A: TMDLs that will result in attainment of water quality standards and beneficial use support have been approved.
	4B: Other pollution control requirements are expected to address pollutants and will result in attainment of water quality standards.
	4C: Impairment caused by pollution, not by a pollutant (e.g., flow or lack of flow are not considered pollutants).
Category 5	Data indicate a designated use is not supported or a water quality standard is not attained and a TMDL is needed. This category constitutes the Section 303(d) list that EPA will approve or disapprove under the Clean Water Act.

DEQ has chosen to interpret existing WQS for the assessment of changing ocean conditions for the Integrated Report. This requires the development of an assessment methodology which will define how numeric criteria will be applied or how narrative criteria will be evaluated using numeric assessment benchmarks. Understanding that the science of evaluating the biological impacts of OAH is evolving, DEQ intends to periodically revisit and revise the OAH assessment methodologies to accommodate new indicators and evolving scientific understanding of OAH condition assessment.

Applicable marine water quality standards

DEQ has three existing WQS that are applicable to assessing the impacts of OAH (**Table 2**). The water quality standard for pH was developed to protect the most sensitive beneficial use, in this case fish and aquatic life. The first numeric criteria for pH in Oregon were promulgated from the U.S. EPA 1986 quality criteria for water (“Gold Book”).[13] While the numeric pH criteria could be used to assess OA, DEQ now recognizes that biological effects can occur at levels above the lower range, and thus these criteria may not be adequate to fully protect aquatic life uses (Weisberg et al., 2016). DEQ intends to include the marine pH range as a potential topic in the next triennial WQS review. Until the marine pH numeric criteria is reevaluated, DEQ will use

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[12] Oregon uses subcategory Category 3C: Insufficient data; Potential Concern to identify waters whose biocriteria O/E scores deviate from reference conditions but are not classified as impaired.

[13] https://www.epa.gov/sites/default/files/2018-10/documents/quality-criteria-water-1986.pdf

discretion when assessing marine pH data for attainment (Category 2). Therefore, the focus of this methodology development process is on interpreting existing narrative biocriteria and marine DO criteria (**Table 2**), which do not currently have defined assessment methodologies.

Table 2. Existing WQS applicable to OA and Hypoxia.

WQS Pollutant/Parameter	Beneficial Use Protected	Criteria		Existing Methodology
		Numeric	Narrative	
pH (Marine waters)	Fish & Aquatic Life	7-8.5		Y
Biocriteria (Marine waters)	Fish & Aquatic Life		"Waters of the State must be of sufficient quality to support aquatic species without detrimental changes in the resident biological communities."	N
Dissolved Oxygen (Marine waters)	Fish & Aquatic Life		"No wastes may be discharged and no activities may be conducted… that will cause violation to the following standards: (6) For ocean waters, no measurable reduction in dissolved oxygen concentration may be allowed"	N

One key component to interpreting these two narrative criteria, is understanding natural background conditions. For biocriteria this is typically done using a comparison of test or sample data to samples from areas in reference condition.[14,15] DEQ's dissolved oxygen WQS includes a preamble that applies to all waters and narrative criteria for marine waters. This criteria is interpreted to state there must be no measurable reduction in DO attributed to wastes discharged or anthropogenic activities (Table 2). The dissolved oxygen standard is not unique in its focus on limiting measurable change. Other Oregon water quality standards limit changes from natural conditions for parameters with natural variability such as temperature, turbidity, and several of the narrative criteria, and the temperature criterion for ocean and bay waters.[16]

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[14] https://www.oregon.gov/deq/wq/Documents/IR22AssessMethod.pdf - Biocriteria chapter
[15] https://www.epa.gov/sites/default/files/2015-10/documents/keyterms-concepts-factsheet.pdf
[16] https://secure.sos.state.or.us/oard/displayDivisionRules.action?selectedDivision=1458

When this DO criterion was adopted in 1996, changing ocean conditions due to climate change were not a factor of consideration.

Past assessment of Oregon's marine waters

In the 2018/2020 Integrated Report, DEQ classified Oregon territorial marine waters as an area of potential concern (Category 3B- insufficient data; potential concern) for ocean acidification and dissolved oxygen. A category 3B listing indicates that there is cause for concern, but either data and/or methods to assess data are insufficient to determine impairment. This determination was made in response to data, information and comments received during the public process (call for data and comment period for the draft 2018/2020 IR). DEQ received information and National Oceanic and Atmospheric Administration data from the Center for Biological Diversity, and a joint letter from sister agencies (Oregon Department of Fish and Wildlife and The Department of Land Conservation and Development) and Oregon's OAH Council requesting changing ocean conditions in Oregon be assessed and listed as impaired in the Integrated Report. At that time, DEQ was unable to conclude that there had been detrimental changes to the resident biological communities within Oregon jurisdictional waters using data and information submitted.[17]

In the 2022 Integrated Report, DEQ received data from the Ocean Observatories Initiative and Newport Hydrographic Line, analyzed the data, but lacked the technical expertise to assess profile and fixed mooring data at ocean depths DEQ does not typically evaluate.[18] Therefore, status remained the same as 2018/2020 (Category 3B- insufficient data; potential concern).

Reporting on beach conditions

DEQ has been assessing and reporting on beneficial use support of coastal water contact recreation for beaches since 2004. In the 2018/2020 Integrated Report, DEQ classified all beach reporting units as impaired for beneficial use support of fishing (consumption) based on fish or shellfish consumption advisories issued by Oregon Department of Agriculture or Oregon Health Authority. Biotoxin advisories in Oregon are issued based on Paralytic Shellfish Toxin (PST) and Domoic Acid (DA) measurements in molluscan bivalve shellfish (clams, oysters, and mussels).[19] These beach reporting units are separate from the marine units that will be used in these proposed assessment methodologies as they are focused on activities related to beach uses (recreation and shellfish harvesting).

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[17] https://www.oregon.gov/deq/wq/Documents/irMethodologyF1820.pdf - Ocean Acidification section

[18] https://www.oregon.gov/deq/wq/Documents/IR22AssessMethod.pdf - Appendix C

[19] Shellfish Recreational Biotoxin (oregon.gov)

Formation of DEQ’s OAH technical workgroup

Oregon is the first West Coast state to propose a comprehensive methodology for assessing OAH impairments as a result of anthropogenic stressors under the CWA framework. DEQ has precedent to use the narrative biocriteria to assess changes in freshwater benthic assemblages, but leading up to the 2024 Integrated Report cycle, did not have expertise to assess biological response to changes in ocean chemistry. In February 2022, DEQ convened a scientific technical workgroup to provide technical expertise on scientific questions relevant to the interpretation of Oregon’s existing narrative WQS. The technical workgroup is composed of over 40 individuals representing a diversity of scientific, technical, and policy expertise in the field of OAH. Workgroup members bring a range of specialized regulatory, research, and academic perspectives to the meetings and include prominent researchers in the field.

In 2022, DEQ coordinated a series of meetings and conversations with workgroup members, including full workgroup meetings, subgroup meetings, and individual conversations. Over the course of these discussions DEQ and workgroup members worked toward defining the scientific basis for assessment methodology development and outlining the critical scientific and policy questions to guide the process. The technical workgroup, including the subgroups, did not inform or make policy decisions. Rather, they facilitated the sharing of scientific data and information, in response to direct questions from DEQ, and provided a review of the factual accuracy of scientific summaries inherent in DEQ’s translation of the science into a policy framework.[20]

Technical workgroup products

The technical workgroup process was productive and DEQ is grateful for the generous contributions of time and effort from workgroup members. With the technical assistance of the group DEQ has redefined marine assessment units, developed a biological Assessment Framework and drafted proposed assessment methodologies for OA and hypoxia.

Marine biocriteria assessment framework

The first major product developed in consultation with the workgroup is DEQ’s assessment roadmap to interpret the narrative biocriteria, which can be framed as guiding principles,

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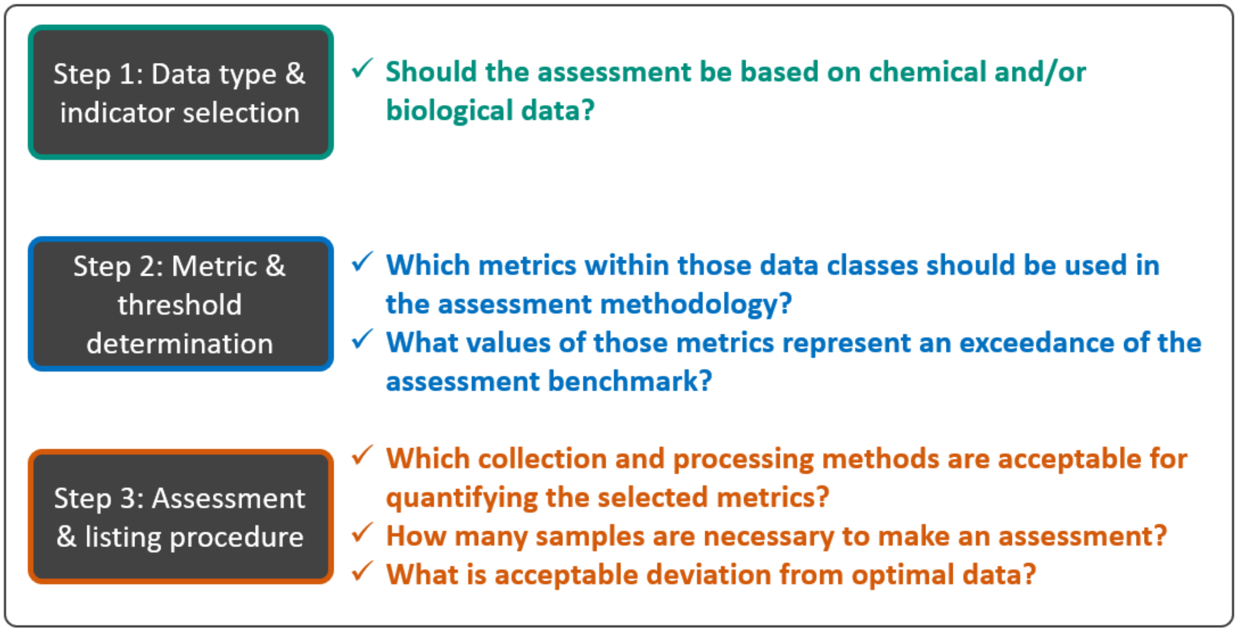
[20] https://www.oregon.gov/deq/wq/Documents/OAH-WorkgroupCharter.pdf

centered around key steps and policy questions (**Figure 2**). The purpose of this section is to summarize the guiding principles used in this approach.



Step 1: Data type & indicator selection

- ✓ Should the assessment be based on chemical and/or biological data?

Step 2: Metric & threshold determination

- ✓ Which metrics within those data classes should be used in the assessment methodology?
- ✓ What values of those metrics represent an exceedance of the assessment benchmark?

Step 3: Assessment & listing procedure

- ✓ Which collection and processing methods are acceptable for quantifying the selected metrics?
- ✓ How many samples are necessary to make an assessment?
- ✓ What is acceptable deviation from optimal data?

Figure 2: The biocriteria assessment roadmap DEQ used to develop an assessment framework for interpreting the biocriteria WQS in Oregon. The approach is defined by a series of key steps and high-level questions.

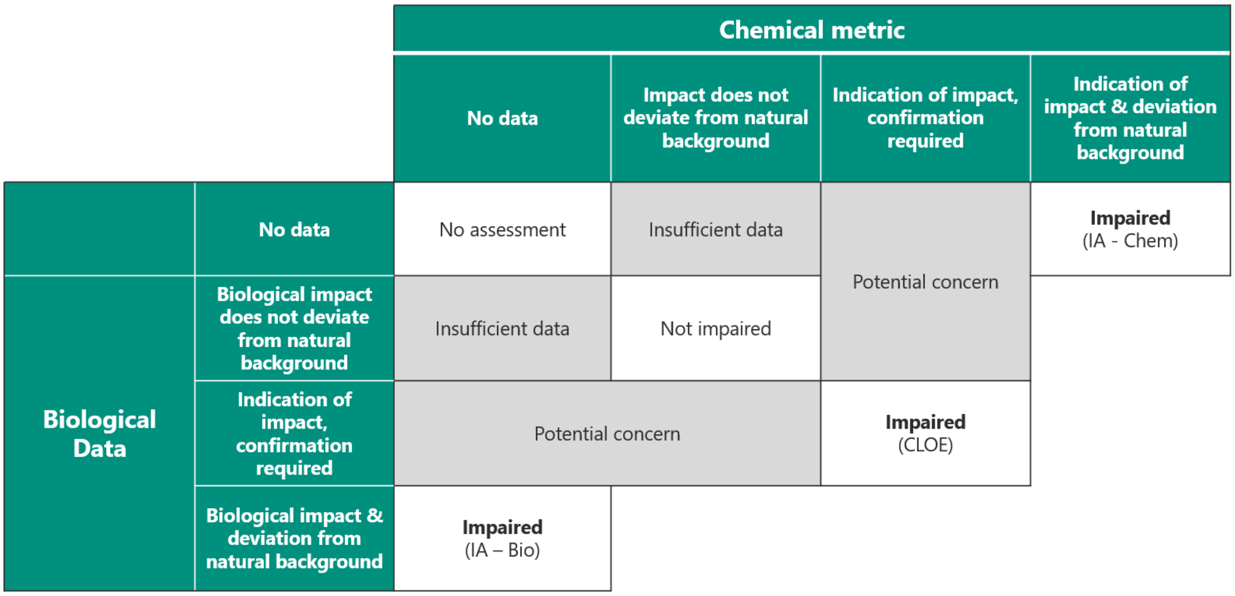
Principles guiding chemical and/or biological lines of evidence in a hybrid framework

DEQ's biocriteria assessment roadmap allows for the use of chemical or biological data, however a hybrid approach combining the two for multiple lines of evidence is preferred. DEQ is proposing to use two types of benchmarks to conduct IR categorical assessment based on individual or combined lines of evidence. One benchmark value, referred to as the "independently applicable (IA)" benchmark, is defined as a value which, if exceeded, there is confidence about biological impact based on biological or chemical data alone. Confidence in this case can be based on scientific consensus or 90th percentile confidence interval as appropriate. The second benchmark value, referred to as the "combined line of evidence (CLOE)" benchmark, is defined as a value which, if exceeded, indicates biological impact, but requires confirmation from an additional line of evidence (**Table 3**). In cases where two lines of evidence are available DEQ will rely on the CLOE benchmark, whereas in instances where only a single line of evidence is available DEQ will employ the IA benchmark for that data. By incorporating the option for multiple lines of evidence this approach can account for some uncertainty inherent in the biological impact benchmark values and/or their deviation from natural background conditions.

Table 3. Assessment benchmark types for a Hybrid Assessment Framework.

Independently applicable (IA)	A value beyond which there is confidence about biological impact based on biological or chemical data alone
Combined line of evidence (CLOE)	A value beyond which indicates biological impact, but requires confirmation from an additional line of evidence

To illustrate how the IA and CLOE benchmarks can be applied to determine impairment, DEQ has developed a hybrid marine biocriteria assessment framework. This framework allows for biological or chemical metrics to be assessed individually or in combination, depending on data availability and adherence to quality requirements (**Figure 3**).[21] Though presented here in narrative form, this framework can be readily adjusted to incorporate numeric metrics, benchmarks, and categorical determinations.



		Chemical metric			
		No data	**Impact does not deviate from natural background**	**Indication of impact, confirmation required**	**Indication of impact & deviation from natural background**
Biological Data	**No data**	No assessment	Insufficient data	Potential concern	**Impaired** (IA - Chem)
	Biological impact does not deviate from natural background	Insufficient data	Not impaired		
	Indication of impact, confirmation required	Potential concern		**Impaired** (CLOE)	
	Biological impact & deviation from natural background	**Impaired** (IA – Bio)			

Figure 3. DEQ's hybrid marine biocriteria assessment framework defines how DEQ will determine impairment based on individual or combined lines of evidence. IA: Independently Applicable benchmark, CLOE: Combined Lines of Evidence benchmark.

This hybrid framework was developed to interpret the biocriteria WQS for the purposes of determining impairment (evidence that at least one beneficial use is not being fully supported). In this framework, a finding of no impairment does not automatically translate to a finding of

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[21] [irDataSubGuide.pdf (oregon.gov)]()

attainment (evidence that beneficial uses are fully supported), but rather, attainment will be considered based on the level of protection granted by the CLOE benchmarks to the assessed waters. While initially developed to interpret the narrative biocriteria for OA stress, this framework may also be adapted to interpret other narrative criterion that reference a change from background condition or multiple lines of evidence, such as the marine DO criteria. This hybrid framework is significant in that it can be used as a roadmap for the scientific community to help inform policy decisions in Oregon.

Severity of response

The framework relies on biological and chemical indicators that target an organismal fitness level response, as DEQ considers a population level response to be too severe and early warning or exposure level response not sufficient to be considered an impairment. For the biological indicator, the assessment methodology should target the most sensitive taxa. The selection of a chemical metric for the assessment methodology should be based on benchmarks derived from the most sensitive taxa and where possible, organisms with a well-defined relationship between OA stress and biological response. As biological response to changing ocean conditions is a burgeoning area of science, the application of assessment benchmarks to determine biological impairment may be adjusted as the understanding of biological response in nearshore ecosystems evolves.

Principles guiding deviation from natural background condition

To determine aquatic life use support based on biological and/or chemical indicators, DEQ's methodology should be based on a difference from natural background condition. This is consistent with freshwater biocriteria assessment methodologies and addresses the "no detrimental changes to biological communities" aspect of the criteria, which is defined as "no loss of ecological integrity when compared to natural conditions at an appropriate reference site or region." Natural background conditions can be established using data from outside Oregon, provided it describes conditions likely to occur in state waters. For example, in freshwater assessment, DEQ will use reference sites in neighboring states that are in the same ecoregion to set expected conditions for streams in Oregon.[22] Natural background conditions can also be estimated using model output, given that the models are of sufficient resolution and are validated within state waters. DEQ will rely on EPA guidance[23] and existing precedent in

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[22] https://www.oregon.gov/deq/wq/Documents/wqaIR2024method.pdf - Assessment – Biocriteria Freshwater section
[23] Guidance for Quality Assurance Project Pans for Modeling (epa.gov)

considering model resolution and validation, and may ask the technical workgroup for assistance in reviewing proposed models.

Precedent for spatial and temporal sampling frequency

DEQ assesses the status of waterbodies at the assessment unit level. Assessment units (AUs) are predetermined waterbody segments used for reporting IR water quality status determinations.[24] In Oregon, AUs represent similar hydrology and environmental characteristics and may contain multiple monitoring locations. For each assessment data window (typically includes the past five to ten years, but may vary depending on the specific assessment), minimum chemical data requirements are defined by the application of statistical methods for determining status or at the individual metric level.[25] For biological data, by precedent, DEQ has used as few as one sample in the data window to evaluate beneficial use support. The rationale for this is that biological indicators live in the conditions and integrate the effects of those conditions over time (in freshwater this is typically one season). However, an ideal dataset would include a higher sampling frequency, such as two or more samples per season. DEQ acknowledges that impairment determinations can be made based on overwhelming evidence where multiple sources of data and/or information indicate impairment, so long as there is confidence in deviation from the natural background condition.[26]

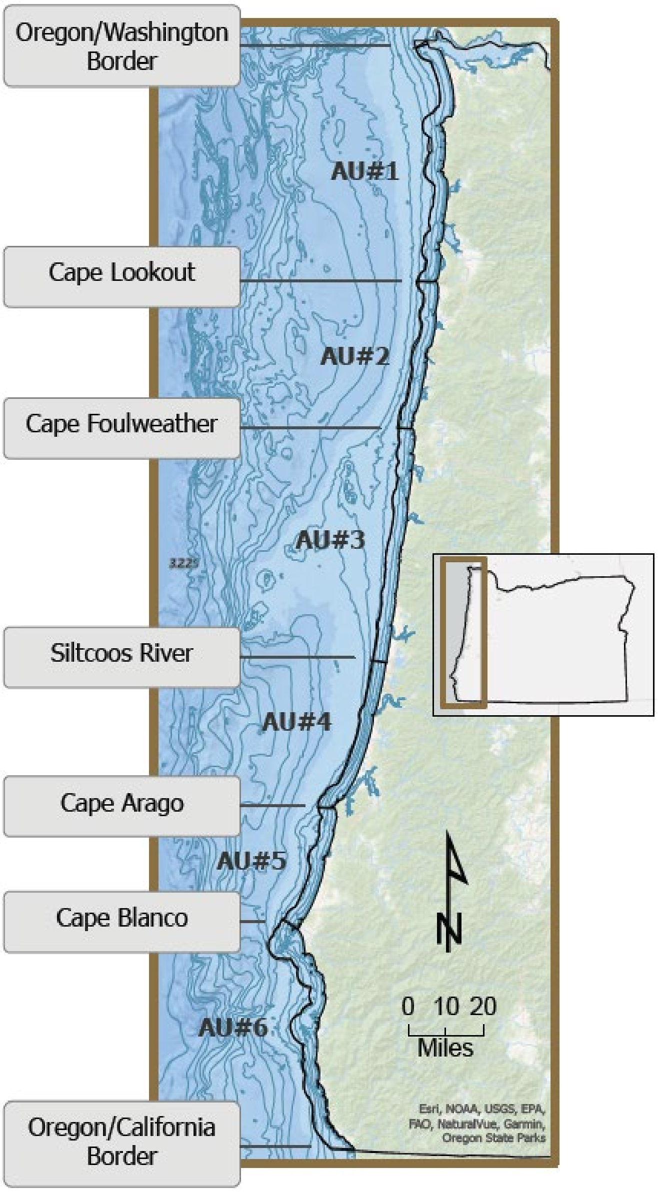

Figure 4. DEQ's marine assessment units (AUs) extend three nautical miles seaward and are divided alongshore by hydrologically relevant coastal features.

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[24] https://www.oregon.gov/deq/wq/Documents/wqaIR2024method.pdf - Assessment units section

[25] https://www.oregon.gov/deq/wq/Documents/wqaIR2024method.pdf - General Methodologies for Parameter Assessments section

[26] https://www.oregon.gov/deq/wq/Documents/wqaIR2024method.pdf - Overwhelming evidence section

Updated marine assessment units

Prior to the IR 2024 cycle, Oregon's marine AUs encompassed Oregon territorial waters and were divided by extensions of land based HUC 8 watershed boundaries from the National Hydrography Dataset.[27] In consultation with the technical workgroup, DEQ redefined the alongshore boundaries of marine AUs to incorporate geographic breakpoints more relevant to reporting on the status of marine waters. DEQ will use six ocean AUs delineated based on headlands, offshore banks, and river mouths (**Figure 4**).Except for one boundary, marine AUs alongshore boundaries are aligned with existing Oregon Department of Agriculture shellfish biotoxin assessment zones and contain multiple zones within each unit.

DEQ proposes to pool data from multiple monitoring locations in a marine AU for assessment purposes. In limited circumstances, there may be a need to determine whether sample results are spatially or temporally representative of the entire AU. In those scenarios, DEQ may rely on the *Assessment By Monitoring Station* approach defined in the IR 2024 draft methodology.[28] DEQ may also use best professional judgment for unique assessment scenarios, and data aggregation decisions will be documented in the assessment rationale section of the IR.

2024 ocean acidification assessment framework

Indicator and data types

Under the CWA framework, detrimental changes in biological integrity are considered a form of pollution that should be included in the assessment of waterbody body status.[29,30] This distinction indicates that waterbodies identified as impaired for biocriteria require pollution prevention plans (such as TMDLs) that may include identification of stressors to those assemblages. EPA guidance recommends using measurable components of an ecological system, including stress response signatures of organism condition, as indicators of aquatic life

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[27] https://www.usgs.gov/national-hydrography/national-hydrography-dataset
[28] https://www.oregon.gov/deq/wq/Documents/wqaIR2024method.pdf
[29] Federal Water Pollution Act Section 502(19) (33 U.S.C 1362) (Clean Water Act)
[30] Oregon Administrative Rules 340-041-0002(39)

beneficial use support.[31,32] In applying the marine biocriteria assessment framework the workgroup was asked to assist in identifying those sensitive taxa that represent the most developed indicators with the clearest lines of evidence to assess biological impacts related to ocean acidification. The workgroup suggestion in response to this charge was to focus the first iteration of the OA assessment methodology on biological impacts to calcifying zooplankton, specifically pteropods (*Limacina helicina)*, in Oregon's territorial waters. Pteropods (*L. helicina*) are pelagic sea snails that rely on the biomineral aragonite ($CaCO_3$) to form and maintain their shells, and as such, the degree of shell dissolution is closely linked with the saturation state of aragonite (Ω_{ar}) in the water column (Bednaršek et al., 2014a, 2016; Feely et al., 2016).

Pteropods are an appropriate focal indicator taxa for DEQ's assessment methodology for several reasons (Bednaršek et al., 2014a, 2017a, 2017b, 2019). First, they are ubiquitous throughout the globe, and their diversity, abundance and distribution are well studied in the CCE (Bednaršek et al., 2012a, 2014a, 2016, 2017a, 2017b; Knecht et al., 2023), where their use in coastwide coordinated monitoring programs is increasing. Second, they are among the most sensitive pelagic indicators of changing OA conditions known to date, with well documented OA stress-specific sensitivity, ranging from evidence of exposure (e.g., shell dissolution), sublethal and lethal responses (Bednaršek et al., 2017b; Lischka et al., 2011; Lischka and Riebesell, 2012). Third, these calcifiers efficiently transfer energy from phytoplankton to higher trophic levels (Lalli and Gilmer, 1989), and as such serve as an important prey group for ecologically and economically important fishes (salmon, cod, herring, sole), bird, and whale in some parts of the Pacific Ocean (Armstrong et al., 2005; Aydin et al., 2005; Karpenko et al., 2007). Fourth, they significantly contribute to carbonate production (Bednaršek et al., 2012b; Fabry, 1990) and carbon sequestration (Knecht et al., 2023).

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[31] Consolidated Assessment and Listing Methodology (epa.gov)

[32] The Biological Condition Gradient (BCG) - A Model for Interpreting Anthropogenic Stress on the Aquatic Environment (epa.gov)

Among the pathways of pteropod physiological responses to OA, the relationship of shell dissolution to Ω_{ar} averaged over the upper 100m of the water column is among the best documented (Bednaršek et al., 2014a, 2017b, 2019; Weisberg et al., 2016). This indicator was developed from more than a decade of research quantifying the biologic response to corrosive conditions, wherein methods and metrics to measure response severity were developed, the response metric was linked to a suite of physiological level effects, laboratory findings were verified with in situ research relevant to coastal ecosystems in the CCE, and thresholds for OA sensitivity were established (Bednaršek et al., 2019, 2017a, 2014a, 2014b, 2012a; Feely et al., 2018, 2016). Early development of the pteropod shell dissolution metrics categorized shell dissolution into different types corresponding to the severity of dissolution effects. Initially, the studies focused on the amount of severe dissolution present (Bednaršek et al., 2014b, 2012a, 2012b) which was later changed to the percent individuals with severe dissolution for the purposes of quicker evaluation, (Bednaršek et al., 2016, 2014a; Feely et al., 2016), recognizing mutual agreement between both metrics. Both the severity of shell dissolution and percent of pteropod individuals with severe dissolution in ocean water samples are inversely related to averaged upper 100m water column Ω_{ar} (**Figure 5**; (Feely et al., 2016)). Finally, Ω_{ar} thresholds of mild to severe dissolution were rated to be of the highest confidence by an expert panel (Bednaršek et al., 2019). This robust and well defined relationship between pteropod shell dissolution and Ω_{ar} provides the critical elements of DEQ’s marine hybrid biocriteria assessment framework (**Figure 3**) that allow biological measurements of severe shell dissolution and chemical measurements of Ω_{ar} to be the basis for biological impact assessment.

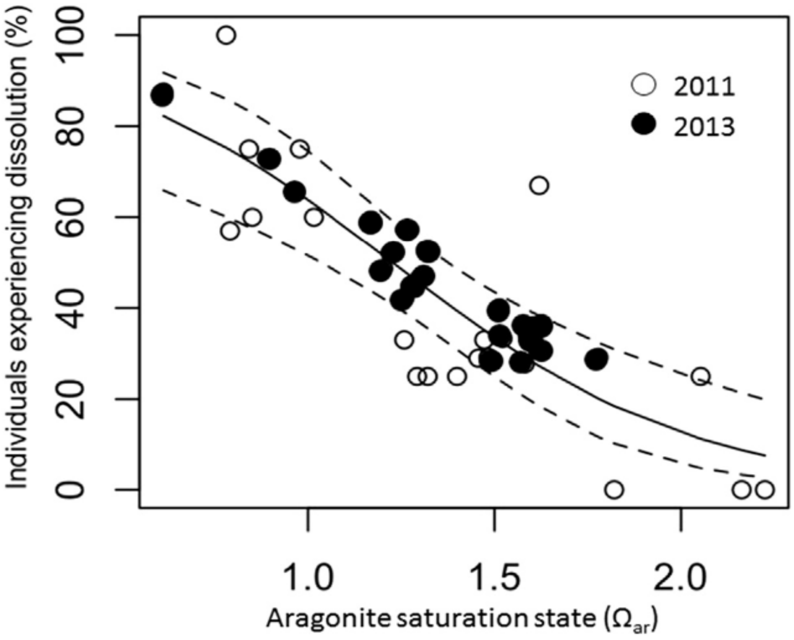

Figure 5. Figure from Feely et al. (2016) illustrates the percentage of individuals experiencing severe dissolution as a function of aragonite saturation state (averaged over the upper 100m). This relationship is derived from 2011 (open circles) and 2013 (closed circles) data. The dashed lines indicate the 95% confidence interval for the logarithmic function: y =-66.29 lnx + 61.21 (R2 = 0.74).

Though shell dissolution is classified as an exposure metric, it is the preferred measurement for biological impairment assessment as it is relatively easy to observe and measure, it can be replicated across laboratories, its presence also best links to physiological impairments (energetic trade-offs), and it serves as a proxy for survivorship (**Figure 6**) and calcification (Bednaršek et al., 2019, 2017b). Importantly, shell dissolution caused by decreasing Ω_{ar} is no longer just an early detection of the OA impacts because it correlates with important physiological processes that are directly related with organism's survival (Bednaršek et al., 2017b).

The workgroup recommended other potential bioindicators be considered in future assessments, such as Dungeness crab, mussels, krill and/or other marine invertebrates, but suggested additional research is needed to better articulate species-specific responses to OA stress.

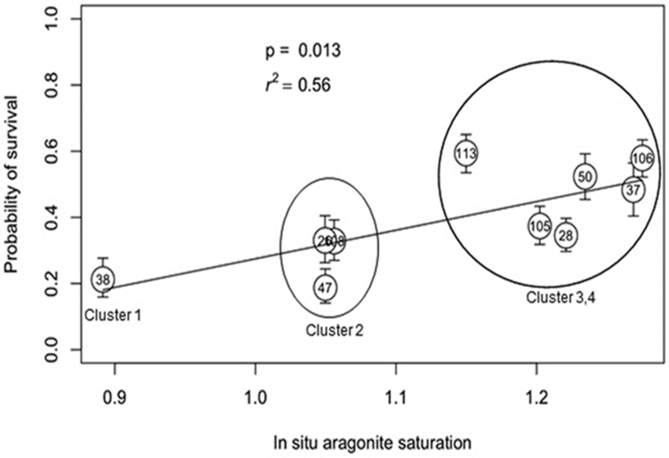

Figure 6. From Bednarsek et al. (2017). Experimentally-derived probability of *L. helicina* survival as a function of in situ Ω_{ar} exposure. Numbers within circles identify the station of origin for pteropods used in the experiments, collected during NOAA's 2016 West Coast OA cruise. In this experiment pteropods were maintained at identical conditions after collection to assess the effect of in situ Ω_{ar} exposure on survival probability.

Metrics and benchmarks

Chemical metric and benchmarks

Aragonite saturation state (Ω_{ar}) will serve as the basis for the chemical metrics used in this assessment because it represents the best available science to quantify OA stress to pteropods (Bednaršek et al., 2019). Procedures and core principles to quantify Ω_{ar} are outlined in McLaughlin et al. (2015) and Dickson (Dickson, 2010; Dickson et al., 2007). These widely approved procedures describe the primary measurement parameters required to derive Ω_{ar}, as well as the relative uncertainty associated with each combination of parameters (McLaughlin et al., 2015). As a derived value, uncertainty in Ω_{ar} calculation is a product of many sources of potential error, including independent measurements of multiple carbonate parameters as well as the thermodynamic constants used to relate carbonate species to one another. To address these and other sources of uncertainty, members of the California Current Acidification Network have suggested an uncertainty range of Ω_{ar} +/- 0.2 when linking changes in ocean chemistry to changes in ecosystem function (McLaughlin et al., 2015).

Benchmark Ω_{ar} values for this assessment methodology were chosen to signify likely biological impact based on the aragonite/pteropod shell dissolution exposure-response relationship (Bednaršek et al., 2019, 2017b; Feely et al., 2016). Ω_{ar} thresholds for severe shell dissolution derived experimentally, through expert consensus, and through a field stress-response study range from 1.06-1.3, with the final recommended value of Ω_{ar} = 1.2 (Bednaršek et al., 2019, 2014a). As outlined in the hybrid framework, two chemical benchmarks, IA and CLOE (**Table 3**), are needed. The IA Ω_{ar} benchmark represents the thresholds below which there is confidence about biological impact based on chemical data alone. The CLOE benchmark is the threshold below which determination of an impact requires confirmation from biological data. For the purposes of this assessment methodology DEQ proposes to adopt the uncertainty range of +/- 0.2 outlined in McLaughlin et al. (2015) to identify the two Ω_{ar} biological impact benchmarks for severe pteropod shell dissolution.

The lower end of the 0.2 range around Ω_{ar} =1.2 will define the IA benchmark and the upper end will define the CLOE benchmark. DEQ and the workgroup believe Ω_{ar} = 1.0 (1.2 - 0.2) is a suitable IA benchmark value that provides the confidence needed to determine impairment on chemical data alone, and Ω_{ar} = 1.4 (1.2 + 0.2) is a suitable CLOE benchmark to indicate biological impact but require biological data confirmation to determine impairment. The application of these chemical benchmarks to the pteropod/aragonite relationship serves as the translation to derive corresponding severe shell dissolution benchmarks (**Figure 7**).

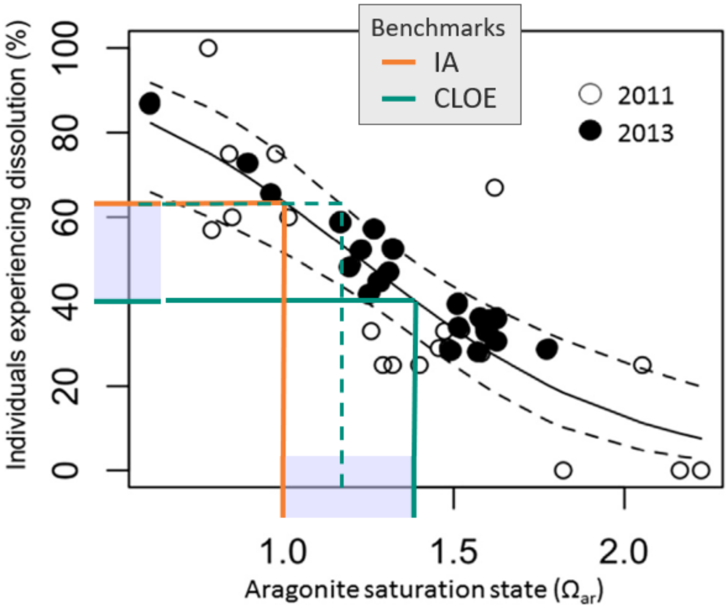

Figure 7. Figure from Feely et al. (2016) (Figure 5) modified to show derivation of DEQ's proposed assessment benchmark values for OA.

Biological metric and benchmarks

The detailed procedures outlined in Bednarsek, et al. (2012a) serve as the basis for quantification of pteropod shell dissolution and calculation of biological metrics used in this assessment. The extent of shell dissolution is documented via scanning electron microscope (SEM) analysis and a categorization scheme applied to describe the category of severity of dissolution used to calculate the biological impact metric.

The calcified layers of pteropod shells are made up of two layers: the outer prismatic layer and the inner crossed-lamellar layer, the level of dissolution of which varied according to the type of dissolution observed (i.e., Type I, II, and III). Type I involves partial dissolution of the prismatic layer; Type II involves dissolution of the prismatic layer to the point of exposure of underlying crossed-lamellar layer, and Type III, where crossed-lamellar layer shows signs of dissolution (Bednaršek et al., 2012a).

Oregon DEQ is proposing to use the percentage of individuals in a biological sample with moderate to severe shell damage (Type II & Type III) as the biological metric, hereafter referred to as severe dissolution. The rationale being this metric will serve as a strong sublethal indicator of fitness impairment that leads (under sufficient duration exposure to OA) to lethal responses in Oregon territorial waters.

DEQ selected 62% and 40% individuals with combined Type II/ III dissolution as the IA and CLOE (**Table 3**) biological benchmarks, respectively. The rationale for this choice is as follows. Utilizing the regression relationship of Ω_{ar} versus percentage of individuals with Type II/III dissolution (Feely et al., 2016), 62% of individuals with dissolution represents the upper 95th confidence limit of an $\Omega_{ar} = 1.2$ (**Figure 7** – dashed line), the threshold at which severe dissolution occurs (Bednaršek et al., 2019). According to Bednarsek et al. (2017; Fig 1d), a benchmark of 62% of individuals with Type II/III dissolution correlates to a mean survival probability of roughly 50%, which aligns with an acute (LC-50) level of mortality, suggesting that 62% of individuals with Type II/III dissolution represents a severe effects/lethality threshold (**Figure 7** – orange line). While the CLOE benchmark (40% individuals with combined Type II/ III dissolution) accounts for some natural variability in biological response, and therefore requires a second line of evidence from the chemical indicator to determine impairment (**Figure 7** – green line).

Ecological integrity of proposed benchmarks

DEQ's OAR 340-041-0002 defines "Ecological Integrity" as "the summation of chemical, physical, and biological integrity capable of supporting and maintaining a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of the natural habitat of the region."[33] It is important to note that while derived from the pteropod severe shell dissolution benchmark of $\Omega_{ar} = 1.2$, both benchmarks also align with a suite of endpoints and biological effects to pteropods and other marine organisms. For example, the benchmark of $\Omega_{ar} \sim 1.1\text{-}1.2$ approximates the threshold at which pteropod shell dissolution rates surpass calcification rates to impact net change in shell mass, an important physiological response affecting vertical migration patterns (Bednaršek, et al., 2014b).

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[33] https://oregon.public.law/rules/oar_340-041-0002

Additionally, as stated in Bednarsek et al. (2017a): "Calcification, growth, and survival all were observed to decline at Ω_{ar} ~1, suggesting that these processes are interconnected and occur at similar threshold value." While rooted in the indication of severe shell dissolution, the suite of pteropod effects observed at and below this value increase confidence in its use for water quality impairment determination.

Defining natural background condition

One of the goals of this assessment methodology is to evaluate biological impacts of OA outside the range of natural background condition. DEQ's OAR 340-041-0002 defines Natural Conditions as "conditions or circumstances affecting the physical, chemical, or biological integrity of a water of the state that are not influenced by past or present anthropogenic activities. Disturbances from wildfire, floods, earthquakes, volcanic or geothermal activity, wind, insect infestation and diseased vegetation are considered natural conditions."[34] Nearshore environments with seasonal upwelling (such as Oregon's territorial sea) intermittently become undersaturated with respect to aragonite ($\Omega_{ar} < 1$) under naturally occurring conditions (Harris et al., 2013). Thus, it is expected that chemical assessment benchmarks may be naturally exceeded with some frequency, and some percentage of pteropods would naturally be affected by Type II/III dissolution.

A critical piece of biocriteria assessment for the determination of aquatic life beneficial use impairment is establishing the natural background exceedance of the IA and CLOE benchmarks. This comparison is crucial in ensuring biological impacts used to determine impairment are outside the range of natural ecosystem variability while also recognizing that anthropogenic activities may intensify the effects of natural background conditions. EPA guidance recommends reference conditions be established using a combination of four elements: "(1) evaluation of historical data; (2) sampling of reference sites; (3) prediction of expected conditions using models; and (4) expert consensus."[35] The lack of seasonally and spatially explicit carbonate baseline conditions in Oregon's territorial sea introduces uncertainty to the assessment process, where natural condition gradients, seasonal upwelling, freshwater inputs, and anthropogenic inputs all contribute to observable conditions on a given day. As such, shifts in these and other processes affecting ocean conditions, alone or in combination, could be considered a deviation from natural background conditions.

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[34] https://oregon.public.law/rules/oar_340-041-0002

[35] Estuarine and Coastal Marine Waters: Bioassessment and Biocriteria Technical Guidance (epa.gov)

A well-developed approach to determine OA natural background condition is to estimate the contribution of anthropogenic carbon (C_{anth}) to observational measurements in order to quantify the shift from pre-industrial times. For example, pre-industrial estimations outlined in Feely et al. (2016) differentiate between the contributions of C_{anth} and natural remineralized carbon (C_{bio}) to the inorganic carbon system in the CCE. In simple terms, this fractioning of inorganic carbon provides regionally averaged pre-industrial estimations of aragonite saturation state in nearshore and offshore waters during specific time periods (Feely et al., 2016). DEQ recognizes the CWA does not require natural background conditions to reflect pre-industrial times, however DEQ considers this approach the best available science to understand how anthropogenic effects are contributing to OA impacts.

For the biological indicator, DEQ is proposing to use the most recently published (Feely et al. 2016) pre-industrial estimates of natural background percentage individuals with Type II/III dissolution in the nearshore (36-39%) as evidence that the CLOE benchmark (40%) is on the upper end of the range of natural background condition (**Figure 8**) and impact should be confirmed with the chemical indicator. Previously, Bednaršek et al. (2014) independently estimated dissolution rates without the contribution of anthropogenic carbon to be around 21% for the nearshore habitats. This adds support to the decision of setting the CLOE benchmark at 40% in that it is on the upper end of pre-industrial estimates of natural background condition while allowing for some degree of dissolution.

Year	Location	Ω_{ar}, preind.	Ω_{ar}, current	% Ind. with severe dissolution, preind.
2011	nearshore	1.39	1.05	39
2013	nearshore	1.46	1.08	36
2011	offshore	2.21	1.51	8
2013	offshore	2.09	1.43	12

Figure 8. Adapted from Feely et al. (2016) reported on average current and estimated pre-industrial period aragonite saturation states and percentage of individuals affected by severe dissolution for nearshore and offshore regions of CCE calculated for years 2011 and 2013.

Unlike the biological indicator, which serves as an integrator of exposure time and frequency in the water column, chemical observational data represent a snapshot in time or a selected portion of the water column. Thus, for the chemical indicator, DEQ is proposing that observational data should not only be compared to benchmark values but also evaluated against estimated background conditions to determine an excursion. Documented biological impacts related to OA taking place from decreasing available aragonite occur in part because the stratified boundary (horizon) of undersaturated ($\Omega_{ar} < 1$) conditions is moving up the water column and into the more productive photic zone (Feely et al., 2016). Pre-industrial estimations of carbonate chemistry can be used to compare present day observations of Ω_{ar} in the vertical water column to those expected in the absence of C_{anth}. Additionally, these pre-industrial estimates can be used to generate a depth horizon for a given Ω_{ar} value, where concentrations in the water column below the horizon are expected to occur under natural background conditions, and above which concentrations were not expected to occur. DEQ believes estimated pre-industrial depth horizons of chemical benchmarks represent one way to compare current observational data with natural background conditions to determine impairment. Data comparison details using the depth horizon approach are outlined below in the Data evaluation section.

Assessment and listing procedures

Data evaluation

For this assessment, DEQ will use the above defined chemical and biological benchmark values to determine a status category for a water body based on pteropod condition impacts. Critical spatial and temporal assessment windows further define the applicability of the assessment methodology to the biological impact it is designed to identify. Deviations from natural background condition and identification of detrimental changes to biological communities outside of natural variability will be assessed using the best available science on pre-industrial conditions. The purpose of this section is to describe the critical assessment windows, approach to evaluating deviation from natural background condition, and statistical methods for determining impairment.

Critical assessment windows

For assessment of fish and aquatic life use, the location and time period in which data are collected can be relevant to application of WQS or assessment benchmarks. In freshwater systems, critical periods are used to identify when the data are most relevant to macroinvertebrate community assemblage assessment and fish spawning times.[36] Similarly, in marine OA assessment, DEQ has outlined a critical period that defines the applicability of the pteropod/aragonite assessment methodology to determine biological impairment. This period is defined by the temporal overlap of (1) the changes in ocean conditions in Oregon associated with seasonal upwelling and (2) the data used to define the pteropod aragonite relationship (Bednaršek et al., 2017a, 2014a; Feely et al., 2016). This critical period, April through the end of September, may be expanded in future assessment cycles as more information becomes available about cohort sensitivities in other times of year and/or more biological data becomes available to expand the temporal window of data used to define the relationship.

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[36] https://www.oregon.gov/deq/wq/Documents/wqaIR2024method.pdf

In addition, DEQ has outlined the components of a critical area, which would limit the applicability of the assessment methodology to certain marine waters. This area is defined by the spatial overlap of three considerations: (1) the boundaries of and/or relevance to Oregon's territorial waters, (2) likely pteropod habitats, and (3) applicability of pre-industrial calculations used to define natural background conditions in nearshore waters. In the 2024 IR cycle, station locations of submitted data will be evaluated based on location to determine if it can be used in a categorical assessment.

Evaluating deviation from natural background condition

DEQ is proposing to define natural background condition for the purposes of this assessment using estimates of the contribution of anthropogenic carbon (C_{anth}) to current ocean conditions. Though based on similar pre-industrial estimates to define background conditions, the approaches DEQ is proposing to use to evaluate biological and chemical data differ.

For biological data, DEQ is proposing that published pre-industrial pteropod dissolution estimates in nearshore environments provide sufficient evidence that levels chosen for the IA and CLOE benchmarks represent a deviation from natural background conditions. For this reason, biological IA and CLOE benchmarks will be evaluated directly to determine an excursion.

For chemical data, DEQ is proposing that observational data must not only be compared to IA and CLOE benchmark values but also evaluated against estimated background conditions to determine an excursion. For this comparison, model derived estimates of depth horizons, defined as the estimated depth to the IA and CLOE aragonite benchmarks (Ω_{ar} = 1.0 & 1.4) in the pre-industrial time period (**Figure 9**).

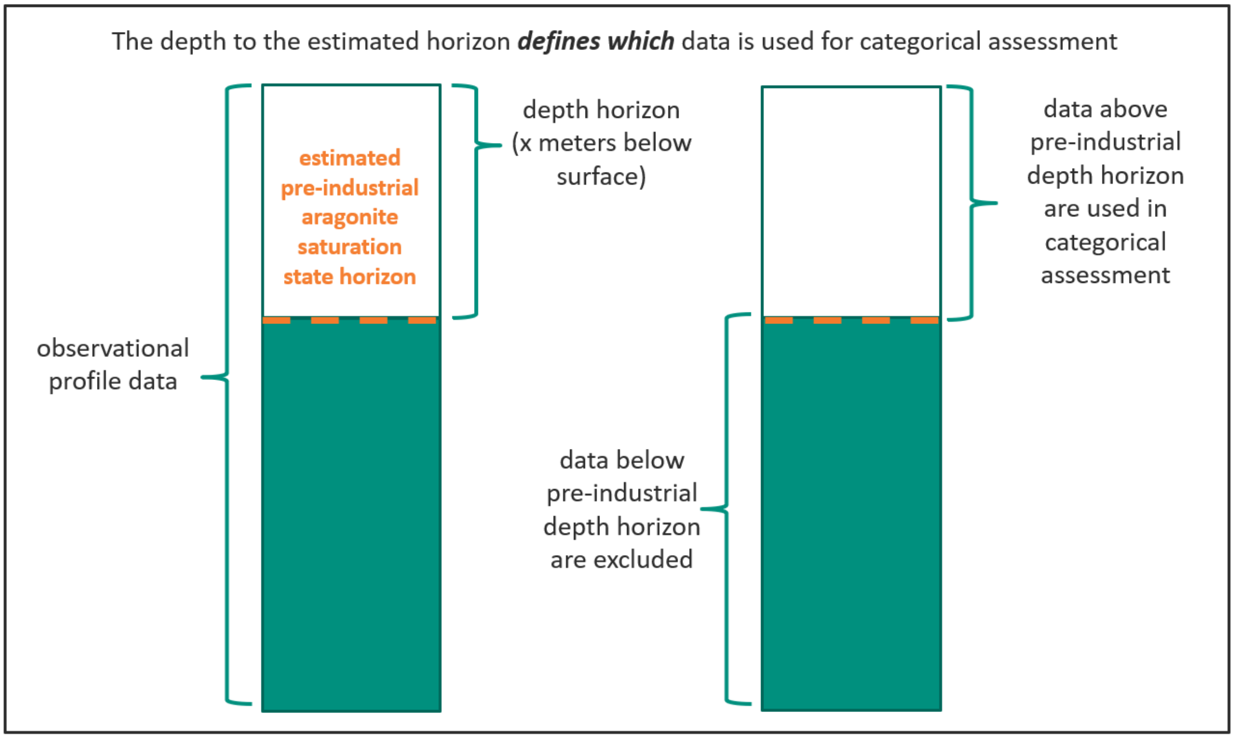

Figure 9: Pre-industrial aragonite saturation state horizon estimates will be used to define which data will be used in categorical assessment to determine impairment.

Based on recommendations from the workgroup, DEQ is proposing that pre-industrial aragonite saturation state estimates in Oregon’s territorial sea could be determined within the context of natural background variability to meet water quality assessment needs. Estimates could be generated and used for assessment purposes by applying existing oceanographic models, calculating site-specific estimates when sufficient data is available, or using regional estimates as appropriate. DEQ has identified a series of high-level steps and requirements to help define how an oceanographic modeling approach could be used to determine deviation from natural background conditions for assessment purposes.

Steps to utilize model simulations to determine natural background:

1. Key high-level model requirements:
    a. The model is a coupled physical-biogeochemical-lower trophic ecosystem model.
    b. The model would need to be validated, at minimum, for dissolved oxygen, carbonate saturation state parameters, temperature, and salinity, within state waters.

    c. Use of the model output for this application would require simulations for the critical period used in this assessment. .
2. Key steps to determine site specific pre-industrial horizons:
    a. Conduct a pre-industrial assessment on model simulations to remove effects of anthropogenic carbon on water chemistry, per methods of Feely et al. (2016).
    b. Subsample the model output to reproduce the locations of each of these observations and create depth-resolved virtual moorings of these locations.
    c. Create a daily average time series of the entire calendar year (or only critical window) at each location;
    d. Calculate the estimated pre-industrial depth horizon to the IA and CLOE aragonite benchmarks (1.0 & 1.4) over the monthly period (percentiles of depth estimates may be used as needed to account for variability in model output); and
    e. If deemed representative, average these depths horizons across the assessment unit. If not deemed representative, depth could be evaluated at individual monitoring locations.
3. For each observational data set, use the estimated pre-industrial depth horizon for the AU to exclude results data (illustrated in Figure *9*) for the applicable benchmark.
4. Pool all remaining results in the AU and use the procedures outlined in the Determining Impairment-Statistical Methods section.

Additionally, given sufficient data within an AU to conduct the analysis, observational data could be used directly to derive pre-industrial depth horizon estimates at the AU scale based on methods outlined in Feely et al (2016). DEQ will evaluate this option on a case-by-case basis and consult with subject matter experts as needed to determine whether there is sufficient observational data to make site specific estimations.

Finally, it is important to note that the steps and model requirements described above to derive pre-industrial horizon estimates are not required to make an assessment. In instances where modeling is not available within an AU or there is not sufficient observational data to derive site specific estimates, DEQ may utilize regional pre-industrial estimates of Ω_{ar} conditions as appropriate. DEQ will include the method used in the parameter assessment rationale portion of the Integrated Report.

Determining impairment - statistical methods

Similar to assessing impacts of other pollutants on fish and aquatic life, shell dissolution severity is linked with exposure history and duration of exposure to corrosive conditions (Bednaršek et al., 2017a). Defining water quality standards or setting assessment benchmarks incorporates magnitude, duration, and frequency of exposure. While providing a target for protection, WQS and benchmarks may not account for natural variation or variability in collecting water samples from that waterbody. Statistical methodologies reduce error in decision making by providing a way to test:[37]

1. How certain are we that the samples collected represent ambient conditions in the waterbody?
2. How certain are we that the samples indicate whether the waterbody as a whole is attaining or exceeding the water quality standard or benchmark?

To account for this, DEQ uses a statistical hypothesis testing approach (binomial test) to derive a critical number of sample excursions (single measurement that does not meet numeric WQ criteria or benchmarks) that scales with the number of representative samples to evaluate beneficial use attainment status of waterbodies.[36,38] The binomial method allows DEQ to quantify a level of statistical confidence and error when different sample sizes are used for making listing and delisting decisions. For listing of conventional (not toxics), DEQ uses the critical exceedance rate of 10% of samples with 90% minimum confidence level. This confidence level was chosen to balance type-I (when an attaining waterbody is incorrectly identified as impaired) and type-II (when an impaired waterbody is incorrectly identified as attaining) error rates.

The CLOE benchmark values for biological and chemical data were chosen to identify biological impact and not to signify aquatic life use protection. For the 2024 IR cycle, DEQ will not be assigning Category 2 – Attaining.

Data requirements

Currently, DEQ does not have a marine water quality monitoring program. Therefore, this assessment will be based on either readily available data, or data submitted through the Call for Data. For all data used in the assessment, DEQ requires a project plan and that widely approved methods are used for sample collection, analysis, and metrics calculation.[39] A project plan should include a purpose statement, the number of samples collected, and quality assurance and quality control protocols for collecting and analyzing samples. Data for both indicator types must be collected within the critical assessment windows.

Biological data evaluation

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[37] DEQ 2018, Integrated Reporting Improvements White Paper - Statistical Methods for Listing and Assessment of Large and Long Term Data Sets - https://www.oregon.gov/deq/FilterDocs/iri-statmethods.pdf

[38] EPA, 2002. Consolidated Assessment and Listing Methodology (CALM) Toward a Compendium of Best Practices, First Edition. United States Environmental Protection Agency. July 2002. Chapter 4.

[39] https://www.oregon.gov/deq/wq/Documents/irDataSubGuide.pdf

Until pteropod collection and processing methodologies are standardized, DEQ will use discretion when evaluating whether submitted data are of sufficient data quality to be consistent with sampling procedures outlined during NOAA hydrographic cruises (Bednaršek et al., 2017a, 2014a). Additionally, when considering submitted biological data, DEQ will evaluate whether data used to calculate the metric (percentage individuals with severe shell dissolution) are consistent with sample processing and the categorization scheme outlined in Bednarsek, et al. (2012a). A minimum of 15 pteropods should be used in calculating this metric. If subsampling, organisms should be randomly selected from the entire sample. The sample of individuals used to calculate this metric will be considered one biological sample. DEQ is proposing to use the average of two or more representative biological samples to assess impairment. This biologic minimum sample size is reflective of the integrated exposure to ambient water conditions over a duration of time.

Chemical data evaluation

For the 2024 IR cycle DEQ is proposing to base the assessment of the chemical indicator on vertical profiles with Ω_{ar} derived from two of four possible carbonate measurements (seawater pH, partial pressure carbon dioxide (pCO_2), total dissolved inorganic carbon (TCO_2), or total alkalinity (TA)) combined with salinity, temperature, and depth (Dickson, 2010; Dickson et al., 2007; McLaughlin et al., 2015). If not reported directly, DEQ will use the seacarb R package to derive Ω_{ar} from monitoring data.[40]

Additional approaches to deriving Ω_{ar} using correlative relationships with other more readily available parameters such as DO and salinity have been developed (Alin et al., 2012; Chan et al., 2017; Feely et al., 2008; Juranek et al., 2009). DEQ will not employ these approaches internally to derive Ω_{ar} in the 2024 IR cycle but will accept pre-calculated Ω_{ar} data derived via widely approved approaches so long as the associated calculation error rates are not greater than those described in McLaughlin et al. (2015). DEQ may adopt additional approaches internally to derive Ω_{ar} in future cycles as they become standardized.

Profile data used in this assessment must have sufficient vertical resolution to be representative of the water column. Each AU must have 5 unique (different date/time) vertical profiles collected during the critical assessment window. This is based on the minimum sample size identified in the binomial table for listing.[41] At each profile monitoring location, DEQ will employ the best available estimate of pre-industrial depth horizon to confirm the deviation from natural background condition. Sample results below the depth horizon will be excluded from the

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[40] CRAN - Package seacarb (r-project.org)

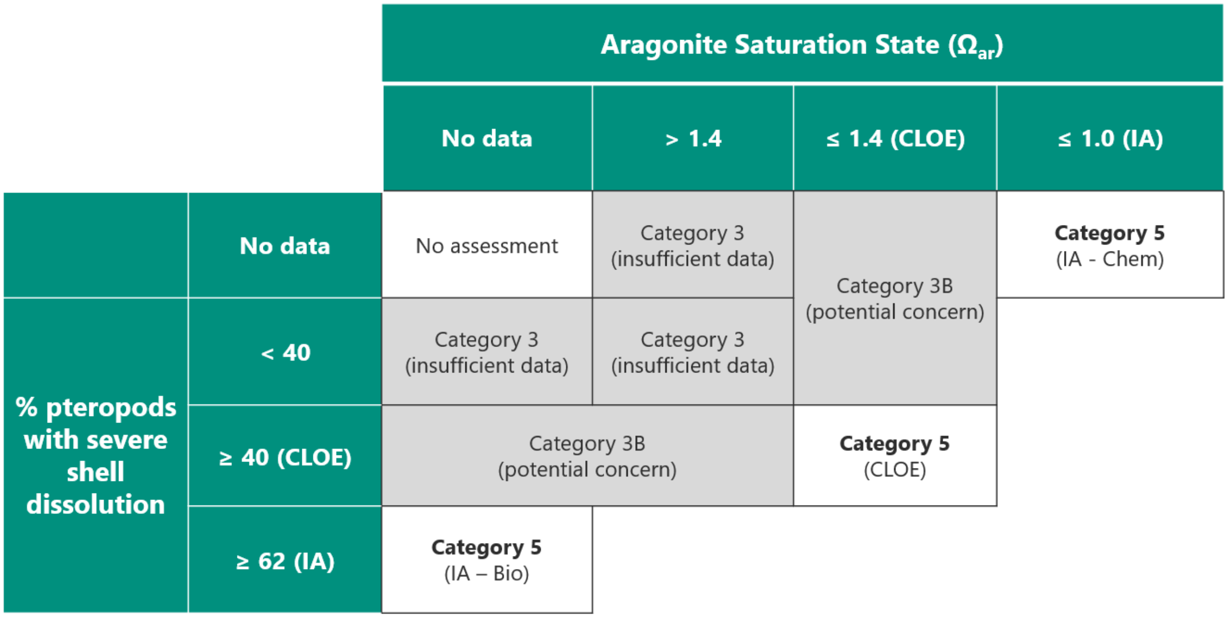
[41] https://www.oregon.gov/deq/wq/Documents/wqaIR2024method.pdf - Table 7

remaining categorical assessment steps. Remaining results above the pre-industrial depth horizon will be pooled by AU, and DEQ will use existing precedent of a 10 percent exceedance rate with a 90 percent confidence rate according to the exact binomial test to determine impairment.

Assignment of assessment categories

For the 2024 IR DEQ will be assessing water bodies for impacts to biological response as a result of changing OA conditions and will therefore be evaluating Categories 5 and 3 using both data types. For the 2024 IR cycle, DEQ will not determine biocriteria attainment (Category 2) because there is uncertainty in the level of protection provided by the current CLOE benchmarks. The hybrid framework for OA biocriteria assessment (**Figure 10**) and flowchart for assigning assessment categories (**Figure 11**) outline how DEQ will assess data for categorical determination. A more detailed description of categorical assignment can be found in the draft Assessment Methodology for Oregon’s 2024 Integrated Report for marine waters.

Additionally, DEQ acknowledges that impairment determinations can be made based on overwhelming evidence where multiple sources of data and/or information indicate impairment. This may include the use of some combination of observational data, published literature, and best professional judgment when interpreting data and information submitted to the agency for assessment purposes. If this approach is taken, a detailed rationale will be included in the Integrated Report.



		Aragonite Saturation State (Ω_{ar})			
		No data	**> 1.4**	**≤ 1.4 (CLOE)**	**≤ 1.0 (IA)**
	No data	No assessment	Category 3 (insufficient data)	Category 3B (potential concern)	**Category 5** (IA - Chem)
% pteropods with severe shell dissolution	**< 40**	Category 3 (insufficient data)	Category 3 (insufficient data)		
	≥ 40 (CLOE)	Category 3B (potential concern)		**Category 5** (CLOE)	
	≥ 62 (IA)	**Category 5** (IA – Bio)			

Figure 10: Proposed framework for OA biocriteria assessment outlining categorical assignments based on biological and chemical data assessed individually or in combination.

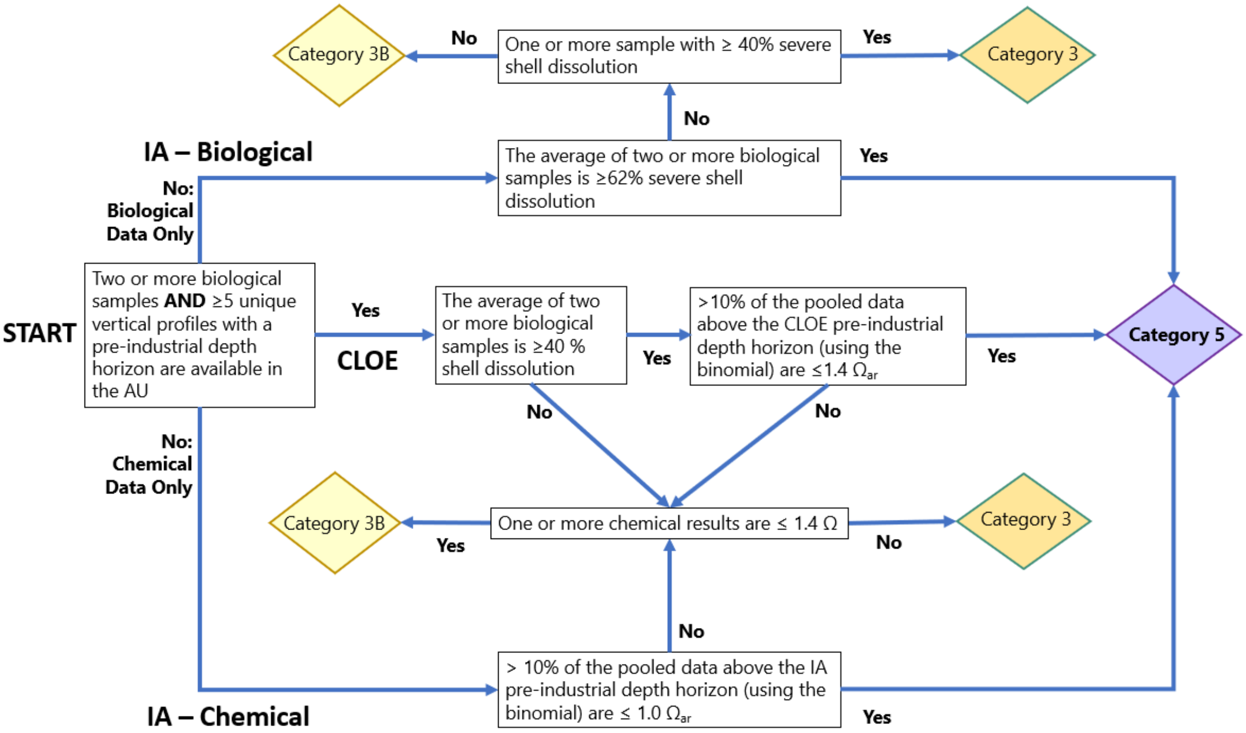


Figure 11. Flowchart for assigning categories based on the OA hybrid biocriteria assessment framework.

2024 Marine dissolved oxygen assessment framework

DEQ is proposing to adapt the Marine Biocriteria Assessment Framework to interpret Oregon's narrative marine DO criteria as it provides a structure for assignment of assessment categories based on multiple lines of evidence and comparisons with background conditions. Oregon's narrative marine DO criteria is defined in OAR-340-041-0016:

> "No wastes may be discharged and no activities may be conducted that either alone or in combination with other wastes or activities will cause violation of the following standards:
> (6) For ocean waters, no measurable reduction in dissolved oxygen concentration may be allowed"

Marine DO is further classified as "No Risk" in Table 21 of OAR-340-041-0016, which states:

> "The only DO criterion that provides no additional risks is "no change from background". Waterbodies accorded this level of protection include marine waters and waters in Wilderness areas."

Though seasonal hypoxia is a natural feature in upwelling regions in the Eastern Pacific, such as Oregon's territorial sea, recent research suggests that hypoxic events have been increasing in frequency, duration, and occurring in locations where they are not commonly observed. These changes have raised concerns that biological impacts are taking place outside of natural condition variability and aquatic life beneficial uses are not being fully supported in some areas. For this assessment, DEQ is proposing an approach that will allow the agency to quantify measurable reduction of DO in Oregon's territorial sea for the purposes of interpreting Oregon's narrative marine DO criteria for aquatic life beneficial use support.

For the 2024 IR report, DEQ is proposing to adopt a hybrid framework wherein two lines of evidence will be used to assess aquatic life beneficial use support. One line of evidence will rely on quantifying measurable reduction by comparing observational data with background conditions established either through long term observational data sets or modeled conditions. The second line of evidence will use established DO biological impact benchmarks to provide a biological lens to determine whether measurable reduction is likely affecting aquatic life beneficial use support.

Indicator and data types

Exposure to low dissolved oxygen conditions contribute to a variety of sublethal endpoints across species in nearshore marine environments. Behavioral effects such as species redistribution and predator/prey interactions are frequently controlled by changes in available habitat in response to low DO (Gilly et al., 2013), whereas ambient DO and temperature stress contributes to biological and metabolic effects on the organism level (Deutsch et al., 2020). Many species found in upwelling ecosystems are adapted to some extent to the large swings in DO conditions naturally found in these areas (Childress and Seibel, 1998; Chu and Gale, 2017). The range of conditions and species responses to multiple co-occurring stressors that accompany these swings make field-based biological measures of sublethal effects attributable to low oxygen difficult to quantify. Currently, DEQ is not aware of a field-based biological measure of low DO conditions with enough data to reliably determine background or reference conditions. Because of these factors DEQ is proposing to focus assessment of aquatic life beneficial use support related to marine DO on chemical data alone with the focus on impairment as a result of potentially lethal effects of hypoxia. In the future, DEQ may expand the assessment to include sublethal effects associated with low oxygen stress.

Metrics and benchmarks

Biologically relevant benchmark

The dissolved oxygen thresholds summarized in Chan et. al. 2019 provide examples of biological responses to low dissolved oxygen conditions in marine environments (Table *4*) and offer biological context for interpreting low oxygen values. Hypoxic conditions (dissolved oxygen levels of 1.4 ml/l (2.0mg/L; 62µmol/kg) or less) are known to have biological impacts, ranging from changes in behavior, decreased metabolic fitness to overall survival for some species (Chan et al., 2019; Vaquer-Sunyer and Duarte, 2008). In the absence of a species-specific comparative analyses of Oregon marine species sensitivities to the hypoxic threshold, global and regional datasets provide insight into how this threshold translates to likely biological response. In their global comparative analysis of species sensitivities to hypoxia, Vaquer-Sunyer and Duarte (2008) showed that the conventional benchmark of 1.4 ml/l (2.0mg/L) surpassed the lethal threshold for ~ 60% of organisms examined in their study, signifying the widespread effects of hypoxia on marine organisms across a wide range of taxa. Therefore, this value is the proposed numeric benchmark used to assess beneficial use support for fish and aquatic life and by which the measurable reduction would be evaluated. Global differences in crustacean sensitivity to hypoxia tolerance explored by Chu and Gale (2017) showed that Eastern Pacific Species are more tolerant of low oxygen conditions (based on metabolic limits) when compared with other ocean basins, with an average oxygen critical value of 0.88 ml/l (n: 58, 95% CI: 0.58-0.96 ml/l). This suggests that the conventional threshold of 1.4 may be more protective of crustaceans in the Eastern Pacific than compared with other oceans, but further regional analyses would improve this understanding. DEQ may revisit this benchmark in future IR cycles as scientific understanding of critical oxygen values and associated species responses in Oregon's territorial waters evolves.

Table 4. Marine dissolved oxygen biological impact benchmark table adapted from Chan et al. 2019.

Threshold class	Dissolved Oxygen threshold values	Biological impact examples associated with DO thresholds
Hypoxia	≤ 1.4 ml l^{-1}	Conventional threshold for biological impacts, though behavior, metabolism, and survival can be affected above the threshold depending on taxa
Severe Hypoxia	≤ 0.5 ml l^{-1}	Operationally defined threshold for impacts such as Dungeness crab mortality
Anoxia	= 0.0 ml l^{-1}	Zero oxygen

Defining natural background conditions

The purpose of Oregon's marine dissolved oxygen narrative criterion is to prevent *wastes or activities that may result in* measurable reductions of dissolved oxygen in marine waters based on the language "…no measurable reduction… *may be allowed*." To assess this narrative WQS, DEQ must identify a natural background condition from which the change is occurring. Changing ocean conditions are typically evaluated on decadal rather than yearly or seasonal scales (Chan et al, 2008). For this assessment, DEQ is proposing to define background conditions based on long-term observational data relevant to Oregon's territorial sea where it is available. DEQ will adapt methodologies outlined in peer reviewed literature to quantify change in marine DO where long-term data sets exist. Defining natural background conditions in this way will provide a comparison for recent observational data collected in these locations to quantify "measurable reduction". Additionally, DEQ will outline an approach to extrapolate background conditions defined in this way to other parts of the territorial sea, that would allow observational data to be compared with background conditions where long-term observational data does not exist. This extrapolation would rely on model output to define the background conditions for comparison purposes.

Chemical data metric

Oceanographic DO data is reported in a variety of common and transformable units. For assessment purposes, DEQ will convert DO measurements to ml/l to be consistent with commonly reported values. The degree of spatial, depth dependent, and seasonal variability in naturally occurring DO conditions requires a strategic approach to choosing suitable metrics that accurately summarize and describe conditions. Additionally, for historical data to be comparable with recent observational data, the chosen metric must allow for consistency between historical monitoring techniques and advanced observational data collection techniques used today. Rather than using a daily average as the metric to represent the water column, DEQ is proposing to use the 10th percentile value DO as the assessment metric from which to evaluate the frequency of exceedances of the biologically relevant benchmark. This metric is DEQ's preferred metric as it is a daily summary statistic that can be applied to both profile and continuous data, allows for comparison between observational data types with varying sampling depths and frequencies and it characterizes the lowest values in the water column where measurable reduction has been documented to occur.

Assessment and listing procedures

Data evaluation

For this assessment, DEQ will use biologically relevant hypoxia benchmarks defined above to determine a status category for a waterbody. Critical spatial and temporal assessment windows further define the applicability of the assessment methodology to the biological impact. Methods for determining reduction in DO from a background condition outside of natural variability are outlined below. The purpose of this section is to describe the critical assessment period, approach to determining background condition, and methods for determining impairment.

Critical assessment period

Seasonality of low DO conditions in Oregon's territorial sea during summer upwelling season, which is commonly defined as between May through September, is well described in the literature (**Figure 12**)(Harris et al., 2013; Pierce et al., 2012;

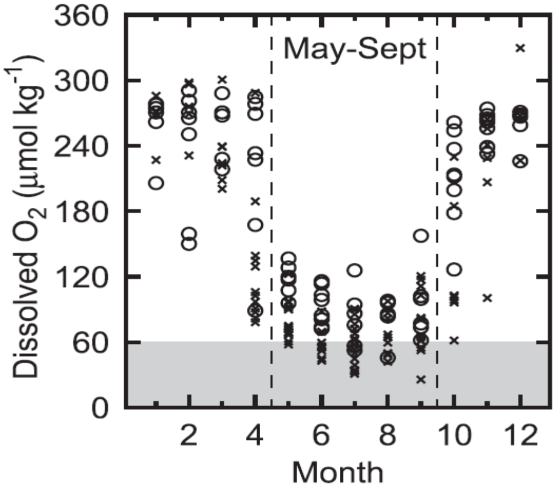


Figure 12. Figure from Pierce et al. 2012 showing prevalence of upwelling season (May- Sept) five miles offshore on the Newport Hydrographic Line.

Schwing et al., 2006). In recent years, increased variability in the onset and duration of the upwelling season have been reported, extending the upwelling conditions into the shoulder seasons in some years.[42] For this reason, DEQ will consider April through the end of September the critical assessment window for marine DO.

Quantifying change from background

Establishing background conditions for comparison purposes is a critical component of determining measurable reduction. Where available, DEQ will evaluate a measurable reduction based on observational data sets collected at consistent locations over multiple decades. In assessment units where this temporal coverage is not available, DEQ will rely on validated model output to quantify background conditions. DEQ may request guidance from technical workgroup members to interpret model performance for temporal, spatial and climatic variability.

Background based on observational data

Long term observational datasets can be found in some parts of Oregon's territorial sea. In these locations where data are of sufficient quality and quantity DEQ will determine natural background conditions to which comparisons can be made with recent observational data. DEQ will adapt methodologies outlined in published literature to quantifying shifts in marine DO relevant to Oregon's territorial waters such as Pierce et. al., (2012), Adams et al., (2013), and others. To account for sampling frequency and consistency limitations of historical observational datasets DEQ will develop background condition estimates for the entire upwelling season (May-Sept). Within this time frame, DEQ will develop a "background sample" of daily 10th percentile DO values as the historical period. This background sample will be compared with recently collected observational data, summarized as a series of daily 10th percentile values, using commonly applied statistical approaches as appropriate (such as two sample t-tests, Wilcox rank sum tests, and/or by anomaly analyses). DEQ will also consult with regional experts as needed to ensure adaptations to methodologies to satisfy the approach outlined in this document are appropriate based on data types and locations. Detailed summaries of the application of these methodologies and statistical approaches used will be provided in the assessment rationale portion of the IR.

Background based on model output

DEQ recognizes that the spatial extent of long-term observational data is limited, hindering the assessment of recently collected data in locations where long-term data sets do not exist. There

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[42] Spring Transition Dates and Fall Transition Dates | Columbia Basin Research (washington.edu)

is a high amount of spatial variability in observed conditions in nearshore environments, largely due to physical characteristics of the shelf (Siedlecki et al., 2015). This can be clearly observed if looking at a large amount of data collected during the same period (see Barth et al., in prep). To address this, DEQ has identified a series of high-level steps and requirements to help define how a historical to present shift based on observational data could be extrapolated to determine background conditions in other parts of the territorial sea using model output.

Step 1: Calculate a historical to present shift using long-term observational data relevant to Oregon's territorial sea where available – summarized within the entire critical assessment period (due to limited sampling frequency in long-term datasets):

Details outlined in the "Background based on observational data" section above.

Step 2: Apply the historical to present shift in Step A to other parts of the territorial sea – account for spatial variability in conditions:

a. Generate a map summarizing the spatial variability in the territorial sea for each month in the critical period. This would be the starting place for the model simulation.
b. Using model simulation, sample over many (recent) years to generate an average (or appropriate comparative statistic) of 10th percentile values across the modeled grid for each month during the critical assessment period of April through the end of September.
c. Average (or appropriate comparative statistic) 10th percentile values across the grid could be used to derive "background" values based on the historical to present shift calculated in Step A. In this calculation the assumption is that the shift (change) quantified using long-term observational data is relatively the same degree of change that has taken place in other parts of the territorial sea.

Step 3: "Background" values across the modeled grid can be compared with recent observational data to quantify measurable reduction of DO in locations where long-term data does not exist.

Evaluating the benchmark

DEQ is proposing to use the conventional hypoxia benchmark of 1.4 ml/l as a second line of evidence to determine whether measurable reduction is likely affecting aquatic life beneficial use support. Similar to the change from background line of evidence, a minimum of five unique vertical profiles will be required within each AU in order to conduct an assessment. Daily 10th percentile values will be generated for each profile, and those data will be pooled by assessment unit. Where greater than 10% of the daily statistic is less than or equal to 1.4 ml/l according to the exact binomial test, the water body would be considered impaired in combination with the first line of evidence.

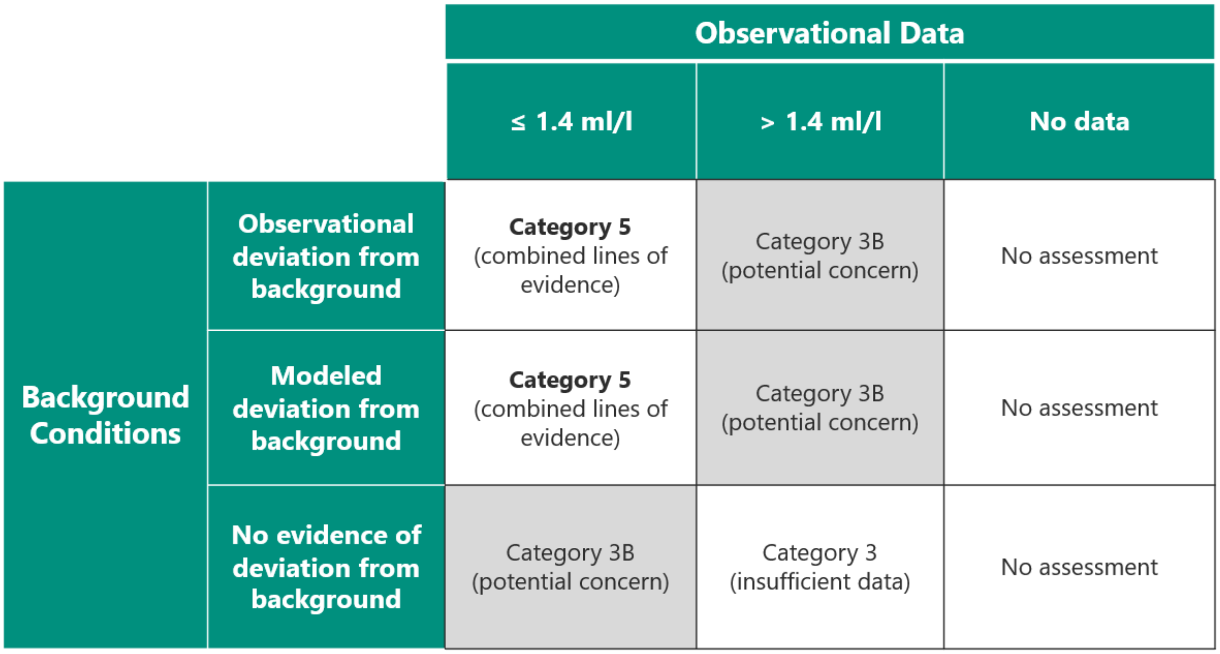
Data requirements

Currently, DEQ does not have a marine water quality monitoring program. Therefore, this assessment will be based on either readily available data or data submitted through the Call for Data. For data used in assessment, DEQ requires a project plan with widely approved methods are used for sample collection, analysis, and metrics calculation. A project plan should include a purpose statement, the number of samples collected, and quality assurance and quality control protocols for collecting and analyzing samples. In instances where a project plan is not readily available, such as in the case of historical data used to determine background conditions, DEQ will consult regional experts and published literature to determine whether data in question meets data quality objectives. Data quality decisions will be described in detail in the assessment rationale section of the IR.

Assignment of assessment categories

For the 2024 IR DEQ will be assessing water bodies for impacts to biological response as a result of increasing frequency and duration of nearshore hypoxic events and will therefore be evaluating Category 5 and 3 (**Table 1**). Without a clear understanding of what values levels of dissolved oxygen in marine waters equate to the beneficial use being fully supporting, DEQ will not be assessing for attainment. The hybrid framework for hypoxia in marine waters assessment (**Figure 13**) and flowchart for assigning assessment categories **(Figure 14**) outline how DEQ will assess data for categorical determination. A more detailed description of categorical assignment can be found in the Hypoxia Marine Waters Assessment Procedure document (link to come).

It is important to note that the two lines of evidence outlined in the hybrid framework are not the only lines of evidence DEQ will consider in marine DO narrative criteria assessment. DEQ acknowledges that impairment determinations can be made based overwhelming evidence where multiple sources of data and/or information indicate impairment. This may include the documented periods of prolonged anoxia tied to biological impact or the use of some combination of observational data, published literature, and best professional judgment to interpreting data and information submitted to the agency for assessment purposes. If this approach is taken, a detailed rationale will be included in the Integrated Report.



		Observational Data		
		≤ 1.4 ml/l	**> 1.4 ml/l**	**No data**
Background Conditions	**Observational deviation from background**	**Category 5** (combined lines of evidence)	Category 3B (potential concern)	No assessment
	Modeled deviation from background	**Category 5** (combined lines of evidence)	Category 3B (potential concern)	No assessment
	No evidence of deviation from background	Category 3B (potential concern)	Category 3 (insufficient data)	No assessment

Figure 13. Proposed assessment framework for hypoxia in marine waters. 10th percentile values are the daily summary statistic used in this assessment framework.

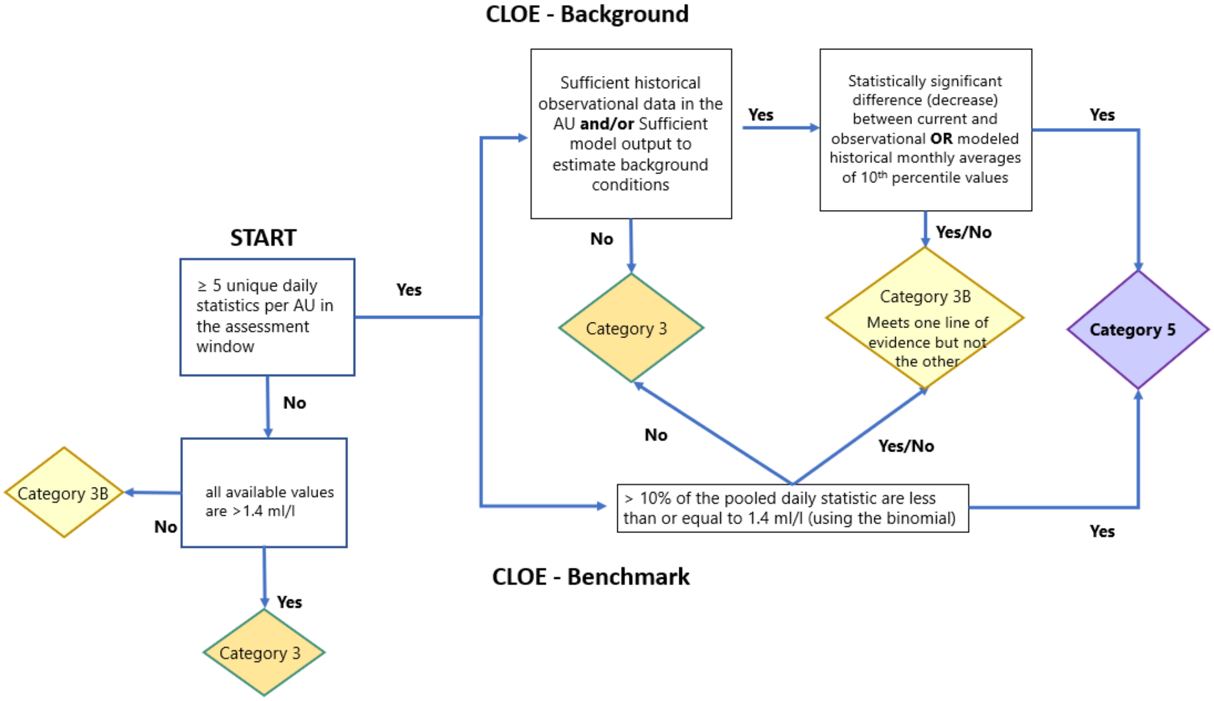


Figure 14. Flowchart for assigning assessment categories.

DELISTING – NEW DATA

Without a pathway to attainment DEQ will evaluate potential delisting on a case-by-case basis.

Future directions

DEQ is using the hybrid approach outlined in this document to assess narrative criteria in marine waters. For OA biocriteria assessment, DEQ will use biological (percentage of individuals with severe shell dissolution) and/or chemical (Ω_{ar}) metrics as the *primary* means of assessing likely impact to pteropods in Oregon's territorial waters. DEQ will use the approach outlined in the marine dissolved oxygen section as the *primary* means of interpreting Oregon's Marine DO narrative WQS.

However, a narrative implementation of a water quality standard does not allow DEQ to require a specific type of analysis or assessment; rather, to allow for various other forms of data to also be used to assess the narrative standard. It is entirely appropriate for a different bioassessment tool to be used to validate or refute a biocriteria listing. However, DEQ reserves the right to review the assessment tool for methodological and statistical rigor and may or may not approve of its use in making an impairment determination. In addition, DEQ is authorized to use other methods of evaluation to assess organism condition, or other ecosystem attributes relevant to biocriteria, so long as natural background conditions can be established to determine whether impact is taking place outside of natural ecosystem variability.

DEQ expects this assessment methodology will be revised to reflect evolving science used to determine policy decisions. It is important to note that given the improvements to the biocriteria and marine DO methodologies that DEQ is undertaking, biological and chemical benchmarks outlined in this document are subject to change in future assessment methodology cycles. To that end, DEQ has gathered recommendations from workgroup participants on key analyses and next steps to build upon and refine the existing assessment methodologies for OA and marine DO for future integrated report cycles.

References

Adams, K.A., Barth, J.A., Chan, F., 2013. Temporal variability of near-bottom dissolved oxygen during upwelling off central Oregon. Journal of Geophysical Research: Oceans 118, 4839–4854. https://doi.org/10.1002/jgrc.20361

Adams, K.A., Barth, J.A., Shearman, R.K., 2016. Intraseasonal Cross-Shelf Variability of Hypoxia along the Newport, Oregon, Hydrographic Line. Journal of Physical Oceanography 46, 2219–2238. https://doi.org/10.1175/JPO-D-15-0119.1

Alin, S.R., Feely, R.A., Dickson, A.G., Hernández-Ayón, J.M., Juranek, L.W., Ohman, M.D., Goericke, R., 2012. Robust empirical relationships for estimating the carbonate system in the southern California Current System and application to CalCOFI hydrographic cruise data (2005–2011). Journal of Geophysical Research: Oceans 117. https://doi.org/10.1029/2011JC007511

Armstrong, J.L., Boldt, J.L., Cross, A.D., Moss, J.H., Davis, N.D., Myers, K.W., Walker, R.V., Beauchamp, D.A., Haldorson, L.J., 2005. Distribution, size, and interannual, seasonal and diel food habits of northern Gulf of Alaska juvenile pink salmon, Oncorhynchus gorbuscha. Deep Sea Research Part II: Topical Studies in Oceanography, U.S. GLOBEC Biological and Physical Studies of Plankton, Fish and Higher Trophic Level Production, Distribution, and Variability in the Northeast Pacific 52, 247–265. https://doi.org/10.1016/j.dsr2.2004.09.019

Arroyo, M.C., Fassbender, A.J., Carter, B.R., Edwards, C.A., Fiechter, J., Norgaard, A., Feely, R.A., 2022. Dissimilar Sensitivities of Ocean Acidification Metrics to Anthropogenic Carbon Accumulation in the Central North Pacific Ocean and California Current Large Marine Ecosystem. Geophysical Research Letters 49, e2022GL097835. https://doi.org/10.1029/2022GL097835

Aydin, K.Y., McFarlane, G.A., King, J.R., Megrey, B.A., Myers, K.W., 2005. Linking oceanic food webs to coastal production and growth rates of Pacific salmon (Oncorhynchus spp.), using models on three scales. Deep Sea Research Part II: Topical Studies in Oceanography, Linkages between coastal and open ocean ecosystems 52, 757–780. https://doi.org/10.1016/j.dsr2.2004.12.017

Barton, A., Hales, B., Waldbusser, G.G., Langdon, C., Feely, R.A., 2012. The Pacific oyster, Crassostrea gigas, shows negative correlation to naturally elevated carbon dioxide levels: Implications for near-term ocean acidification effects. Limnology and Oceanography 57, 698–710. https://doi.org/10.4319/lo.2012.57.3.0698

Barton, A., Waldbusser, G.G., Feely, R.A., Weisberg, S.B., Newton, J.A., Hales, B., Cudd, S., Eudeline, B., Langdon, C.J., Jefferds, I., King, T., Suhrbier, A., McLaughlin, K., 2015. Impacts of

Coastal Acidification on the Pacific Northwest Shellfish Industry and Adaptation Strategies Implemented in Response. Oceanography 28, 146–159.

Bednaršek, N., Ambrose, R., Calosi, P., Childers, R.K., Feely, R.A., Litvin, S.Y., Long, W.C., Spicer, J.I., Štrus, J., Taylor, J., Kessouri, F., Roethler, M., Sutula, M., Weisberg, S.B., 2021a. Synthesis of Thresholds of Ocean Acidification Impacts on Decapods. Frontiers in Marine Science 8, 1542. https://doi.org/10.3389/fmars.2021.651102

Bednaršek, N., Calosi, P., Feely, R.A., Ambrose, R., Byrne, M., Chan, K.Y.K., Dupont, S., Padilla-Gamiño, J.L., Spicer, J.I., Kessouri, F., Roethler, M., Sutula, M., Weisberg, S.B., 2021b. Synthesis of Thresholds of Ocean Acidification Impacts on Echinoderms. Front. Mar. Sci. 8, 602601. https://doi.org/10.3389/fmars.2021.602601

Bednaršek, N., Feely, R.A., Beck, M.W., Alin, S.R., Siedlecki, S.A., Calosi, P., Norton, E.L., Saenger, C., Štrus, J., Greeley, D., Nezlin, N.P., Roethler, M., Spicer, J.I., 2020. Exoskeleton dissolution with mechanoreceptor damage in larval Dungeness crab related to severity of present-day ocean acidification vertical gradients. Science of The Total Environment 716, 136610. https://doi.org/10.1016/j.scitotenv.2020.136610

Bednaršek, N., Feely, R.A., Beck, M.W., Glippa, O., Kanerva, M., Engström-Öst, J., 2018. El Niño-Related Thermal Stress Coupled With Upwelling-Related Ocean Acidification Negatively Impacts Cellular to Population-Level Responses in Pteropods Along the California Current System With Implications for Increased Bioenergetic Costs. Front. Mar. Sci. 5, 486. https://doi.org/10.3389/fmars.2018.00486

Bednaršek, N., Feely, R.A., Howes, E.L., Hunt, B.P.V., Kessouri, F., León, P., Lischka, S., Maas, A.E., McLaughlin, K., Nezlin, N.P., Sutula, M., Weisberg, S.B., 2019. Systematic Review and Meta-Analysis Toward Synthesis of Thresholds of Ocean Acidification Impacts on Calcifying Pteropods and Interactions With Warming. Frontiers in Marine Science 6, 227. https://doi.org/10.3389/fmars.2019.00227

Bednaršek, N., Feely, R.A., Reum, J.C.P., Peterson, B., Menkel, J., Alin, S.R., Hales, B., 2014a. Limacina helicina shell dissolution as an indicator of declining habitat suitability owing to ocean acidification in the California Current Ecosystem. Proceedings of the Royal Society B: Biological Sciences 281, 20140123. https://doi.org/10.1098/rspb.2014.0123

Bednaršek, N., Feely, R.A., Tolimieri, N., Hermann, A.J., Siedlecki, S.A., Waldbusser, G.G., McElhany, P., Alin, S.R., Klinger, T., Moore-Maley, B., Pörtner, H.O., 2017a. Exposure history determines pteropod vulnerability to ocean acidification along the US West Coast. Sci Rep 7, 4526. https://doi.org/10.1038/s41598-017-03934-z

Bednaršek, N., Harvey, C.J., Kaplan, I.C., Feely, R.A., Možina, J., 2016. Pteropods on the edge: Cumulative effects of ocean acidification, warming, and deoxygenation. Progress in Oceanography 145, 1–24. https://doi.org/10.1016/j.pocean.2016.04.002

Bednaršek, N., Klinger, T., Harvey, C.J., Weisberg, S., McCabe, R.M., Feely, R.A., Newton, J., Tolimieri, N., 2017b. New ocean, new needs: Application of pteropod shell dissolution as a biological indicator for marine resource management. Ecological Indicators 76, 240–244. https://doi.org/10.1016/j.ecolind.2017.01.025

Bednaršek, N., Tarling, G.A., Bakker, D.C., Fielding, S., Cohen, A., Kuzirian, A., McCorkle, D., Lézé, B., Montagna, R., 2012a. Description and quantification of pteropod shell dissolution: a sensitive bioindicator of ocean acidification. Global Change Biology 18, 2378–2388. https://doi.org/10.1111/j.1365-2486.2012.02668.x

Bednaršek, N., Tarling, G.A., Bakker, D.C.E., Fielding, S., Feely, R.A., 2014b. Dissolution Dominating Calcification Process in Polar Pteropods Close to the Point of Aragonite Undersaturation. PLOS ONE 9, e109183. https://doi.org/10.1371/journal.pone.0109183

Bednaršek, N., Tarling, G.A., Bakker, D.C.E., Fielding, S., Jones, E.M., Venables, H.J., Ward, P., Kuzirian, A., Lézé, B., Feely, R.A., Murphy, E.J., 2012b. Extensive dissolution of live pteropods in the Southern Ocean. Nature Geosci 5, 881–885. https://doi.org/10.1038/ngeo1635

Boehm, A., Jacobson, M., O'Donnell, M., Sutula, M., Wakefield, W.W., Weisberg, S., Whiteman, E., 2015. Ocean Acidification Science Needs for Natural Resource Managers of the North American West Coast. oceanog 25, 170–181. https://doi.org/10.5670/oceanog.2015.40

Chan, F., Barth, J.A., Blanchette, C.A., Byrne, R.H., Chavez, F., Cheriton, O., Feely, R.A., Friederich, G., Gaylord, B., Gouhier, T., Hacker, S., Hill, T., Hofmann, G., McManus, M.A., Menge, B.A., Nielsen, K.J., Russell, A., Sanford, E., Sevadjian, J., Washburn, L., 2017. Persistent spatial structuring of coastal ocean acidification in the California Current System. Sci Rep 7, 2526. https://doi.org/10.1038/s41598-017-02777-y

Chan, F., Barth, J.A., Kroeker, K.J., Lubchenco, J., Menge, B.A., 2019. THE DYNAMICS AND IMPACT OF OCEAN ACIDIFICATION AND HYPOXIA: Insights from Sustained Investigations in the Northern California Current Large Marine Ecosystem. Oceanography 32, 62–71.

Chan, F., Barth, J.A., Lubchenco, J., Kirincich, A., Weeks, H., Peterson, W.T., Menge, B.A., 2008. Emergence of Anoxia in the California Current Large Marine Ecosystem. Science 319, 920–920. https://doi.org/10.1126/science.1149016

Chavez, F.P., Pennington, J.T., Michisaki, R.P., Blum, M., Chavez, G.M., Friederich, J., Jones, B., Herlien, R., Kieft, B., Hobson, B., Ren, A.S., Ryan, J., Sevadjian, J.C., Wahl, C., Walz, K.R., Yamahara, K., Friederich, G.E., Messié, M., 2017. Climate Variability and Change: Response of a Coastal Ocean Ecosystem. Oceanography 30, 128–145.

Childress, J.J., Seibel, B.A., 1998. Life at Stable low Oxygen Levels: Adaptations of Animals to Oceanic Oxygen Minimum Layers. Journal of Experimental Biology 201, 1223–1232. https://doi.org/10.1242/jeb.201.8.1223

Chu, J.W.F., Gale, K.S.P., 2017. Ecophysiological limits to aerobic metabolism in hypoxia determine epibenthic distributions and energy sequestration in the northeast Pacific ocean. Limnology and Oceanography 62, 59–74. https://doi.org/10.1002/lno.10370

Deutsch, C., Ferrel, A., Seibel, B., Pörtner, H.-O., Huey, R.B., 2015. Climate change tightens a metabolic constraint on marine habitats. Science 348, 1132–1135. https://doi.org/10.1126/science.aaa1605

Deutsch, C., Penn, J.L., Seibel, B., 2020. Metabolic trait diversity shapes marine biogeography. Nature 585, 557–562. https://doi.org/10.1038/s41586-020-2721-y

Dickson, A., 2010. The carbon dioxide system in seawater: Equilibrium chemistry and measurements. Guide to Best Practices for Ocean Acidification Research and Data Reporting 17–40.

Dickson, A.G., Sabine, C.L., Christian, J.R., Bargeron, C.P., North Pacific Marine Science Organization (Eds.), 2007. Guide to best practices for ocean CO2 measurements, PICES special publication. North Pacific Marine Science Organization, Sidney, BC.

Fabry, V.J., 1990. Shell growth rates of pteropod and heteropod molluscs and aragonite production in the open ocean: Implications for the marine carbonate system. Journal of Marine Research 48, 209–222. https://doi.org/10.1357/002224090784984614

Feely, R.A., Alin, S.R., Carter, B., Bednaršek, N., Hales, B., Chan, F., Hill, T.M., Gaylord, B., Sanford, E., Byrne, R.H., Sabine, C.L., Greeley, D., Juranek, L., 2016. Chemical and biological impacts of ocean acidification along the west coast of North America. Estuarine, Coastal and Shelf Science 183, 260–270. https://doi.org/10.1016/j.ecss.2016.08.043

Feely, R.A., Okazaki, R.R., Cai, W.-J., Bednaršek, N., Alin, S.R., Byrne, R.H., Fassbender, A., 2018. The combined effects of acidification and hypoxia on pH and aragonite saturation in the coastal waters of the California current ecosystem and the northern Gulf of Mexico. Continental Shelf Research 152, 50–60. https://doi.org/10.1016/j.csr.2017.11.002

Feely, R.A., Sabine, C.L., Hernandez-Ayon, J.M., Ianson, D., Hales, B., 2008. Evidence for Upwelling of Corrosive "Acidified" Water onto the Continental Shelf. Science. https://doi.org/10.1126/science.1155676

Gilly, W.F., Beman, J.M., Litvin, S.Y., Robison, B.H., 2013. Oceanographic and biological effects of shoaling of the oxygen minimum zone. Ann Rev Mar Sci 5, 393–420. https://doi.org/10.1146/annurev-marine-120710-100849

Grantham, B.A., Chan, F., Nielsen, K.J., Fox, D.S., Barth, J.A., Huyer, A., Lubchenco, J., Menge, B.A., 2004. Upwelling-driven nearshore hypoxia signals ecosystem and oceanographic changes in the northeast Pacific. Nature 429, 749–754. https://doi.org/10.1038/nature02605

Hales, B., Karp-Boss, L., Perlin, A., Wheeler, P.A., 2006. Oxygen production and carbon sequestration in an upwelling coastal margin. Global Biogeochemical Cycles 20. https://doi.org/10.1029/2005GB002517

Harris, K.E., DeGrandpre, M.D., Hales, B., 2013. Aragonite saturation state dynamics in a coastal upwelling zone. Geophysical Research Letters 40, 2720–2725. https://doi.org/10.1002/grl.50460

Huyer, A., 1983. Coastal upwelling in the California current system. Progress in Oceanography 12, 259–284. https://doi.org/10.1016/0079-6611(83)90010-1

Juranek, L.W., Feely, R.A., Peterson, W.T., Alin, S.R., Hales, B., Lee, K., Sabine, C.L., Peterson, J., 2009. A novel method for determination of aragonite saturation state on the continental shelf of central Oregon using multi-parameter relationships with hydrographic data. Geophysical Research Letters 36. https://doi.org/10.1029/2009GL040778

Karpenko, V., Volkov, A., Koval, M., 2007. Diets of Pacific Salmon in the Sea of Okhotsk, Bearing Sea, and Northwest Pacific Ocean. North Pac Anadromous Fish Commission Bull 4.

Knecht, N.S., Benedetti, F., Hofmann, U., Bednaršek, N., Chaabane, S., Weerd, C. de, Peijnenburg, K., Schiebel, R., Vogt, M., 2023. The impact of zooplankton calcifiers on the marine carbon cycle (preprint). Preprints. https://doi.org/10.22541/essoar.167283650.05543210/v1

Lalli, C.M., Gilmer, R.W., 1989. Pelagic Snails: The Biology of Holoplanktonic Gastropod Mollusks. Stanford University Press.

Laruelle, G.G., Cai, W.-J., Hu, X., Gruber, N., Mackenzie, F.T., Regnier, P., 2018. Continental shelves as a variable but increasing global sink for atmospheric carbon dioxide. Nat Commun 9, 454. https://doi.org/10.1038/s41467-017-02738-z

Lischka, S., Büdenbender, J., Boxhammer, T., Riebesell, U., 2011. Impact of ocean acidification and elevated temperatures on early juveniles of the polar shelled pteropod *Limacina helicina*: mortality, shell degradation, and shell growth. Biogeosciences 8, 919–932. https://doi.org/10.5194/bg-8-919-2011

Lischka, S., Riebesell, U., 2012. Synergistic effects of ocean acidification and warming on overwintering pteropods in the Arctic. Global Change Biology 18, 3517–3528. https://doi.org/10.1111/gcb.12020

McLaughlin, K., Weisberg, S., Dickson, A., Hofmann, G., Newton, J., Aseltine-Neilson, D., Barton, A., Cudd, S., Feely, R., Jefferds, I., Jewett, E., King, T., Langdon, C., McAfee, S., Pleschner-Steele, D., Steele, B., 2015. Core Principles of the California Current Acidification Network: Linking Chemistry, Physics, and Ecological Effects. oceanog 25, 160–169. https://doi.org/10.5670/oceanog.2015.39

Osborne, E.B., Thunell, R.C., Gruber, N., Feely, R.A., Benitez-Nelson, C.R., 2020. Decadal variability in twentieth-century ocean acidification in the California Current Ecosystem. Nat. Geosci. 13, 43–49. https://doi.org/10.1038/s41561-019-0499-z

Osborne, E.B., Thunell, R.C., Marshall, B.J., Holm, J.A., Tappa, E.J., Benitez-Nelson, C., Cai, W.-J., Chen, B., 2016. Calcification of the planktonic foraminifera Globigerina bulloides and carbonate ion concentration: Results from the Santa Barbara Basin. Paleoceanography 31, 1083–1102. https://doi.org/10.1002/2016PA002933

Peterson, J.O., Morgan, C.A., Peterson, W.T., Lorenzo, E.D., 2013. Seasonal and interannual variation in the extent of hypoxia in the northern California Current from 1998–2012. Limnology and Oceanography 58, 2279–2292. https://doi.org/10.4319/lo.2013.58.6.2279

Pierce, S.D., Barth, J.A., Shearman, R.K., Erofeev, A.Y., 2012. Declining Oxygen in the Northeast Pacific. Journal of Physical Oceanography 42, 495–501. https://doi.org/10.1175/JPO-D-11-0170.1

Sato, K.N., Andersson, A.J., Day, J.M.D., Taylor, J.R.A., Frank, M.B., Jung, J.-Y., McKittrick, J., Levin, L.A., 2018. Response of Sea Urchin Fitness Traits to Environmental Gradients Across the Southern California Oxygen Minimum Zone. Frontiers in Marine Science 5.

Sato, K.N., Levin, L.A., Schiff, K., 2017. Habitat compression and expansion of sea urchins in response to changing climate conditions on the California continental shelf and slope (1994–2013). Deep Sea Research Part II: Topical Studies in Oceanography 137, 377–389. https://doi.org/10.1016/j.dsr2.2016.08.012

Schwing, F.B., Bond, N.A., Bograd, S.J., Mitchell, T., Alexander, M.A., Mantua, N., 2006. Delayed coastal upwelling along the U.S. West Coast in 2005: A historical perspective. Geophysical Research Letters 33. https://doi.org/10.1029/2006GL026911

Siedlecki, S.A., Banas, N.S., Davis, K.A., Giddings, S., Hickey, B.M., MacCready, P., Connolly, T., Geier, S., 2015. Seasonal and interannual oxygen variability on the Washington and Oregon continental shelves. Journal of Geophysical Research: Oceans 120, 608–633. https://doi.org/10.1002/2014JC010254

Vaquer-Sunyer, R., Duarte, C.M., 2008. Thresholds of hypoxia for marine biodiversity. Proceedings of the National Academy of Sciences 105, 15452–15457. https://doi.org/10.1073/pnas.0803833105

Waldbusser, G.G., Hales, B., Langdon, C.J., Haley, B.A., Schrader, P., Brunner, E.L., Gray, M.W., Miller, C.A., Gimenez, I., 2015. Saturation-state sensitivity of marine bivalve larvae to ocean acidification. Nature Clim Change 5, 273–280. https://doi.org/10.1038/nclimate2479

Weisberg, S.B., Bednaršek, N., Feely, R.A., Chan, F., Boehm, A.B., Sutula, M., Ruesink, J.L., Hales, B., Largier, J.L., Newton, J.A., 2016. Water quality criteria for an acidifying ocean: Challenges and opportunities for improvement. Ocean & Coastal Management 126, 31–41. https://doi.org/10.1016/j.ocecoaman.2016.03.010