Scientific Assessment for the British Columbia Ocean Acidification and Hypoxia Action Plan

February 14, 2023

About this document

This scientific assessment provides the necessary context and supporting information for the recommended actions within the British Columbia Ocean Acidification and Hypoxia Action Plan (the "BC OAH Action Plan"). Herein are descriptions of key information obtained through a BC OAH Action Plan workshop series including the state of knowledge for the manifestation of OAH in BC coastal waters and the biological impacts to BC marine species. Details are also provided on OAH adaptation and mitigation, as well as the information needs for the emerging interface between OAH and marine carbon dioxide removal. Gaps exist in all areas of OAH research in BC – particularly with regard to collaboration, coordination, and understanding of OAH manifestations (*e.g.*, on management-relevant forecast timeframes from models, for rates of change from observations in coastal waters, and on biological impacts on many economically and culturally important species). The recommendations within the BC OAH Action Plan target the gaps and needs identified in this report. It is the view of the authors that this report, and the accompanying BC OAH Action Plan, represent a significant step by the Province of British Columbia to address OAH. As an endorsed project for the Ocean Acidification Research for Sustainability program under the United Nations Decade of Ocean Science for Sustainable Development ("the Ocean Decade"), this scientific assessment should serve as a baseline for gauging progress made over the coming years in implementing recommendations provided within the BC OAH Action Plan.

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Acronyms and Glossary

Adaptation - activities designed to help ecosystems and human communities adapt to a changing climate including increasing manifestations of ocean acidification and hypoxia.

Alkalinity - a commonly measured property of seawater that is roughly proportional to its buffering capacity. Seawater with higher alkalinity will have higher pH and more capacity to absorb CO_2 for the same TCO_2.

Anaerobic pathways - Metabolic reactions occurring in the absence of free oxygen.

Anoxic - effectively zero oxygen concentration.

Antagonistic, synergistic or additive effects - Modes of interaction among multiple stressors. Antagonistic: Combined effects less than responses to single stressors. Additive: Combined effects equal to the sum of responses to single stressors. Synergistic: Combined effects more than the sum of responses to single stressors.

Anthropogenic - originating from human activity.

Aragonite - one of the crystalline forms of calcium carbonate.

Autotrophs – an organism that uses inorganic carbon to produce its own organic matter.

Bioaccumulation - Gradual build-up of substances, such as pollutants, heavy-metals or other chemicals, in an organism.

Biocalcification - Type of biomineralization process that involves the formation and subsequent accumulation of calcium carbonate minerals mediated by organisms to form hard structures such as shells.

Biogeochemistry - The science of the cycling of chemical elements in the environment and their transformation by both biotic and abiotic processes.

Blue carbon (BC) - organic carbon captured and stored in coastal and marine ecosystems, such as seagrass meadows, tidal marshes and mangrove forests (collectively called Blue Carbon Ecosystems - BCEs).

Buffering - chemical conditions that accommodate the absorption of acid (or CO_2) with little change in pH. Well buffered seawater will experience a smaller change in pH compared to weakly-buffered seawater (*i.e.*, low alkalinity) for the same input of anthropogenic CO_2.

Calcite - one of the crystalline forms of calcium carbonate.

Calcium carbonate - Calcium carbonate ($CaCO_3$) minerals are present in the shells and exoskeletons of many marine organisms. The shells of oysters and clams are the most familiar examples. The two primary forms of calcium carbonate are calcite and aragonite.

BC CAS - British Columbia Climate Action Secretariat.

Cellular acid-base regulation - Collection of molecular and physiological processes that maintain intracellular and extracellular pH levels in the narrow ranges optimal for organisms.

Cellular signal pathways - Biochemical mechanisms that allow organismal cells to receive, process, and transmit information with its environment and with itself and to respond to external stimuli.

CIOOS - Canadian Integrated Ocean Observing System.

CO_2 - Carbon dioxide.

CO_3^{2-} - carbonate ion.

Coastal communities - a group with a direct interest in coastal marine activities.

Complex life cycle - Organisms with multiple discrete life stages that differ in form or function and often occupy different ecological niches (*e.g.*, swimming larval phase versus sessile adult stage).

Decision-makers - those responsible for assessing situations and implementing management or policy decisions.

Deep water renewal - natural exchanges of deep water between the open ocean and semi-enclosed basins including inlets and fjords.

Density surface - an interior layer of the ocean associated with a particular seawater density (*e.g.,* 1026 kg/m^3). Seawater density almost always increases with depth. Also called an isopycnal.

Deoxygenation - the global trend toward lower concentration of oxygen in the ocean interior, caused by increasing surface temperature and stratification.

DFO - Fisheries and Oceans Canada.

Dissociation constant - a measure of the propensity of a chemical compound to separate (dissociate) reversibly into its components (e.g., HCO_3^- dissociates to H^+ and CO_3^{2-}).

Dissolution - dissolving of (*e.g.*, calcium carbonate) minerals; dissolution of $CaCO_3$ is favoured in seawater with low carbonate ion concentration.

Downscaling - Using a high-resolution regional model to simulate future climates at scales that cannot be resolved by global climate models, using the climate model output to force the regional model at the boundaries. Downscaling models are frequently ocean-only or atmosphere-only but can also include regional high-resolution coupled ocean-atmosphere models.

FTE - Full time equivalent.

Heterotroph - an organism that consumes organic carbon for energy and nutrients.

H_2CO_3 - carbonic acid.

HCO_3^- - bicarbonate ion.

Homeostasis - the tendency toward a stable equilibrium between interdependent elements, especially as maintained by physiological processes.

Hypoxia - low concentrations (<60 μmol O_2/kg seawater) of dissolved oxygen that negatively affect most macrofauna such as fish.

Immune responses - Physiological processes that prevent infection and defend an organism from disease.

Inorganic carbon - 'free' carbon compounds such as CO_2 and HCO_3^-.

MAF - Ministry of Agriculture and Food (British Columbia).

Marine CO_2 removal - engineering solutions that involve marine environments for the removal of carbon dioxide from the atmosphere.

MENV - Ministry of Environment and Climate Change Strategy (British Columbia).

MEOPAR - The Marine Environmental Observation, Prediction and Response Network.

Metabolism - chemical reactions in cells that change food into energy.

Mitigation - activities directed at reducing the effects of present and future climate change, *e.g.*, by reducing CO_2 emissions or enhancing the sinks for greenhouse gases, which includes the reduction of seawater CO_2 content for the benefit of marine calcifiers.

Monitoring or time series - long-term data collection as part of an observing program.

Natural Climate Solutions (NCS) - conservation and management actions that enhance natural processes to reduce greenhouse gas (GHG) emissions and harness the potential of natural processes to sequester atmospheric carbon dioxide.

Negative emissions technologies - technologies that remove carbon dioxide from the atmosphere.

Net ecosystem production - the total amount of organic carbon produced by autotrophs minus the respiration by all organisms within the marine environment.

Net primary production – the total amount of organic carbon produced by autotrophs in the marine environment minus the autotrophs' own respiration.

NOAA - National Oceanic and Atmospheric Administration (U.S.).

Numerical model - Mathematical equations representing physical and biological processes translated into computer code and implemented on large computer systems; usually involves mapping of properties like temperature or oxygen concentration onto a grid of discrete points spaced 1-100 km apart.

Observing - activity to directly measure ocean conditions.

Ontogenic - Related to the development of an individual organism or a part of an organism from fertilization of the egg to adult.

Organic carbon - carbon compounds derived from living tissue (*e.g.*, proteins and carbohydrates).

Organic matter remineralization - the decomposition of organic matter by organisms, which often involves the consumption of oxygen (O_2) and results in the release of inorganic nutrients and CO_2.

Oxyconformer - Organism whose oxygen consumption rate is dependent on ambient oxygen levels.

Oxyregulator - Organism able to maintain their oxygen consumption rates independently of ambient oxygen levels.

pCO_2 - Carbon dioxide partial pressure, a measure of aqueous CO_2 concentration relative to the solubility of CO_2.

pH - a logarithmic measure of hydrogen ion content, indicating acidic ($pH < 7$) or basic ($pH > 7$) conditions.

Photosynthesis - the process by which organisms (*e.g.,* marine algae) use sunlight, water, and carbon dioxide to create oxygen and organic matter.

Policy-makers - those who draft and write government policy.

Precipitation - the formation of (*e.g.*, calcium carbonate) minerals; precipitation of $CaCO_3$ is favoured in seawater with high carbonate ion concentration.

Resilience - the ability and capacity to anticipate, prepare for, and respond quickly to hazardous events, trends, or disturbances related to climate change.

Respiration - the process of breathing in (utilizing) oxygen and exhaling carbon dioxide.

Restorative aquaculture - commercial or subsistence aquaculture that provides direct ecological benefits to the environment.

Saturation state (for aragonite or calcite) - a ratio of the product of *in situ* concentrations of carbonate and calcium ions over the solubility product of a particular calcium carbonate mineral, for example aragonite. The solubility product is an equilibrium constant for a solid in solution, which varies as a function of temperature, salinity, and pressure. Higher values (above 1) favour precipitation, while values below 1 favour dissolution.

Sequestration - long-term storage of carbon, isolated from exchange with the atmosphere.

Skill - Measures of how well models reproduce the observed state of a system.

Solubility product - an equilibrium constant for precipitation/dissolution of solid $CaCO_3$, which varies as a function of temperature, salinity, and pressure**.**

Stakeholders - any non-governmental sector of society with a stake in the marine environment.

TCO_2 or DIC - total dissolved inorganic carbon (aqueous CO_2 + bicarbonate + carbonate).

Upwelling/Downwelling - physical processes that transport ocean waters vertically. For example, coastal upwelling off Vancouver Island brings cold, nutrient-rich subsurface waters to the surface in summer.

Ventilation - exposure to the atmosphere-ocean boundary, allowing exchange of gases and heat, and the transport of surface waters into the ocean interior, replenishing interior ocean waters with oxygen.

μmol/kg - molecular concentration, micro (10^{-6}) mole per kilogram of seawater.

British Columbia's focus on climate change, ocean acidification, and the emergence of an ocean acidification and hypoxia action plan

Climate change is impacting British Columbia (BC) in a number of ways including receding glaciers, increasing temperatures, intensifying wildfires, and a changing ocean environment. These manifestations of climate change are the result of a common driver - the input of carbon dioxide (CO_2) and other greenhouse gases to the atmosphere from human activity. Provincial leadership made important steps to help address the driver of climate change in 2018 by legislating the *Climate Change Accountability Act* and establishing the *CleanBC* plan. The *Climate Change Accountability Act* amended and renamed the *Greenhouse Gas Reductions Target Act* of 2007, and set new emission targets for 2030, 2040, and 2050. These targets are 40%, 60%, and 80% reductions in greenhouse gas emissions relative to 2007 levels. The *CleanBC* plan is the Provincial Government's roadmap to achieve these emission targets.

Also in 2018, the BC Auditor General released a report, *Managing Climate Change Risks: An Independent Audit*, that detailed how the government of BC had not comprehensively assessed climate change risks to the province. The Auditor General's report highlighted that both mitigation and adaptation are needed for BC to increase resilience to climate change.

In response to the Auditor General's report, the Climate Action Secretariat (CAS) within the BC Ministry of Environment and Climate Change Strategy (MENV) completed a *Preliminary Strategic Climate Risk Assessment for British Columbia* in 2019, which was the first report of its kind in Canada that examined provincial-scale climate risks. This assessment identified ocean acidification's potential impact on fisheries and aquaculture as an immediate high-risk threat in need of further evaluation to understand impacts across species, ecosystems, and services provided by the marine environment. According to this report, direct and indirect economic consequences to the fish and shellfish industry alone could exceed $100 million, and the cost to the government, including lost revenue as well as programs to help the shellfish industry cope with ocean acidification, could be up to $375 million.

BC's *Climate Change Accountability Act* was amended in 2019 to add an interim emission target for 2025 of a 16% reduction relative to 2007, and to enhance annual reporting that integrates climate change risks and adaptation. Following this, the annual *Climate Change Accountability Report* to the BC legislature in 2019 and 2020 both highlighted ocean acidification as an important threat to be addressed within the *Climate Preparedness and Adaptation Strategy* produced by CAS.

In 2021, BC released the *Roadmap to 2030* and the draft *Climate Preparedness and Adaptation Strategy*. The *Roadmap to 2030* built on the *CleanBC* plan with enhanced measures to help ensure emission targets are met, including the potential use of negative emissions technologies to offset emissions in hard-to-decarbonize industries. In the ocean environment, these technological measures are termed marine CO_2 removal approaches. The *Climate Preparedness and Adaptation Strategy* laid out actions needed to elevate the province to a state of greater resilience, including the development of an ocean acidification action plan. The draft *Climate Preparedness and Adaptation Strategy* was updated in 2022 to outline actions for 2022-2025, which include addressing ocean acidification to foster resilient species and ecosystems.

Ocean acidification is a global condition with local effects, and does not occur in isolation from other climate change stressors in the ocean environment. BC's *Preliminary Strategic Climate Risk Assessment* considered compounding risk events, but the co-occurrence of hypoxia and ocean acidification was not considered. Hypoxia in coastal waters is of great and growing concern, and is often linked to ocean acidification. As will be shown, corrosive and hypoxic conditions have both been documented in BC coastal waters, which could lead to adverse effects to marine species and biodiversity, and ultimately implications to food security, economy and society.

This scientific assessment provides supporting information for the BC Ocean Acidification and Hypoxia (OAH) Action Plan. Included within this assessment is the information that forms the basis for recommendations made within the BC OAH Action Plan. These recommendations were developed through consultation with science, stakeholder, and coastal communities and First Nations, and aim to build collaboration, increase public and government awareness, advance scientific understanding, evaluate interactions between proposed marine CO_2 removal approaches and OAH, and enhance mitigation, adaptation, and resilience to OAH in BC's coastal waters.

Why does British Columbia need an ocean acidification and hypoxia action plan?

The need for an OAH Action Plan in BC stems from concern with regard to BC's extensive seafood sector as well as the resilience of coastal and First Nations communities, which rely on seafood harvests. In 2020, BC harvested 272,000 tonnes of seafood, amounting to a wholesale value of $1.62 billion (BC MAF 2022). The aquaculture, fisheries, and related processing sectors provide thousands of jobs to British Columbians, employing 14,631 (direct, indirect, and induced FTEs) in 2020 (Big River Analytics Ltd. 2021). The top commercial fisheries in BC are salmon, crab, geoduck and groundfish. The aquaculture sector grows finfish, shellfish and marine plants for harvest. Currently, the aquaculture production volume and landed value in BC is 58% and 64%, respectively, of Canada's total aquaculture production (DFO 2022). The most significant aquaculture species in BC is salmon (Pacific and Atlantic), with a wholesale value of $750 million. BC is the world's fourth largest producer of Atlantic salmon after Norway, Chile and the United Kingdom. Shellfish aquaculture (oysters, mussels and clams) is another significant part of BC's aquaculture sector with a wholesale value of almost $33 million. Other species (trout, sablefish, Arctic char, tilapia, barramundi, sturgeon, microalgae, kelp, and other seaweeds) make up the balance with a wholesale value of $40 million.

First Nations have strong ties to coastal waters and have been participating in fisheries, including shellfish culture, since time immemorial. For example, evidence suggests that clam gardens have been in use in BC for 3,500 years (Smith et al. 2019). First Nations are significant participants in BC commercial fisheries, primarily in the fishing fleet, the processing sector, and more recently the aquaculture sector. For example, on the north and central coasts of BC, First Nation participation in seafood processing, commercial fishing, aquaculture, and the operation of fish hatcheries generated an estimated annual revenue of $150M, employing 1,700 in seafood processing, 140 in aquaculture and hatcheries and 811 Fisher Registration Card Holders in 2008 (Ference Weicker & Company Ltd. 2009). On the southern BC coast, First Nations involvement in salmon aquaculture generates $83M in direct, indirect and induced economic activity, $47.8M in GDP and 707 jobs earning $36.6M in salaries (Coalition-of-First-Nations-for-Finfish-Stewardship 2022). Previous estimates suggest that one third of all commercial fishing and processing jobs are held by Indigenous persons; however, participation ranges significantly (0-80%) for different fisheries (James 2003). A more recent survey of First Nation's leaders in the southwest coast region found that fisheries, aquaculture and value-added seafood were more commonly ranked as the strongest economic sectors (B.C. Ministry of Jobs 2018).

Indigenous coastal communities consume up to 15 times more seafood than non-Indigenous populations (Cisneros-Montemajor et al. 2020), with an estimated 90% of dietary protein being derived from seafood in BC coastal First Nations (Mos et al. 2004). A reduced capacity to access traditional harvests due to climate change (Weatherdon et al. 2016) will have a particular risk for coastal communities with a high dependency on marine fisheries. Access to traditional foods is not only important for Indigenous food security in British Columbia (Batal et al. 2021a; Batal et al. 2021b), but also for human health and nutrition (Marushka et al. 2021; Marushka et al. 2019) and for cultural connections to key traditional food species (Blanchet et al. 2021). This access is recognized as a part of their inalienable rights with implications for food security particularly for small, remote nations with limited access to affordable food alternatives. Observed and projected climate change is an expressed concern in Indigenous communities, where impacts may be linked to a loss of social, economic and cultural rights in addition to implications for food security and nutrition (Batal et al. 2021a; Weatherdon et al. 2016; Whitney et al. 2020), increasing the stresses and adaptation responses needed for the sustainability of coastal Indigenous communities.

As noted in the *Preliminary Strategic Climate Risk Assessment for British Columbia,* initial estimates on the cost to the seafood sector and government from ocean acidification could be in the hundreds of millions. It is likely the cost will be higher, particularly when considering the additional stressors of ocean warming and hypoxia. Smith et al. (2021) estimated that the global economic cost from marine heat wave events alone exceeds US$800 million in direct losses or > US$3.1 billion in indirect losses of ecosystem services for multiple years. However, the cost to food security and culturally to BC coastal communities is beyond estimation. The BC OAH Action Plan presents recommended actions needed to address knowledge and capacity gaps, which will lead to greater resilience to these threats for British Columbians.

What are ocean acidification and hypoxia?

The marine carbonate chemistry and “the other CO_2 problem”

The mass of atmospheric carbon has increased by 48% from the start of the industrial era (1750) to 2021, largely due to fossil CO_2 emissions (465±25 GtC; GtC = gigatonne = 10^9 tonnes of carbon) along with contributions from land-use change (205±60 GtC; Friedlingstein et al. 2022). This has resulted in atmospheric CO_2 content increasing from 278 ppm in 1765 to 417 ppm in 2022. The atmosphere is currently a reservoir for ~41% of the total anthropogenic emissions (fossil CO_2 emission plus land-use change), with the remaining portion partitioned between uptake by the terrestrial biosphere (~31%) and uptake by the ocean (~26%). Increasing CO_2 in the atmosphere leads to global warming, estimated as 1.1°C above the pre-industrial baseline (*i.e.*, the difference between 2011-2020 and 1850-1900 global means; Gulev et al. 2021), and would be significantly higher without uptake by the terrestrial biosphere and ocean.

While ocean uptake of anthropogenic CO_2 emissions may avoid potentially greater global warming, it is leading to changes in ocean chemistry known as ocean acidification. Ocean acidification can adversely affect various marine species with cascading impacts on marine food webs that have potential to alter cultural and socio-economic benefits society receives from the ocean, and has been referred to as “the other CO_2 problem” (Doney et al. 2009). Aqueous CO_2 is formed when CO_2 from the atmosphere enters the ocean by gas exchange. Once in seawater, aqueous CO_2 reacts with water molecules to form carbonic acid ($\mathrm{H_2CO_3}$), a weak acid that further dissociates by losing hydrogen ions in two steps to form bicarbonate ($\mathrm{HCO_3^-}$) and carbonate ($\mathrm{CO_3^{2-}}$) ions. As described by Doney et al. (2009), this series of chemical reactions can be expressed as:

$$\mathrm{CO_{2(atmosphere)}} \leftrightarrow \mathrm{CO_{2(aqueous)}} + \mathrm{H_2O} \leftrightarrow \mathrm{H_2CO_3} \leftrightarrow \mathrm{H^+} + \mathrm{HCO_3^-} \leftrightarrow \mathrm{2H^+} + \mathrm{CO_3^{2-}},$$

where each transition is reversible at a rate determined by a dissociation constant, and, with the exception of gas exchange between the atmosphere and ocean, is in thermodynamic equilibrium. Full equilibration time between the atmosphere and ocean can take up to a year (Jones et al. 2014) and is dependent on the depth over which the surface ocean is mixed, wind speed, and the ocean’s carbonate chemistry. The sum of the major components of ocean carbonate chemistry; $CO_{2(aqueous)}$, $\mathrm{H_2CO_3}$, $\mathrm{HCO_3^-}$, and $\mathrm{CO_3^{2-}}$, is referred to as dissolved inorganic carbon (DIC) or total CO_2 (TCO_2). Over time, ocean acidification increases DIC and alters the relative contribution of its components (Figure 1). Based on the above equation, continued input of anthropogenic CO_2 into the ocean increases the concentration of hydrogen ions ($[H^+]$), decreasing pH, and decreasing the concentration of carbonate ions ($[CO_3^{2-}]$). The decrease in $[CO_3^{2-}]$ results in a decrease in the saturation state (Ω) of calcium carbonate biominerals. Ω is a ratio of the product of $[CO_3^{2-}]$ and calcium concentration over the solubility product for the specific calcium carbonate biomineral (*i.e.*, Ω_{arag} for aragonite and Ω_{calc} for calcite). Aragonite is the most soluble form (Millero 2007), and when this ratio is < 1, aragonite dissolution is favored over precipitation. Ω values > 1 favor precipitation of the biomineral. Calcite is the least soluble form of calcium carbonate, such that when calcite saturation state (Ω_{calc}) is < 1, all forms of calcium carbonate are prone to dissolution.

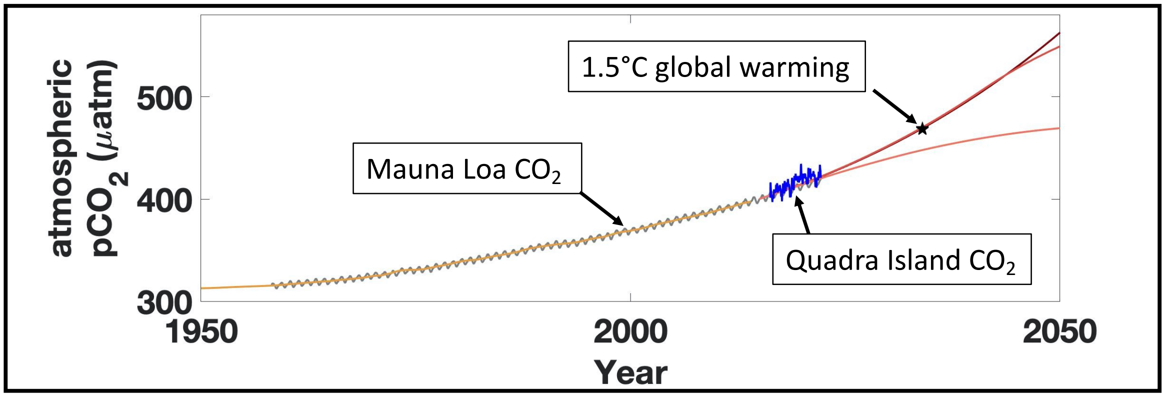
Example calculation of ocean acidification for BC waters

For surface seawater found along the outer BC coast in equilibrium with a near contemporary atmospheric CO_2 level of 400 ppm, the partitioning of DIC is such that approximately 94% is in the form of HCO_3^-, 6% is CO_3^{2-}, and < 1% is $CO_{2(aqueous)}$ (Figure 1). For these conditions, seawater pH would be 8.03.

Also with these conditions, the saturation state for aragonite (Ω_{arag}), a parameter that defines the tendency to either dissolve or precipitate the mineral aragonite used by many marine organisms to produce shells, would be 1.69. Saturation state can also be computed for calcite (Ω_{calc}). When the saturation state for either calcium carbonate mineral has a value <1, there is a tendency for dissolution (*i.e.*, the mineral will dissolve). The mineral can precipitate at saturation state >1. However, conditions may still be stressful for some organisms at higher values <2 because of the energetic demands of physiological processes that might be happening concurrently (Waldbusser et al. 2013).

At a pre-industrial atmospheric CO_2 of 280 ppm, the partitioning of DIC components shifts to ~92% and ~7% for bicarbonate and carbonate respectively, along with a lower DIC and higher pH (8.17), compared to contemporary conditions. Ω_{arag} at this pre-industrial atmospheric CO_2 would be 2.21. The difference in DIC between contemporary and pre-industrial conditions in this example is 55 µmol/kg, and is referred to as the anthropogenic CO_2 contribution, as this represents the increase in DIC that has occurred through uptake from the atmosphere over the industrial era.

At higher atmospheric CO_2 levels consistent with a 1.5°C warmer world targeted by the Paris Agreement (UNFCC, 2015; 470 ppm) and near the highest projected emissions for 2050 (600 ppm), concentrations of oceanic DIC and H^+ increase further. This leads to additional reductions in pH and Ω (Figure 1), increasing ocean acidification. While these examples are meant to resemble BC conditions, carbonate chemistry changes are being observed in multi-decadal time-series from monitoring locations located all over the world (Bates et al. 2014).



atmospheric CO_2	**280**	**400**	**470**	**600**
gas exchange **ocean**				
carbonic acid $CO_2 + H_2O \leftrightarrow H_2CO_3$	**13**	**18**	**21**	**27**
bicarbonate $H_2CO_3 \leftrightarrow H^+ + HCO_3^-$	**1791**	**1874**	**1907**	**1951**
carbonate $HCO_3^- \leftrightarrow CO_3^{2-} + H^+$	**145**	**111**	**98**	**80**
dissolved inorganic carbon	**1949**	**2003**	**2026**	**2058**
pH	**8.17**	**8.04**	**7.97**	**7.88**

Figure 1: Measured and projected atmospheric CO_2 content and associated changes in ocean carbonate chemistry. The top panel shows atmospheric pCO_2 from 1950 to 2050. Historical (orange) and projected atmospheric pCO_2 traces are from the Shared Socio-Economic Pathways (SSP) used in the IPCC Sixth Assessment Report. The three atmospheric CO_2 projections are SSP5-8.5 (burgundy), SSP5-3.4-OS (red), and SSP1-2.6 (orange). These atmospheric CO_2 projections equate to a high emissions scenario, an "overshoot" (OS) scenario with initially high emissions before steep reductions, and a low emissions scenario consistent with the Paris Agreement's 1.5°C global warming target. The atmospheric pCO_2 corresponding to the Paris Agreement target is marked as a black star on the high emissions projection. Also shown are measurements of atmospheric CO_2 from Mauna Loa, Hawaii (gray) and Quadra Island, British Columbia (blue). The table shows changes in ocean carbonate chemistry due to equilibration with an atmospheric pCO_2 of 280 (preindustrial atmosphere), 400, 470 (1.5°C target), and 600 µatm. Theoretical changes are based on seawater temperature, salinity, and alkalinity of 10°C, 30 g/kg, and 2150 µmol/kg, respectively. As atmospheric pCO_2 increases, aqueous CO_2, bicarbonate, and DIC increase, while carbonate, pH, and Ω_{arag} decrease. Credit: Wiley Evans/Hakai Institute.

Measuring the marine carbonate system

A number of key ocean carbonate chemistry parameters have been introduced. However only a subset of these are measurable. Specifically, DIC, alkalinity, and pH can each be directly determined in seawater spanning a typical oceanic salinity range with a high degree of accuracy. A fourth measured parameter is the CO_2 partial pressure (pCO_2), which is equal to $CO_{2(aqueous)}$ divided by the solubility of CO_2. The pCO_2 gradient between the surface ocean and the atmosphere determines the direction of exchange between these two carbon reservoirs, or in other words, whether an ocean region absorbs CO_2 from or releases CO_2 to the atmosphere. Collectively these four measurable parameters have been referred to as the fundamental "keystone variables" of the ocean carbonate system (Byrne 2014; Millero 2007). With measurements of any two of these four keystone variables, all remaining carbonate system parameters can be computed (Dickson et al. 2007).

The buffering state of seawater is its ability to resist acidification, which is dependent on the availability of bases (proton acceptors) to neutralize acids (proton donors). The extent of acidification in terms of the relative change in pH is dependent on the ratio of alkalinity to DIC (Feely et al. 2018). In seawater with high alkalinity relative to DIC (*i.e.*, well-buffered seawater), the change in acidity will be of a lesser magnitude compared to seawater containing similar levels of alkalinity and DIC (*i.e.*, weakly-buffered seawater) for the same level of anthropogenic CO_2 input.

DIC and alkalinity are also conservative with respect to changes in state; *e.g.,* temperature or pressure. In contrast, pH and pCO_2 are not conservative with respect to changes in temperature and pressure (meaning that when the surface mixed layer warms in the sun, the pH and pCO_2 will change but the DIC and alkalinity do not). Another complication is that alkalinity can be difficult to interpret at lower salinities typically found in coastal waters. This is due to the presence of dissolved organic molecules that can be a significant contributor to total alkalinity (Sharp and Byrne 2020). Because of this complexity, the ideal pairing of measured keystone variables for coastal water is DIC and pCO_2 or DIC and pH (Byrne 2014; Patsavas et al. 2015).

Ocean deoxygenation, hypoxia, and the metabolic linkage between carbon and oxygen

The production and degradation of organic matter in the ocean plays a dominant role in shaping the distributions of both carbonate chemistry and dissolved oxygen through the following reaction:

$$106\mathrm{CO_2} + 16\mathrm{NO_3^-} + 1\mathrm{H_3PO_4} + 122\mathrm{H_2O} \leftrightarrow (\mathrm{CH_2O})_{106}(\mathrm{NH_3})_{16}\mathrm{H_3PO_4} + 138\mathrm{O_2}$$

where CO_2, inorganic nutrients (*e.g.*, NO_3^-), and water (H_2O) are converted to organic matter and oxygen via photosynthesis (Figure 2). The reverse of this reaction is the remineralization of organic matter by microorganisms, which consumes oxygen and produces CO_2 and inorganic nutrients. It is important to recognize this linkage between O_2 production and CO_2 drawdown (and vice versa) in the ocean, as well as the ways in which anthropogenic climate change are influencing these processes (Figure 2). The ocean is a reservoir for anthropogenic CO_2, but also for heat; *i.e.*, ocean temperature is increasing in response to the growing concentrations of heat-trapping gases in the atmosphere. Ocean warming accounts for 91% of the excess heat added to the Earth system by anthropogenic climate change (Fox-Kemper et al. 2021).

This additional heat leads to both a decrease in solubility of CO_2 and O_2 and an increase in stratification of the upper ocean. Increasing temperature also enhances the remineralization of organic matter. The combination of these factors due to warming has decreased ocean oxygen content by ~2% since 1960 and led to the expansion of oxygen minimum zones around the world (Breitburg et al. 2018). The global scale decline of oxygen in the ocean is referred to as deoxygenation, and in coastal environments this can be enhanced by the local respiration of organic matter.

When oxygen decreases to levels that harm most macrofauna such as fish, nominally below a threshold value of about 61 µmol/kg (or 2 mg/l or 1.4 ml/l), conditions are considered hypoxic. Since 1960, the number of coastal sites reporting hypoxia has grown significantly (Breitburg et al. 2018). Anthropogenic nutrient input from runoff can be a contributor to the occurrence of hypoxia in coastal settings by enhancing organic matter production in the surface layer that is then respired at depth, consuming O_2 and releasing CO_2 (Cai et al. 2011). This respiratory CO_2 signal is added to the natural and anthropogenic CO_2 signals, potentially amplifying local acidification in these areas (Cai et al. 2021; Feely et al. 2018). This one-two punch of acidified and hypoxic conditions serves as a multi-stressor that can greatly increase negative impacts on ecosystems.

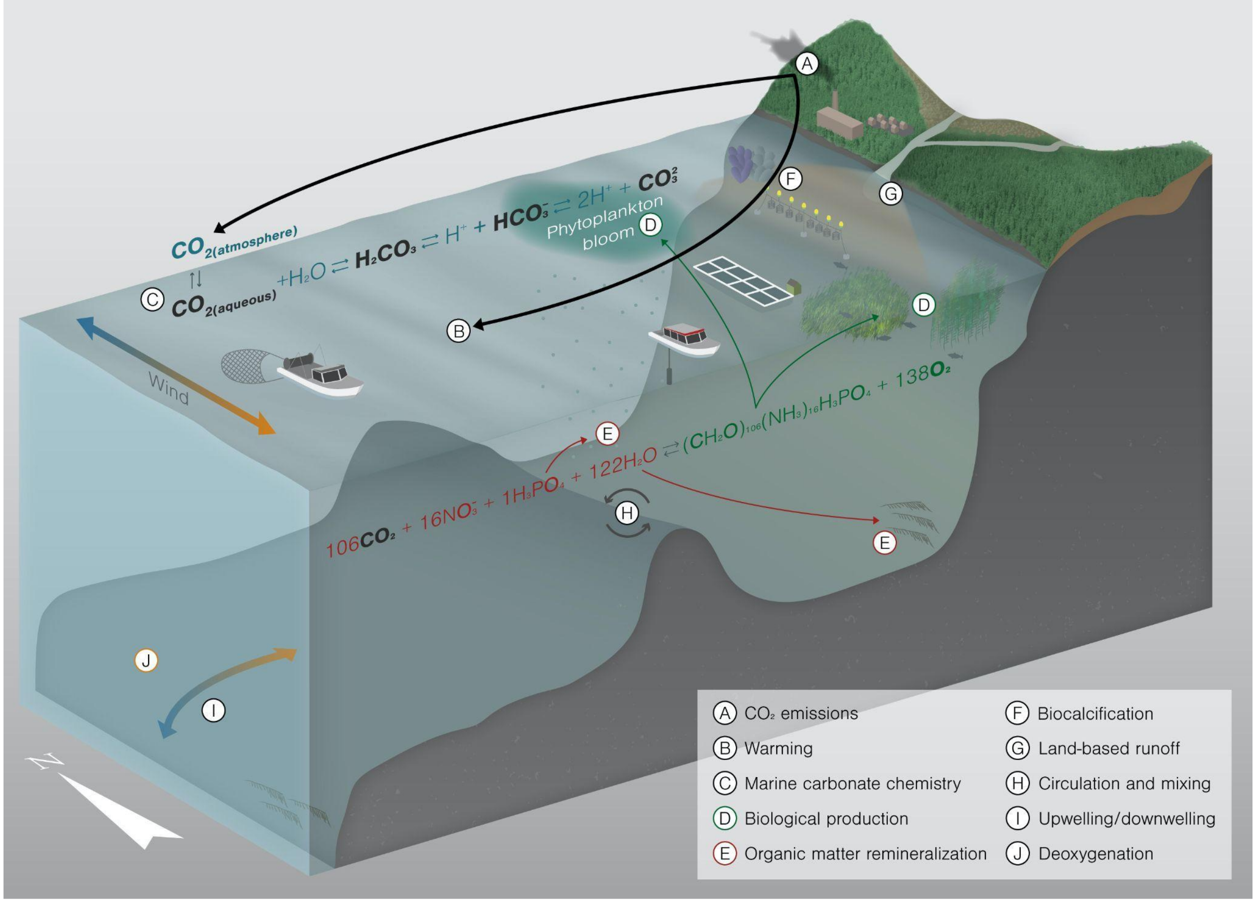


Figure 2: Overview of major processes driving variability in the marine carbonate system and oxygen concentration of coastal waters in British Columbia. Anthropogenic CO_2 from CO_2 emissions (A) results in ocean warming (B) and acidification through its impact on marine carbonate chemistry (C). These changes are occurring against a backdrop of natural processes that alter the ocean's marine carbonate system and oxygen levels, including: biological production (D), organic matter remineralization (E), biocalcification (F), land-based runoff (G), circulation and mixing (H), and wind-driven upwelling and downwelling (I). Southward (northward) winds along the British Columbia coast during summer (winter) drive the upwelling (downwelling) of deep open ocean water onto the continental shelf. This upwelled water is high in nutrients, and enhances the growth of phytoplankton that support productive marine food webs. The production of organic matter by phytoplankton and marine vegetation acts to remove CO_2 from seawater as well as produce O_2. This organic matter is either remineralized in coastal waters, whereby O_2 is consumed and CO_2 is produced, or exported off the continental shelf to deeper open ocean waters. If exported to depths below 1000 m, the CO_2 produced during remineralization would be removed from contact with the atmosphere (*i.e.*, sequestered) for > 200 years (Siegel et al. 2021). Ocean warming alters the rate of organic matter remineralization, the vertical layering of the water column (*i.e.*, stratification), and the solubility of gases (*e.g.*, CO_2 and O_2) in seawater. This combination of factors is leading to ocean deoxygenation (J). When this low-O_2 water is supplied to the continental shelf by wind-driven upwelling, O_2 can be further reduced by organic matter remineralization and lead to hypoxic levels that are harmful for many marine species. Land-based runoff can also supply nutrients that promote phytoplankton

growth, as well as dilute seawater DIC and alkalinity. Biocalcification also reduces alkalinity, and both reductions in alkalinity and increases in CO_2 lead to more weakly-buffered seawater conditions that would exhibit faster rates of change in response to anthropogenic CO_2 uptake. Credit: Mark Garrison/Hakai Institute.

Regional patterns of ocean acidification and hypoxia along the Pacific Coast

The interior Northeast Pacific between 200 and 2000 m is the area of lowest pH in the global ocean (Lauvset et al. 2020). This seawater is very old (*i.e.*, in terms of the length of time since last contact with the atmosphere), and has experienced high cumulative organic matter remineralization that has resulted in low pH and oxygen (Lauvset et al. 2020; Ross et al. 2020). The shallowest portion of this low pH and undersaturated seawater with respect to aragonite is upwelled to the surface along the Northeast Pacific coast by upwelling-favourable winds during the summer months, from British Columbia to California (Fassbender et al. 2018; Feely et al. 2008; Feely et al. 2018). Upwelling also brings nutrients into the sunlit portion of the water column, resulting in high rates of primary production that support highly productive fisheries (Ware and Thomson 2005).

Although the seasonal upwelling of low pH and aragonite saturation state seawater is a natural phenomenon, anthropogenic CO_2 is affecting the extent, duration, and intensity of these conditions (Feely et al. 2016; Hauri et al. 2013). This has had direct impacts on the shellfish industry along the U.S. west coast (Barton et al. 2015), leading to the so-called “oyster seed crisis”. In the mid-2000’s, the saturation state of upwelled water was recognized as impacting the commercial production of oyster larvae in hatchery settings and caused seed shortages for the shellfish industry (Barton et al. 2015). Continuous monitoring with instruments on buoys and within hatcheries became critical lines of defense for the shellfish industry to “dodge the punch” of ocean acidification during periods of upwelling.

A clearer picture of anthropogenic CO_2 distribution and its impacts has emerged since the mid-2000’s. Surface waters, away from the influence of upwelling, are now known to contain the highest anthropogenic CO_2 content (Carter et al. 2019; Evans et al. 2022; Feely et al. 2016; Lauvset et al. 2020). However, despite having a lower anthropogenic CO_2 content, upwelled waters are weakly-buffered, and therefore experience a greater change in pH and further reduction in aragonite state (Lauvset et al. 2020). This has led to large declines in aragonite saturation state and observations of shell dissolution in pteropods, which are key prey species in ocean food webs (Bednaršek et al. 2014; Bednaršek et al. 2021a; Feely et al. 2016). Hypoxic conditions have also intensified along the U.S. West Coast (Bograd et al. 2008; Chan et al. 2008; Crawford and Peña 2013; Pierce et al. 2012). The combined effect of ocean acidification and hypoxia can form a “one-two punch” for vulnerable species like Dungeness crab (Berger et al. 2021).

Biological impacts of ocean acidification and hypoxia

Biological responses to OAH have been described for many marine organisms, and across multiple stages of species with complex life cycles (Cooley et al. 2022; Gobler and Baumann 2016; Kroeker et al. 2013). Among the acute and chronic effects observed, many adversely affect individual organisms, although the severity and lethality of impacts depend on the magnitude and duration of exposure. A myriad of physiological and biological processes including early ontogenic development and growth, survival, calcification, respiration, photosynthesis, reproduction, feeding, as well as a wide range of behavioural and immune responses are sensitive to pCO_2, pH or saturation state (Cooley et al. 2022; Haigh et al. 2015; Kroeker et al. 2013; Wittmann and Pörtner 2013). Low oxygen concentrations can elicit negative effects on growth, survival, physiology, and reproduction, as well as disrupt patterns of behaviour (Breitburg et al. 2018; Cooley et al. 2022; Gobler and Baumann 2016; Somero et al. 2015; Wu 2002).

Most of our scientific understanding of species responses to OAH comes from experimental laboratory-based studies that focus on responses of single species to single environmental stressors (Baumann 2019). Marine calcifiers have been identified as facing heightened vulnerability to OA because they build their shells, skeletons, and other calcified structures out of calcium carbonate (Cooley et al. 2022; Kroeker et al. 2013; Wittmann and Pörtner 2013). In contrast, organisms with higher metabolic demands, particularly benthic and sessile organisms, have been identified as particularly vulnerable to severe and persistent hypoxic events (Cooley et al. 2022; Grieshaber et al. 1993).

Although understanding the physiological and cellular processes that lead to sensitivity to OAH is an active area of research, to date a few mechanisms have been identified in vulnerable species. More acidified environmental conditions resulting in higher pCO_2, lower calcium carbonate saturation states, and lower pH can lead to the disruption of organisms' cellular acid-base regulation (Pörtner 2008) direct impairment of biocalcification and shell repair through exposure of the calcifying surfaces or fluids to unfavourable environmental conditions (Melzner et al. 2011; Waldbusser et al. 2013) or indirectly through increased energetic costs (Pan et al. 2015) and alteration of cellular signaling pathways that can affect behavioural responses (Clements and Hunt 2015) and immunological status, leading to increased vulnerability to pathogens (Bibby et al. 2008; Wang et al. 2016). Ocean acidification will also increase marine shellfish bioaccumulation or negative effects of exposure to pharmaceuticals via wastewater (Costa et al. 2020a; Costa et al. 2020b; Dionísio et al. 2020) or susceptibility to *Vibrio* species and other pathogen species exposures (Byers 2021; Ferchichi et al. 2021; Schwaner et al. 2020).

Hypoxia can disrupt the acid-base balance within cells, shift metabolism to anaerobic pathways, and affect respiration rates, energy expenditure, physiological stress responses and behaviour

(Gobler and Baumann 2016; Wu 2002). Although survival can be affected, for most marine organisms, significant mortality is not observed until environmental conditions approach extreme or persistent hypoxia (chronic hypoxia). Most of the research to date has focused on acute hypoxic stress and has revealed that some organisms are able to adjust their respiration rate as a response to lower oxygen concentrations (oxyconformers); these are considered more resilient than organisms that maintain the same respiration rates throughout a range of oxygen levels (oxyregulators; Pörtner 2010). However, even for relatively tolerant species, persistent or extreme hypoxic events can trigger significant adverse physiological responses (Falfushynska et al. 2020; Ouillon et al. 2021; Steffen et al. 2020).

Identifying OAH impacts on marine organisms

Identification of sensitivity thresholds for OAH is key to better predicting outcomes under future environmental conditions and to better parameterizing models to identify potential hotspots of vulnerability. OAH thresholds are life-stage, species, and population specific, and also depend on the duration and magnitude of exposure (Figure 3). For example, hypoxia has a general oxygen threshold of 61 μmol/kg (or 2 mg/l or 1.4 ml/l) to indicate adverse conditions for a wide range of organisms, however, more refined thresholds have been compiled for a wide range of organisms (Vaquer-Sunyer and Duarte 2008, 2011), or even among different populations (Chu and Tunnicliffe 2015).

Defining global sensitivity thresholds for OA has proven more complicated as multiple carbonate chemistry parameters can drive different physiological responses (Hurd et al. 2020). For example, biocalcification has been found to be driven by saturation state or $[\mathrm{HCO_3^-}/\mathrm{H^+}]$ in bivalves (Gazeau et al. 2011; Thomsen et al. 2015; Waldbusser et al. 2015a; Waldbusser et al. 2015b), coccolithophores (Bach et al. 2013) and corals (Jokiel 2013). In contrast, work on bivalve larvae revealed pH as the parameter driving respiration responses (Waldbusser et al. 2015b), and pCO_2 and aragonite saturation state as impairing feeding (Gray et al. 2017; Waldbusser et al. 2015b). Accordingly, organismal sensitivity thresholds for various carbonate chemistry parameters have been defined (Cooley et al. 2022) and are currently in use in BC-focused initiatives, such as the Canadian Integrated Ocean Observing System (CIOOS) Baynes Sound Monitor, to indicate instances when local environmental conditions might be harmful for oysters and krill. Despite shell dissolution being thermodynamically favoured when calcium carbonate saturation states are less then 1, some organisms that utilize aragonite exhibit impaired calcification and development when Ω_{arag} is less than 1.5 to 1.7 (*e.g.*, early larval stages of mussels and oysters; Waldbusser et al. 2015a; Waldbusser et al. 2015b). Mild and severe dissolution has also been observed for pteropods exposed for 5- and 14-day periods to Ω_{arag} values of 1.5 and 1.2, respectively (Bednaršek et al. 2019). pH thresholds for multiple physiological processes and species have also been identified. For example, respiration in early mussel larvae is disrupted at pH <7.4 (Waldbusser et al. 2015b) and Pacific krill larval development is impaired at pH ~7.69 (McLaskey et al. 2016). A suite of biological thresholds for various life-stages have been identified between at pH 7.2-7.8 for echinoderms (Bednaršek et al. 2021b), and at pH 7.4-7.8 for decapods (Bednaršek et al. 2021c). Although significant gaps in identifying OA thresholds for marine organisms remain, observed complex biological responses to OA reinforce the need to fully constrain the carbonate chemistry system to be able to better predict the fate of organisms under future environmental conditions.

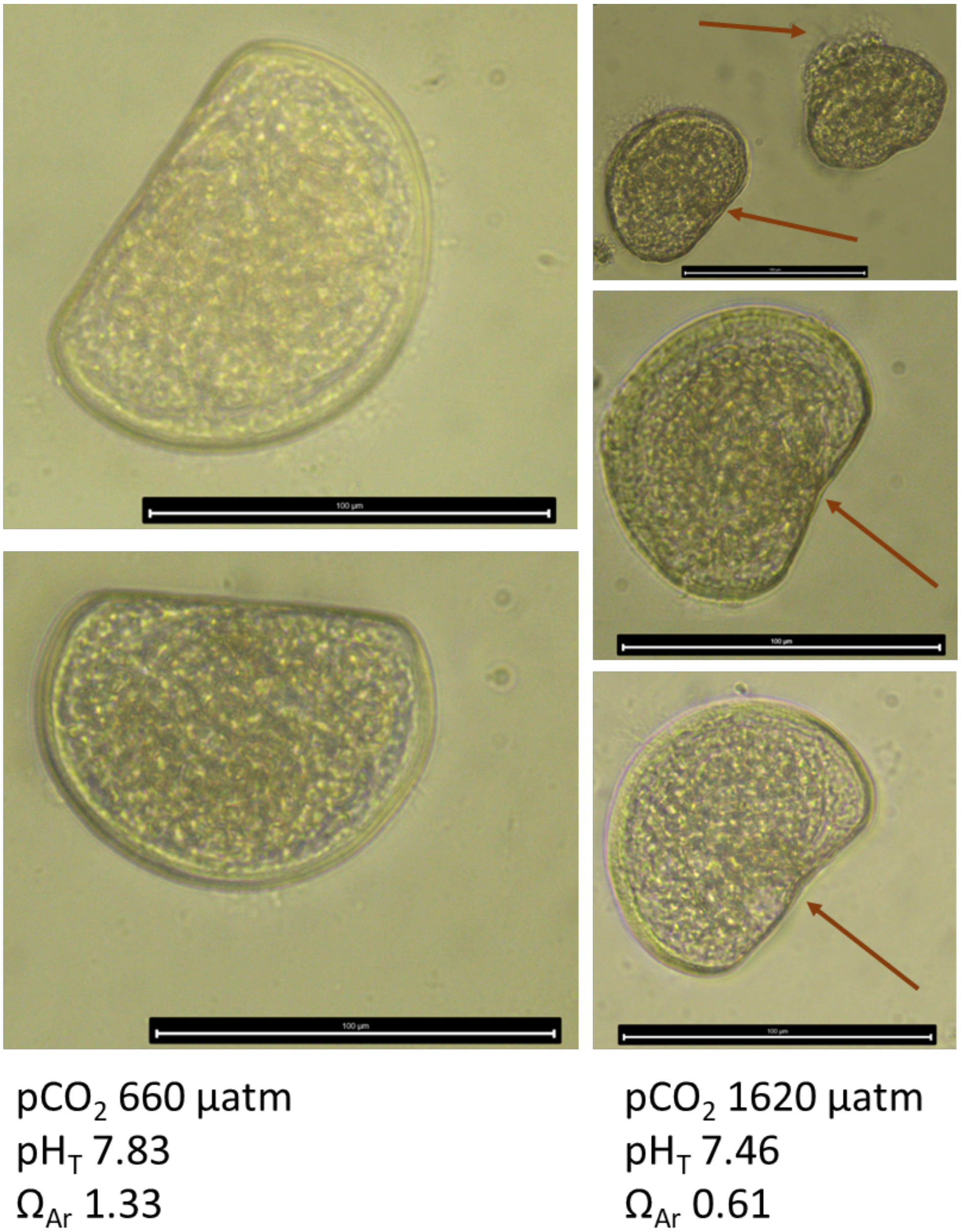


Figure 3: Bay mussel larvae from the same brood stock parents raised at the Hakai Institute under high and low pCO_2 experimental conditions. Representative larvae were imaged using light-microscopy and 40x magnification 2 days after fertilization. The development of the first shell is impaired under more corrosive conditions (right). Arrows show defects in the development of the D-hinge shell shape and extensive protrusion of the velum. Scale bar is 100 µm. Credit: Iria Gimenez / Hakai Institute.

Resiliency or vulnerability to OAH is also modulated by their co-occurrence and their interaction with other stressors, particularly temperature. Low oxygen and elevated CO_2 levels in the environment are both expected to reduce existing optimum thermal windows for marine organisms (Pörtner 2015). Conversely, concurrent exposures to increasing temperature, OA and hypoxia in various combinations can cause antagonistic, synergistic or additive effects on organisms (Gobler and Baumann 2016). Given the diversity of biological processes affected and the variety of mechanisms of sensitivity and modes of action, OA can be considered an environmental multi-stressor in itself (Hurd et al. 2020; Waldbusser et al. 2015b). Although extensive research is needed to better understand marine species' responses to multi-stressors, evidence to date suggests that OAH exposure often exacerbates sensitivities to other environmental stressors (Boyd et al. 2015; Cooley et al. 2022; Gobler and Baumann 2016; Gunderson et al. 2016; Stevens and Gobler 2018).

Informing the BC OAH Action Plan

To inform the BC OAH Action Plan, a series of virtual workshops were convened to produce a synthesis of the current state of knowledge regarding OAH in BC and engage external perspectives to provide input on recommended actions needed to address knowledge and capacity gaps. The four workshops were hosted by the Quadra Centre for Coastal Dialogue, built upon one another, and helped facilitate feedback from a variety of sectors and interested parties. The four workshops were: (1) *State of the Science on Ocean Acidification and Hypoxia Research in British Columbia;* (2) *BC Seafood Harvester and Producer Perspectives on OAH*; (3) *BC Coastal Communities' Perspectives on OAH*; and, (4) *Policy and Governance Considerations for BC's OAH Action Plan.* Workshops hosted invited speakers with relevant subject matter expertise, presented background knowledge of OAH research in BC, facilitated dialogue and exchange on the topic among participants based on key discussion questions, and provided opportunities for feedback on draft recommendations. Gaps associated with information exchange, collaboration, scientific understanding, and in our ability to adapt and mitigate OAH manifestations in BC were identified and used to build and refine recommendations developed through the workshop series. The workshop series was, by design, open and inclusive, and provided opportunity for engagement after presentations, during break-out sessions, and during extended periods of open comment for participants.

State of the Science on OAH Research in BC, November 2-4 2021

The *State of the Science on Ocean Acidification and Hypoxia Research in British Columbia* (BC) workshop hosted 92 participants that included scientists, researchers, Indigenous community members, commercial fishers, food harvesters, aquaculture producers, and local, provincial and federal government representatives. The aim of the workshop was to produce an environmental scan of what we know and what we need to know related to patterns, trajectories, and impacts of ocean acidification and hypoxia (OAH) along the British Columbia coastal margin (Figure 4). This aim was achieved by creating a synthesis of current scientific knowledge and discussions related to gaps in our understanding. The summary of these discussions helped to formulate draft recommendations that were further evaluated through the remaining 3 workshops in the series. Dr. Jan Newton and Dr. Richard Feely, both international leaders in the ocean acidification research community as well as participants in the development of the *Washington State Blue Ribbon Panel Report on Ocean Acidification* and the *State of California Ocean Acidification Action Plan*, were invited speakers and provided valuable insight that helped to set the stage for the State of the Science Workshop.

Several key points surfaced through the workshop, including that there are a number of action plans proposed worldwide for the management and mitigation of OAH from which BC can draw. However, the relative importance of oceanic processes varies regionally, and local conditions can impact the chemical, biological, and physical makeup of the system. As such, the uniqueness of BC conditions must be understood and reflected within the BC OAH Action Plan. Decision-makers can also learn from case studies from other regions to help manage OAH impacts. Efforts to mitigate and adapt to OAH conditions must also include multiple viewpoints and perspectives to be effective, including the seafood producers, community members, subject matter experts, provincial, local, federal government and First Nations representatives. An action priority matrix can be a helpful tool for decision-makers to define and elevate particular activities, and it is vital to include social assessments when measuring the impact of OAH. Bringing the human aspect in allows decision-makers and communities to see the direct impacts that OAH will have on their lives, the broader communities, and the environment. Sustained long-term monitoring, regional modeling, and studies of biological impacts are of vital importance to understanding regional OAH trends and impacts within a region. British Columbia should also have an OAH task force as a coordinating body, similar to the OAH task force in California. This task force should help to identify management decisions that are most dependent on monitoring and modeling, assess how well the current systems are informing the decision-makers, and identify any areas within the systems in need of improvement. The OAH community in BC should also promote regional collaborations with groups that have similar objectives. Significant gaps in terms of predictive modeling capacity, sustained observing efforts that are paired with biological measurements, and the inclusion of Traditional Ecological Knowledge (TEK) were also identified during the workshop.

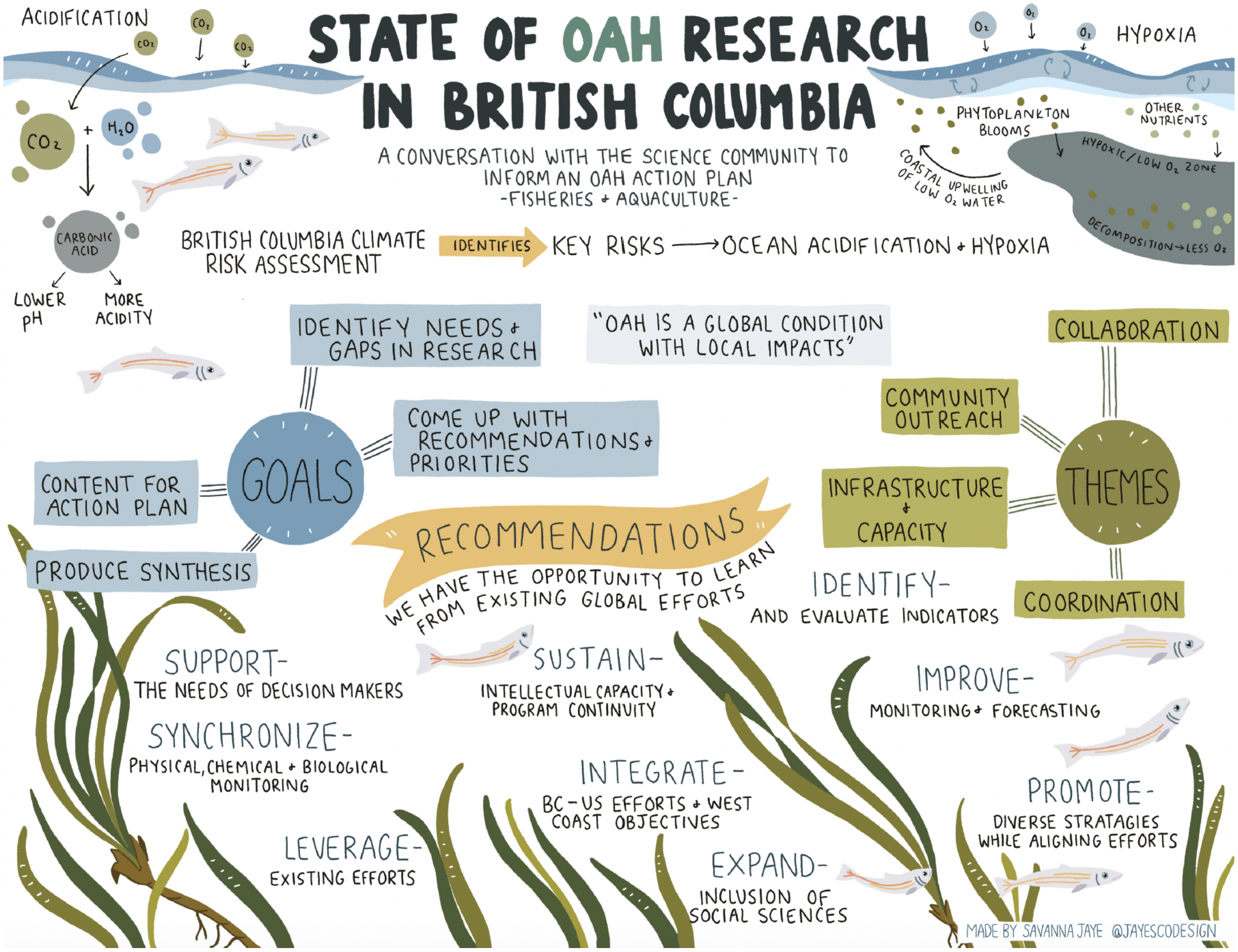


Figure 4: Overview graphic from the *State of the Science on Ocean Acidification and Hypoxia Research in British Columbia* workshop.

BC Seafood Harvester and Producer Perspectives on OAH, January 27-28 2022

The *BC Seafood Harvester and Producer Perspectives on OAH* workshop hosted 86 participants that included scientists, researchers, Indigenous community members, commercial fishers, food harvesters, aquaculture producers and local, provincial and federal government and First Nation representatives and an international representative from the Seafood Business for Ocean Stewardship (SeaBOS) initiative and senior advisor to the UN Global Compact. The aim of the workshop was to review the key themes and recommendations developed from the first workshop (the *State of the Science on OAH Research in BC*) and give an opportunity for BC's commercial harvesters, food-fish harvesters, and aquaculture producers to share their views and perspectives (Figure 5). This aim was achieved by creating a synthesis of current scientific knowledge from the first workshop as well as presentations from harvesters and producers regarding their needs, concerns, and mitigation approaches. The summary of these discussions helped to further formulate the action plan's draft recommendations.

Some key points from this workshop were that there is an urgent need to reform and streamline regulations, and to modernize fisheries related data collection, in order to allow for industries to be nimbler and respond to rapidly changing climate conditions. Of particular interest is for the research community to identify OA indicator species or other biological metrics that fisheries can use and to develop tools that will forecast change on management-relevant timescales. An opportunity also exists to incorporate farm sites/commercial fisheries into data collection efforts and to bridge TEK and western science frameworks. Data on economic impacts to fisheries and support businesses is also needed, as is improved capacity for industries to engage in and adapt to OAH. Industry leaders highlighted the BC needs to continue to support and advocate for more locally produced seafood as a climate change solution, and for funding for restorative aquaculture and fishing practices that builds collaborations between stakeholders and rightsholders. Carbon accounting frameworks for the fisheries section was also a highlighted need, including baseline data to gauge decarbonization approaches and progress. A scientific assessment of mitigation and adaptation strategies and technologies is needed, including funding for programs that reduce the financial burden on fisheries to undertake adaptation and mitigation projects. Frameworks are also needed for the assessment of marine carbon dioxide removal that incorporates industry perspectives including how to effectively monitor environmental co- and dis-benefits. Finally, a coordinated coastwide approach to restoring and conserving submerged aquatic vegetation habitat is needed, as well as a coordination between BC and the federal government to ensure plans for climate change mitigation and adaptation are aligned.

Figure 5: Overview graphic from the BC Harvester and Seafood Producer Perspectives on OAH workshop.

BC Coastal Communities’ Perspectives on OAH, February 15-16 2022

The *BC Coastal Communities’ Perspectives on OAH* workshop hosted 44 participants that included scientists, Indigenous community members, commercial fishers, food harvesters, aquaculture producers, and government representatives. The aim of the workshop was to review the key themes and recommendations from the previous 2 workshops (the *State of the Science on OAH Research in BC* and the *BC Seafood Harvester and Producer Perspectives on OAH)* and give an opportunity for BC’s coastal community members to share their views and perspectives on potential impacts as well as approaches for adaptation and mitigation (Figure 6). Additionally, Dr. Sarah Cooley from the Ocean Conservancy, a leader in the field of OA research, OA policy, and marine CO_2 removal, was invited to present on topics including actions to address OAH and lessons learned from her experiences in engaging decision-makers on OAH across various levels of governance (Figure 7). This discussion helped to frame open dialogues with participants to gauge how OAH might be impacting participants’ communities, what observations participants have made, and what aspects of OAH aren’t being addressed.

The draft recommendations for the BC OAH Action Plan were also presented to participants for further refinement.

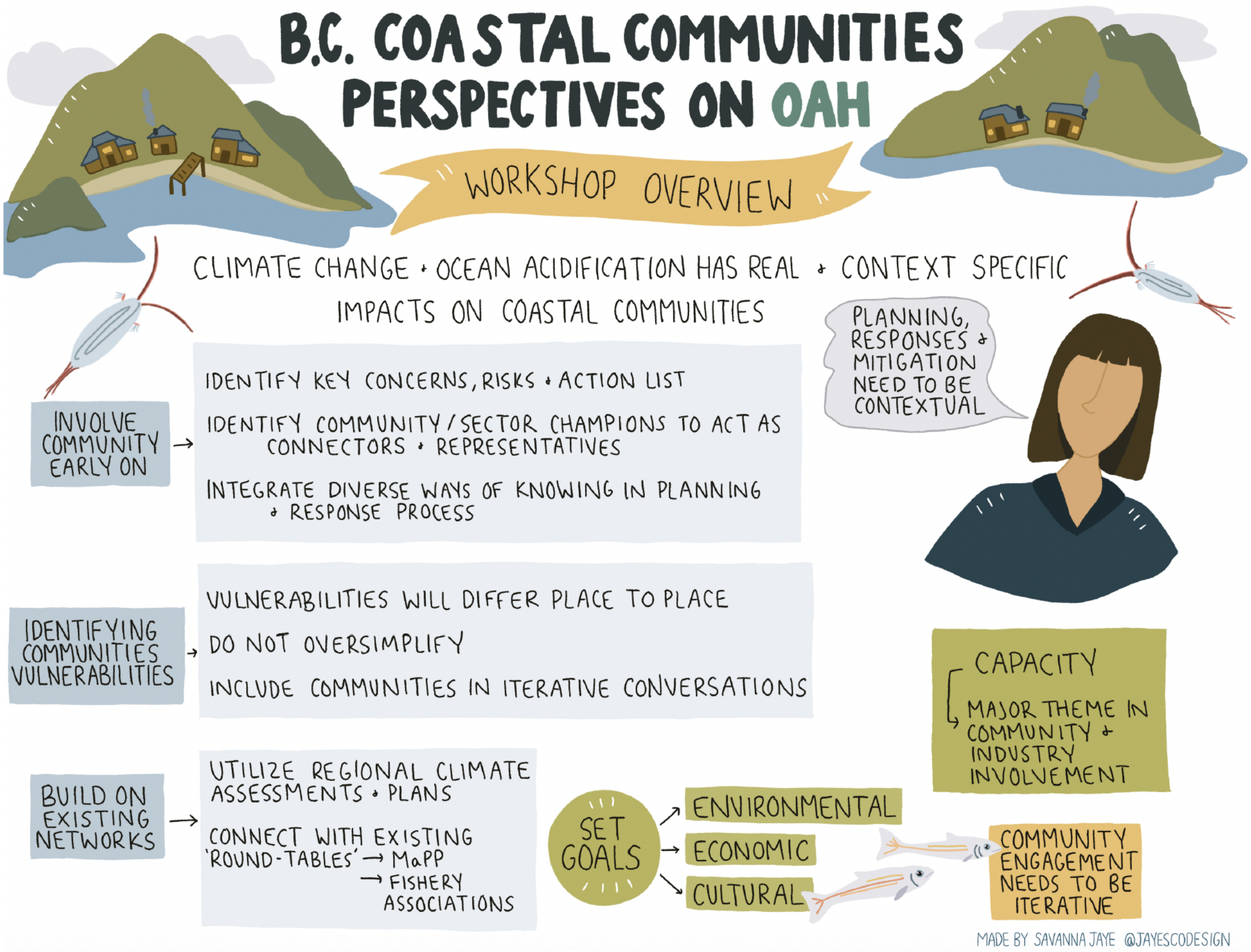


Figure 6: Overview graphic from the BC Coastal Communities' Perspectives on OAH workshop.

The group discussions and breakouts during the Coastal Communities' Perspectives workshop highlighted a number of key aspects that require resolution for BC to be able to successfully adapt to and mitigate OAH. Most notably during all discussions was the limited capacity for communities' to actively engage in both the research and development of approaches for mitigation and adaptation, and the broad group identified some key gaps, opportunities, and recommendations. Specifically, communities need support to build capacity to actively engage in finding climate change solutions such as closing knowledge gaps, enhancing education, and managing for resilience. Increasing public awareness of the issues can help ensure that key questions are identified to assist decision-makers in developing efforts that are designed to address OAH. Bringing Indigenous and other coastal community members together with decision-makers to articulate and discuss their concerns and values, as well as to identify potential solutions, is critical and should aim to co-produce tools solutions. In addition to highlighting common threads of interest, emphasizing positive wins, and working towards the same goals, it is important to recognize specific needs and vulnerabilities of different communities, stakeholders, and rights-holders. Finally, when discussing actions, consideration should be given to long-range solutions that can serve many needs and goals of different groups and the support needed to realize these goals (*e.g.*, information, equipment, funding).

Figure 7: Overview graphic from discussions with Dr. Sarah Cooley regarding getting action on OAH during the BC Coastal Communities' Perspectives on OAH workshop.

Policy and Governance Considerations for BC's OAH Action Plan, March 15 2022

The *Policy and Governance Considerations for BC's OAH Action Plan* virtual discussion was the 4th and final instalment of the series of virtual workshops used to inform the development of the BC OAH Action Plan. The focus of this workshop was to engage with provincial, federal, local and First Nation policy makers, and hosted 20 participants. The aim of the workshop was to review the key themes and recommendations from the previous 3 workshops (the *State of the Science on OAH Research in BC*, *BC Seafood Harvester and Producer Perspectives on OAH* and the *BC Coastal Communities' Perspectives on OAH*) and give an opportunity for policy-makers to share their views, perspectives, and insights. This aim was achieved by creating a synthesis presentation of the past 3 workshops and preparing specific questions for the attendees. The summary of these discussions helped the BC OAH Action Plan Advisory Committee consider how the draft recommendations could be supported through various government entities.

Key points from this workshop included the need to build more science into future decision-making, and that there should be alignment between the BC OAH Action Plan and BC's *Roadmap to 2030*. The BC OAH Action Plan should be viewed as a "living document" that will undergo evaluation and updates on a schedule set by the provincial government ideally through a BC OAH Task Force (similar to *Washington State's 2017 Addendum to Ocean Acidification: From Knowledge to Action, Washington State's Strategic Response*). A project manager appointed by the government would greatly benefit the implementation of the action plan. At this point it is unclear which ministry would take the lead role in administering the action plan, and it is likely that multiple ministries will play a role. Implementation will require more details on costs that did not accompany the recommendations made within the BC OAH Action Plan. The BC OAH Action Plan could form a discrete action from the Coastal Marine Strategy. It also has some synergy with the federal Blue Economy Strategy. Communication between the various agencies developing these plans and strategies will be critical. As part of implementation, there is a need to collaborate across all scales and boundaries (local, provincial, federal, First Nations). It would potentially be beneficial to look at this action plan more as a collaboration network than a government mandated body, similar to a working-level collaboration that is integrated into the different jurisdiction's committees possibly at the ADM level supported by a group of experts.

What do we know about OAH in British Columbia?

Existing Monitoring Programs

There are several active ocean monitoring programs in BC producing data related to ocean acidification and hypoxia (Appendix 1). We identify here those programs directly measuring the necessary ocean variables that quantify both ocean acidification and hypoxia. While many more monitoring programs measure ocean temperature and even dissolved oxygen concentrations, few routinely make measurements that quantify both marine carbonate chemistry, necessary for assessing ocean acidification, and dissolved oxygen, to detect hypoxic conditions (Figure 8).

There are two means for making core carbon and oxygen measurements. First is a more classic approach of collecting discrete seawater samples, and subjecting them to specific chemical analyses to assess a wide range of water properties that includes carbonate chemistry, dissolved gases (*e.g.*, oxygen), and other major constituents, such as nutrients. The second and still an emerging approach is to harness an instrumented sensor system which makes specific measurements that allow determination of the desired variables. For ocean biogeochemistry, sensor development for routine monitoring is less than 20 years old, and new and improved technologies are constantly being adapted. The water sample approach is well established, but resource intensive, while instrumented systems are most often very site-specific (*e.g.*, fixed on a mooring) or limited to the surface ocean (*e.g.*, configured on vessels-of-opportunity) but provide near continuous monitoring necessary to capture variability over shorter time spans than the typical interval between research cruises.

Shown in Figure 8 are the known assets where both ocean acidification and hypoxia are routinely monitored. The assets shown include oceanographic stations where both marine carbonate chemistry and oxygen are measured, and high-resolution monitoring sites on fixed or mobile platforms that measure marine carbonate chemistry and/or oxygen. Readers should be aware that there are a significant number of oceanographic stations where oxygen but not carbonate chemistry are measured. These stations are not included here but are visible on the CIOOS Pacific data portal. The distribution of assets is presented in Figure 8 relative to DFO's defined Pacific Ocean Federal Marine Bioregions. Resources are generally concentrated in the Southern Shelf and Strait of Georgia Bioregions due to the presence of essential infrastructure and regular access from key operators (*e.g.*, DFO, Ocean Networks Canada, and Hakai Institute). A few sites are established specifically to support socio-economic activities, such as Baynes Sound in the northern Strait of Georgia, where there are numerous shellfish aquaculture facilities. There are notable areas with limited observing infrastructure and routine oceanographic sampling for oxygen and marine carbonate chemistry, including areas of the Northern Shelf Bioregion specifically around Haida Gwaii.

A key recommendation in the BC OAH Action Plan is a more thorough assessment of the monitoring needs along all of BC's coastal regions. In particular, this assessment will need to consider both present and future marine conditions, along with community and stakeholder vulnerability, and identify priority monitoring locations and approaches. This assessment will also need periodic review, as changes in marine conditions, stakeholder activity, and technology evolve.

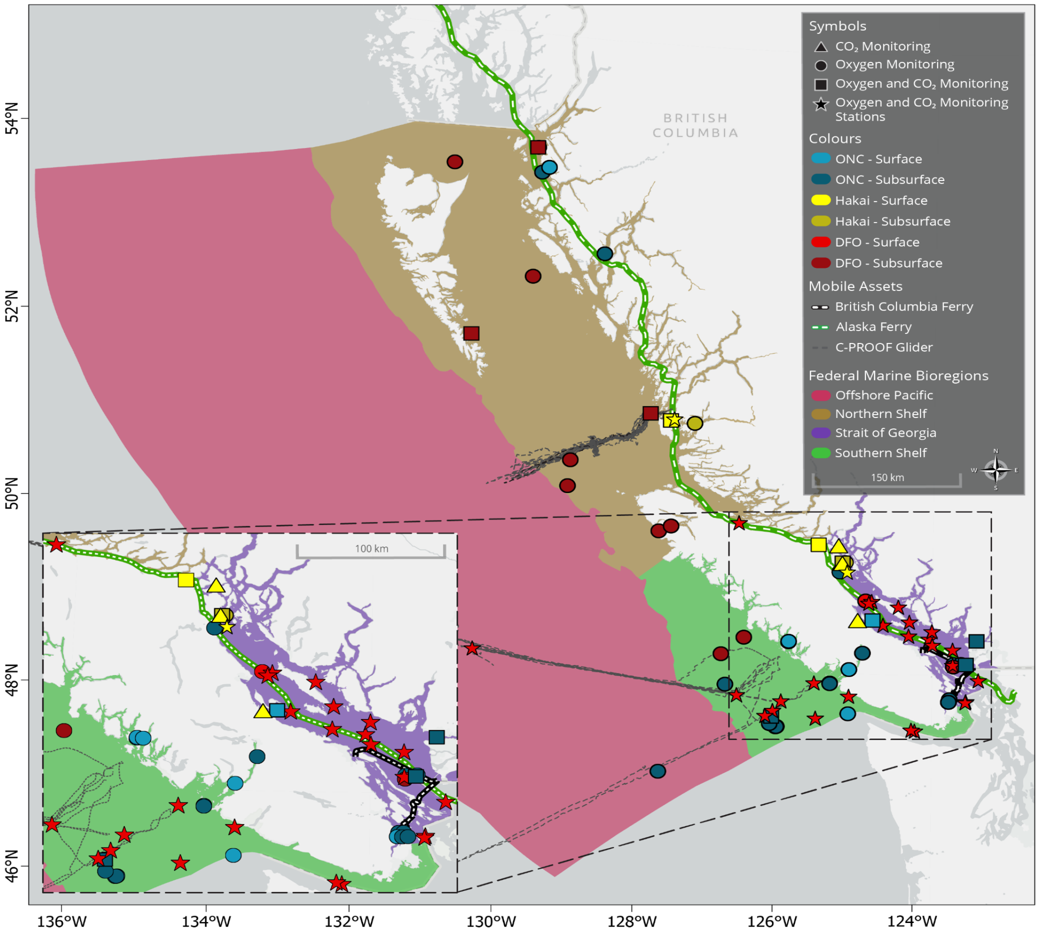


Figure 8: Locations of high-resolution monitoring assets and oceanographic stations where both marine carbonate chemistry and oxygen are measured within the Pacific Federal Marine Bioregions. Readers should note that oceanographic stations where only oxygen is measured are not included here but can be found within the CIOOS Pacific data portal. Credit: Adrienne Shumlich/Ocean Networks Canada.

Observations of OAH in the offshore Pacific and continental shelf waters

One of Canada's most significant achievements in ocean science is sustained monitoring in the Northeast Pacific along "Line P", which is a series of oceanographic stations extending from the continental shelf west of Vancouver Island to Ocean Station Papa located roughly 1500 km from shore. Oceanographic data has been collected along Line P since 1956 (Whitney et al. 2007). Over 60 years of oxygen measurements have been made along Line P; carbon chemistry measurements are more recent but are still among the longest ocean carbon time series in the world (Franco et al. 2021; Ross et al. 2020).

A recent analysis by Ross et al. (2020) reports a 15% reduction in oxygen in the upper 3000 m of the Northeast Pacific along Line P over the last 60 years. This far exceeds the global average open ocean decline of 2% reported by Breitburg et al. (2018). Associated with this oxygen decline is expansion of the oxygen minimum zone. In the Northeast Pacific, the oxygen minimum zone extends from about 480 to 1700 m, and is expanding at ~3 m/yr at its base (Ross et al., 2020). Along with these changes in oxygen, aragonite and calcite saturation horizons (the depth where saturation state = 1) have been shoaling by 1-2 m/yr since the 1980s (Ross et al., 2020).

Using Line P data, Franco et al. (2021) analyzed how the marine carbonate system changed from 1990 to 2019. Time series of salinity-normalized DIC (nDIC; normalization removes the impact of changes in salinity on measured DIC), pCO_2, pH, and aragonite saturation state in surface water all exhibited long-term trends influenced by anthropogenic CO_2 uptake (Figure 9). However, trends also were less than what would be expected from anthropogenic CO_2 uptake alone, indicating that ocean processes are masking the expected trends. This result illustrates that long time series measurements are essential to capture interactions between ocean processes and anthropogenic CO_2 uptake. For example, trends in CO_2 in the subsurface ocean were also affected by increasing remineralization.

The carbon time series along Line P was long enough to identify an 18.6-year cycle in the data associated with variability in the moon's orbit, known as the Lunar Nodal Cycle, and the impact of this pattern in shaping the trends. Such multi-decadal oscillations have been reported previously from northeast Pacific oxygen time series (Crawford and Peña 2016). Such low frequency patterns could lead to inaccurate assessments of long-term trends without long time series measurements.

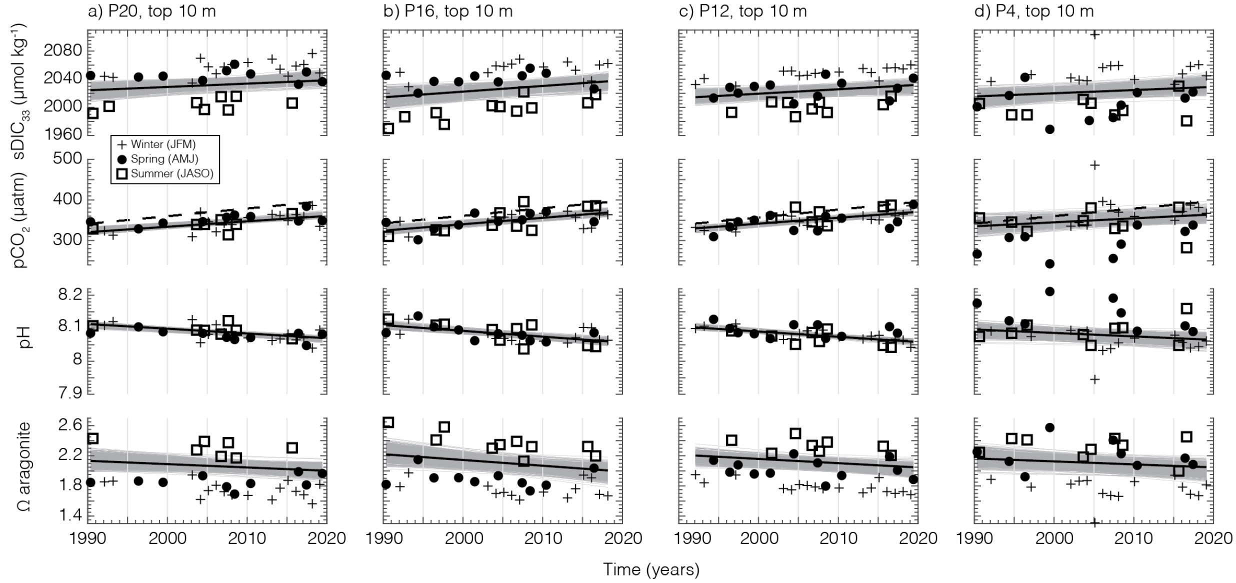


Figure 9: Time series of surface (upper 10 m) $sDIC_{33}$ (μmol/kg; DIC normalized to a salinity of 33), pCO_2, pH, and aragonite saturation state at four stations along Line P from offshore (P20) to the continental shelf (P4). Figure from Franco et al. (2021).

Crawford and Peña (2013) produced a synthesis of subsurface oxygen measurements for the Canadian Pacific coast using data from 1934 to 2011. Results from this study revealed a decline in subsurface oxygen from west to east across the Pacific, and the northward transport of low oxygen water from the eastern subtropical Pacific by the California Undercurrent. This low-O_2 water upwells onto the BC continental shelf during summer, and can be further depleted of oxygen due to high organic particle fluxes associated with upwelling.

Ianson et al. (2003) reported that water upwelled onto the BC continental shelf in summer also has high CO_2 and nutrient concentrations, and that conditions over the continental shelf can change quickly with reversals in the wind direction. Crawford and Peña (2013) observed hypoxia on the mid-shelf west of Vancouver Island, but not on the inner shelf. During 2021, extreme hypoxia was observed in this region (Ross et al. 2022). This was an exceptional hypoxia event because it was observed from Oregon to BC, and the oxygen levels seen in this area on the BC shelf were the lowest ever recorded. Observations from the inner shelf region suggest some protection from hypoxia by the Vancouver Island Coastal Current (Crawford and Peña 2013)). Areas like Barkley Sound may experience seasonal hypoxia at depth over winter due to stagnation before deep water is refreshed during the summer upwelling season (Pawlowicz 2017). These complexities highlight that conditions over the BC continental shelf are variable over a broad range of spatial and temporal scales due to interactions with the topography, local currents, and variable wind forcing.

Observations of OAH in the nearshore shelf waters

The synthesis by Crawford and Peña (2013) also highlighted hypoxic conditions in a number of BC fjords. Some of these have time series spanning over 50 years, allowing for long-term trends to be assessed. Jackson et al. (2021b) evaluated the long-term trends in oxygen, temperature and salinity within four of BC's prominent mainland fjords; significant decreases in oxygen and increases in temperature and salinity were observed in the three fjords that had less direct exchange with the open ocean. In these fjords, temperature trends exceeded the global average. The excess heat decreases oxygen solubility and was responsible for at least a quarter of the decline in oxygen. Warmer waters also accelerate the remineralization of organic matter, leading to lower oxygen content. The input of deep open ocean water into these fjord settings combined with high seasonal primary production in the surface layer and subsequent decomposition of organic matter raining to subsurface waters from the surface is one mechanism that acts to establish an oxygen minimum layer within the water column (Jackson et al. 2021a). In some cases, the oxygen minimum layer may persist all year (Hare et al. 2022). In extreme cases, seasonal anoxic conditions can develop within fjords such as Saanich Inlet, which has a shallow sill and limited deep-water renewal (Zaikova et al. 2010). However, as mentioned previously, organisms may respond negatively to concentrations above hypoxic thresholds. For instance, a recent study from Hebert Inlet in Clayoquot Sound reported seasonal hypoxic conditions developing at shallow depths in the water column (up to 12 m depth), but that slightly higher oxygen levels known to be unfavorable for salmon (< 4.9 ml/l; Davis 1975) were present year-round over 50% to 100% of the upper 50 m of the water column (Rosen et al. 2022).

Exchange between the open ocean and coastal areas, and the extent of mixing and ventilation that occurs along the flow path, are important factors establishing how sensitive nearshore regions might be to increasing ocean acidification and hypoxia. For example, oxygen has declined in the deep water in the Strait of Georgia due to the decrease in oxygen within upwelled source water entering the semi-enclosed basin during summer (Johannessen et al. 2014). However, Johannessen et al. (2014) showed that mixing of deep water with more oxygenated shallow water along the flow path into the Strait of Georgia can maintain the oxygen content of deep water, even if oxygen concentration is very low in the open ocean source water.

Ianson et al. (2016) showed that, despite mixing in Haro Strait providing protection from hypoxia, this is not the case for ocean acidification, because carbon dioxide equilibration time scales are slow (order of months) relative to the rapid transport of seawater through the mixing zone (order of days). Ianson et al. (2016) also highlighted that the Strait of Georgia has naturally high carbon content relative to open ocean seawater, and this characteristic enhances the region's vulnerability to ocean acidification. Evans et al. (2019) further highlighted that the lower alkalinity and salinity within the Strait of Georgia relative to the open shelf, combined with high carbon, leads to weakly-buffered seawater that is also undersaturated with respect to aragonite over most of the water column except within the surface layer, where biological uptake of CO_2 is large. This relatively thin (~20 m) surface layer is favorable for calcium carbonate precipitation during summer, but can be disrupted periodically by wind-driven mixing events (bringing undersaturated, *i.e.*, corrosive, water to the surface), and then breaks down during the winter.

Recent studies have also documented high sensitivity to ocean acidification in coastal areas and fjords on the periphery of the Salish Sea (Hare et al. 2020), including within Baynes Sound and Okeover Inlet (Simpson et al. 2022) – important regions for shellfish aquaculture. Seawater that is highly sensitive to ocean acidification is inherently weakly-buffered, meaning small changes in DIC result in large changes in pCO_2 and hydrogen ion concentration. Small changes in DIC can result from a variety of processes operating over a range of timescales; including hourly (tidal), daily, and weekly timescales. Continuous monitoring from moorings or other platforms is a powerful approach to capture variability on these shorter timescales. Such variability can be easily missed by even regular ship-based surveys, but can have significant implications for the aquaculture industry and other stakeholders, as was realized during the summer 2021 heat dome (Raymond et al. 2022). Thermal effects from the June 2021 heat dome were impactful (Philip et al. 2022; Raymond et al. 2022), and as described above, temperature can act as a co-stressor with ocean acidification and hypoxia leading to potentially amplified impacts on biological communities. BC has only a limited number of continuous monitoring assets currently in place to track variability on such short timescales as seen during the 2021 heat dome (Figure 8). CIOOS provides key information from a set of such monitoring assets for the shellfish industry, serving as an excellent example of what is possible with future investment.

Time series of the marine carbonate system in coastal waters are generally short along the BC continental margin (compared to the multi-decade record from Line P). The longest continuous record only began in 2014 (Evans et al. 2019). Variability in coastal settings is large relative to the amplitude of long-term change, so decades of measurements may be needed to resolve secular trends (Sutton et al. 2019). However, estimates of change can be made using the limited time series data currently in existence, assuming that surface seawater is tracking the atmospheric CO_2 increase and that the contributions from other oceanic processes are largely stable through time. Such estimates have been made for coastal waters in BC, and suggest that acidification exceeds the global average (Evans et al. 2022; Evans et al. 2019; Hare et al. 2020; Simpson et al. 2022). The most recent analysis by Evans et al. (2022) illustrates how the acidification signal varies regionally and seasonally using high-resolution data collected from an Alaskan ferry transiting through BC waters (Figure 10). This analysis also included a projection for what the acidification signal may be with an atmospheric CO_2 level consistent with a 1.5°C warmer world; the preferable Paris Agreement target (UNFCC 2015). The contemporary acidification signal accrued over the 250-year period since the start of the industrial era was on average around 40% and exceeded the global average (Jiang et al. 2019). At an atmospheric CO_2 of only 468 ppm (around 56 ppm above the 2019 level and consistent with a 1.5°C warmer world), the average acidification signal increased by another 15%. This is potentially an extraordinarily rapid change; at the current rate of global emissions this atmospheric CO_2 level could be reached near 2035. Tracking and understanding the impact of this potentially rapid change in BC's coastal waters requires sustained, continuous, and expanded monitoring within BC's coastal waters.

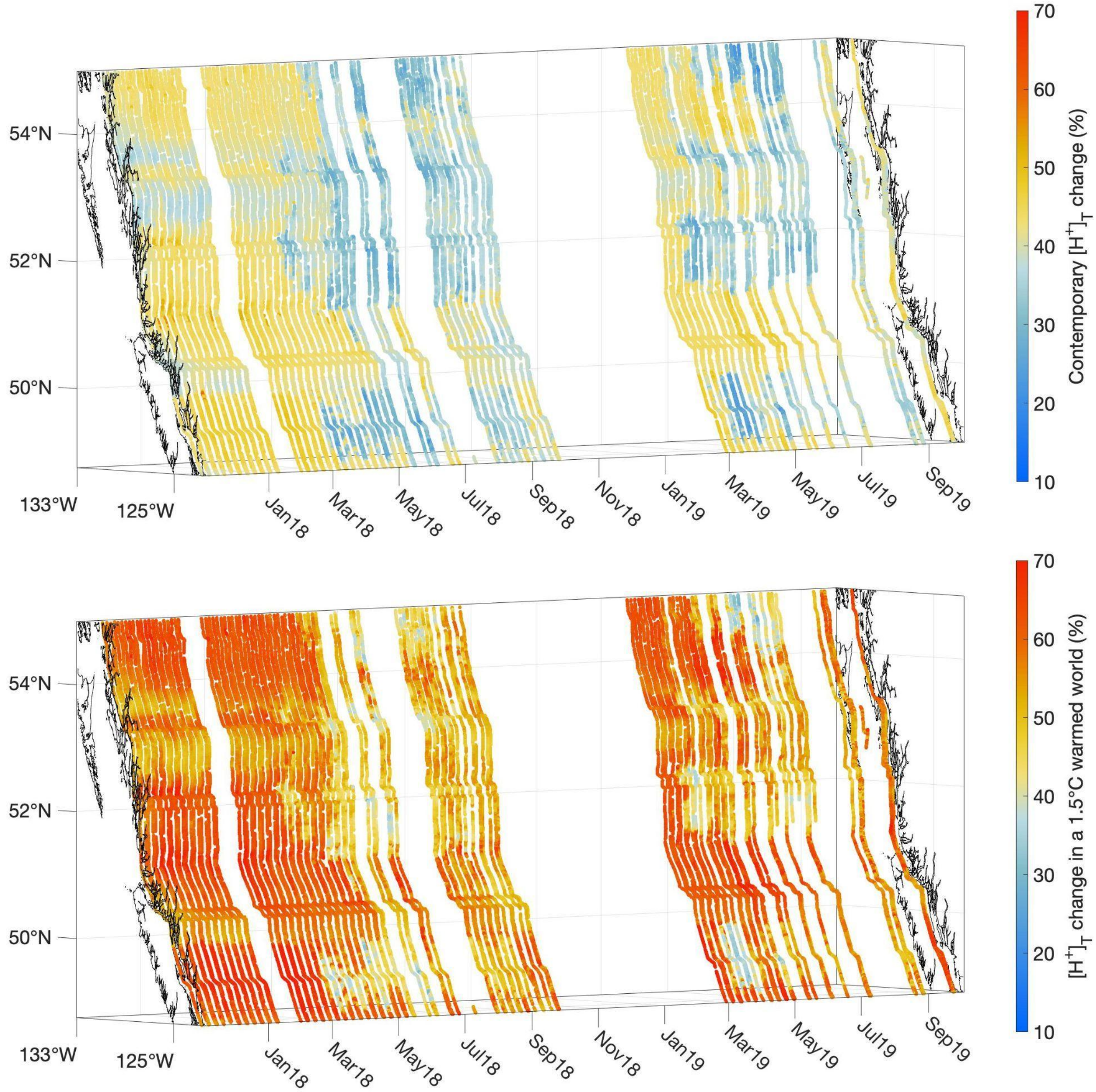


Figure 10: Acidification estimates (as percent change in hydrogen ion content) for contemporary surface water (top) and to an atmospheric CO_2 level consistent with a 1.5°C warmed world (bottom)**.** The average contemporary acidification level in BC nearshore waters is a near 40% increase above pre-industrial levels, which exceeds the global average increase of 30%. There is notable seasonal and spatial variability with a greater increase in acidification during winter. At an atmospheric CO_2 level consistent with a 1.5°C warmed world (468 ppm), the average increase in acidification reaches 55% relative to pre-industrial levels. With our current emissions trajectory, we will reach this atmospheric CO_2 level within the next 15 years. Data and analysis from Evans et al. (2022).

Gaps in OAH observing

While Canada maintains one of the longest marine carbonate chemistry time series in the world and the observing network in coastal waters is expanding in terms of the volume of measurements and its spatial footprint, gaps remain that inhibit our understanding of OAH patterns and impacts. Large areas remain unsampled, particularly in the North Coast Bioregion and in many fjords along the mainland and west Vancouver Island coasts (Figure 8). Routinely occupied oceanographic stations where both CO_2 and O_2 are measured with high accuracy are limited to mainly the Strait of Georgia and along Line P. Where high-resolution observations are being made, they are often limited to either CO_2 or O_2, cover only 1 depth, and, for the case of CO_2, are single marine carbonate system measurements (*i.e.*, pCO_2 or pH with no second marine carbonate system parameter for constraining the entire system). All of these factors limit our interpretations and result in higher uncertainty in characterizing OAH sensitivity. Importantly, and as is covered more in the biological impacts section, there are very limited co-occurring measurements of ocean chemistry and biology needed to assess impacts *in situ*. A gap in the communities' ability to coordinate and collaborate was also identified through the process of creating this action plan.

Modelling of OAH on the British Columbia coastal margin

Numerical models are a critical element of the contemporary practice of science, particularly in the ocean and atmospheric sciences. On the BC continental margin, a variety of numerical ocean models have been developed to address issues of ocean acidification and hypoxia, mainly by Fisheries and Oceans Canada and the University of British Columbia (Table 1). Such models typically include an ocean circulation model (flows forced mainly by the wind and the tides) and an ocean biogeochemistry component; the latter of which models the chemistry (speciation) of dissolved carbon dioxide, the solubility of carbon dioxide and oxygen, exchange with the atmosphere, and biological sources and sinks.

Table 1: 3-dimensional ocean models used for various applications along the BC coast. N/A means circulation model that does not yet include biogeochemistry.

Model	**Modelling system**	**Horizontal Resolution**	**BGC model**	**References**
NEP36-CanOE	**NEMO**	**2-3 km**	**CanOE**	**Holdsworth et al. 2021**
BCCM	**ROMS**	**2-3 km**	**BCCM**	**Peña et al. 2019**

SalishSeaCast	**NEMO**	**187-518 m**	**SMELT**	**Olson et al. 2020**
Broughton Archipelago	**FVCOM**	**10s-1000s m**	**N/A**	**DFO 2021**
West Coast Vancouver Island	**FVCOM**	**10s-1000s m**	**N/A**	**DFO 2021**
Discovery Islands	**FVCOM**	**10s-1000s m**	**FVCOM-ICM**	**DFO 2021**
Baynes Sound	**FVCOM**	**10s-1000s m**	**FVCOM-ICM**	**Guyondet et al. 2022**

Models provide a range of useful information that is not available from observations alone. One important function is to "fill in the gaps" in space and time. For example, observations collected from ships are usually sparse. Models constrained by observations where they are present are the best available means of extrapolating to three-dimensional fields in a dynamically consistent way. Models also provide a means of creating projections of potential future climates: it is a truism that there are no observations of the future. For example, downscaled climate projections for the BC continental margin suggest that low-pH and low-oxygen waters will increasingly encroach on the continental shelf, and that this result is not sensitive to which emission scenario is used (Holdsworth et al. 2021; see Figure 11). Finally, models can make forecasts of conditions on time scales of up to a few years (with declining skill over time). This is the most familiar application (it is analogous to the weather forecasts we consult daily), but the least developed for ocean biogeochemistry models to date in BC. Canada maintains several operational forecast systems for the physical ocean, but operational forecasting of ocean chemistry is still in an early stage of development. Washington State has maintained an operational OA forecast system since 2013 (Siedlecki et al. 2016), which covers a limited area of BC waters adjacent to the border.

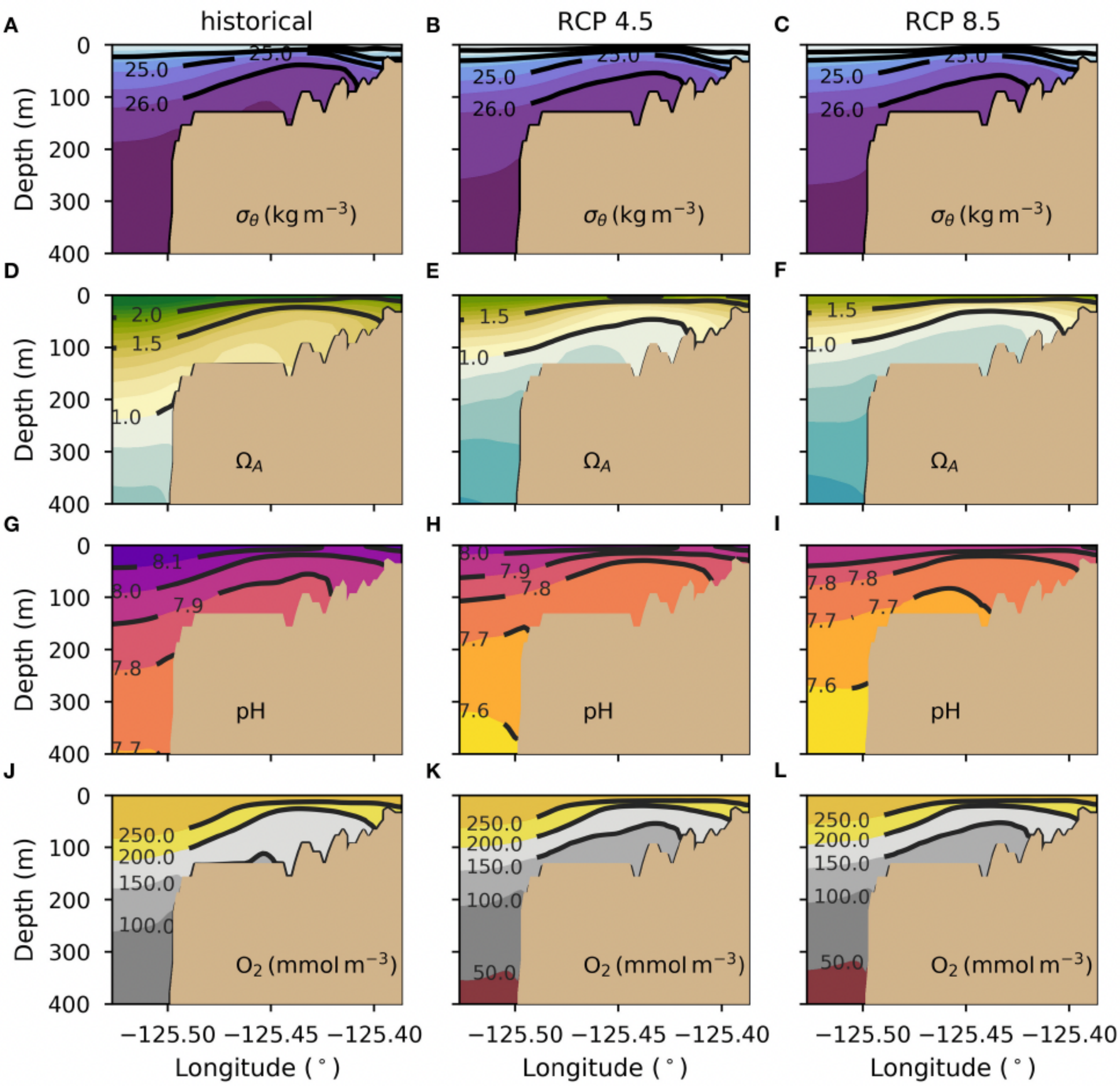


Figure 11: Vertical cross-sections showing modeled change in ocean acidification and hypoxia across the continental margin off Vancouver Island. Summer climatological conditions for historical (1986-2005) and future (2046-2065) simulations with the NEP36 model. σ_θ = density anomaly (relative to 1000 kg m^{-3}), Ω_A = aragonite saturation state. Reproduced with permission from Holdsworth et al. (2021).

The utility of model outputs is often limited by model resolution: a numerical model discretizes space on a grid with a resolution of *e.g.*, a few kilometres. Global climate models have an ocean resolution of ~100 km; climate projections must therefore be downscaled to give useful projections in the coastal zone (Figure 12). Coastwide downscaling experiments have been conducted at a resolution of 2-3 km (Foreman et al. 2014; Holdsworth et al. 2021; Peña et al. 2018), but even this is very inadequate for the extremely complex and convoluted coastlines of the BC coast. Therefore, a set of models have been developed that represent limited areas at very high resolution using unstructured grids. A regular grid has a point, for example, every 3 km in the N-S and E-W directions; an unstructured grid has variable resolution so that open water areas can be represented with a smaller number of points while resolution along a complex coastline is much finer. Several areas of the BC coast are now represented by high-resolution unstructured-grid models (Figure 13).

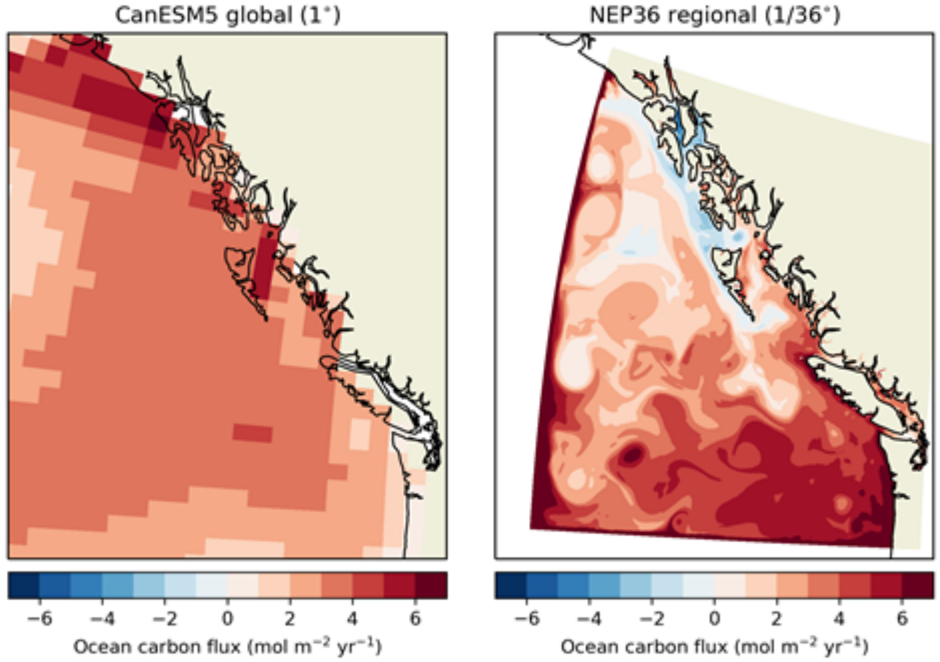


Figure 12: Example of resolution-dependence of ocean properties and emergence of small-scale processes in a downscaling simulation. Left panel: air-sea CO_2 flux from CanESM5 (~1° resolution; Swart et al. 2019). Right panel: air-sea CO_2 flux from NEP36-CanOE (2-3 km resolution; Holdsworth et al., 2021).

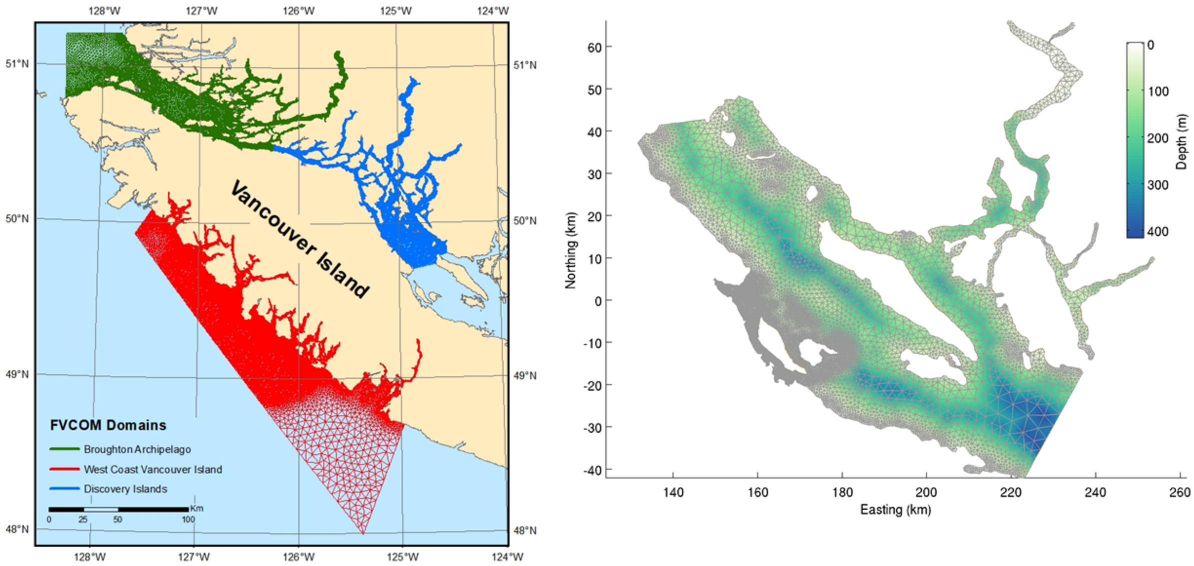


Figure 13: Locations of high-resolution model domain. Example locations of high-resolution coastal FVCOM domains maintained by Fisheries and Oceans Canada on the BC continental margin (left). Reproduced with permission from DFO (2021). High-resolution coastal FVCOM grid for Baynes Sound and the surrounding area with bathymetry (right). Reproduced with permission from Guyondet et al. (2022).

Modelling capabilities and gaps

Some ocean biogeochemical modelling capacity currently exists for regions of the BC coast (Holdsworth et al. 2021; Jarníková et al. 2022; Olson et al. 2020; Peña et al. 2018; Peña et al. 2019), however, significant gaps remain. There are real limitations to these capabilities in terms of regions covered, resolution, and type of simulations conducted. For example, for the Salish Sea there is short-term forecast capability (1-day) but no downscaled climate projections. Short term forecasts do not exist elsewhere. Coastwide models (Holdsworth et al. 2021; Peña et al. 2018; Peña et al. 2019) include the Salish Sea but have too coarse resolution to give accurate results there. Seasonal forecasts are generated operationally by Environment and Climate Change Canada for the physical ocean using coarse-resolution global climate models. Downscaling such forecasts is clearly possible, but no clear path to operationalizing such a capability currently exists. Simulating biogeochemistry with high-resolution irregular grid models (DFO 2021; Guyondet et al. 2022) is new and still in an early stage of development. Further refinement of the biological and chemical components of these models is also required (*e.g.*, inclusion of benthic respiration, more accurate representation of river water chemical composition).

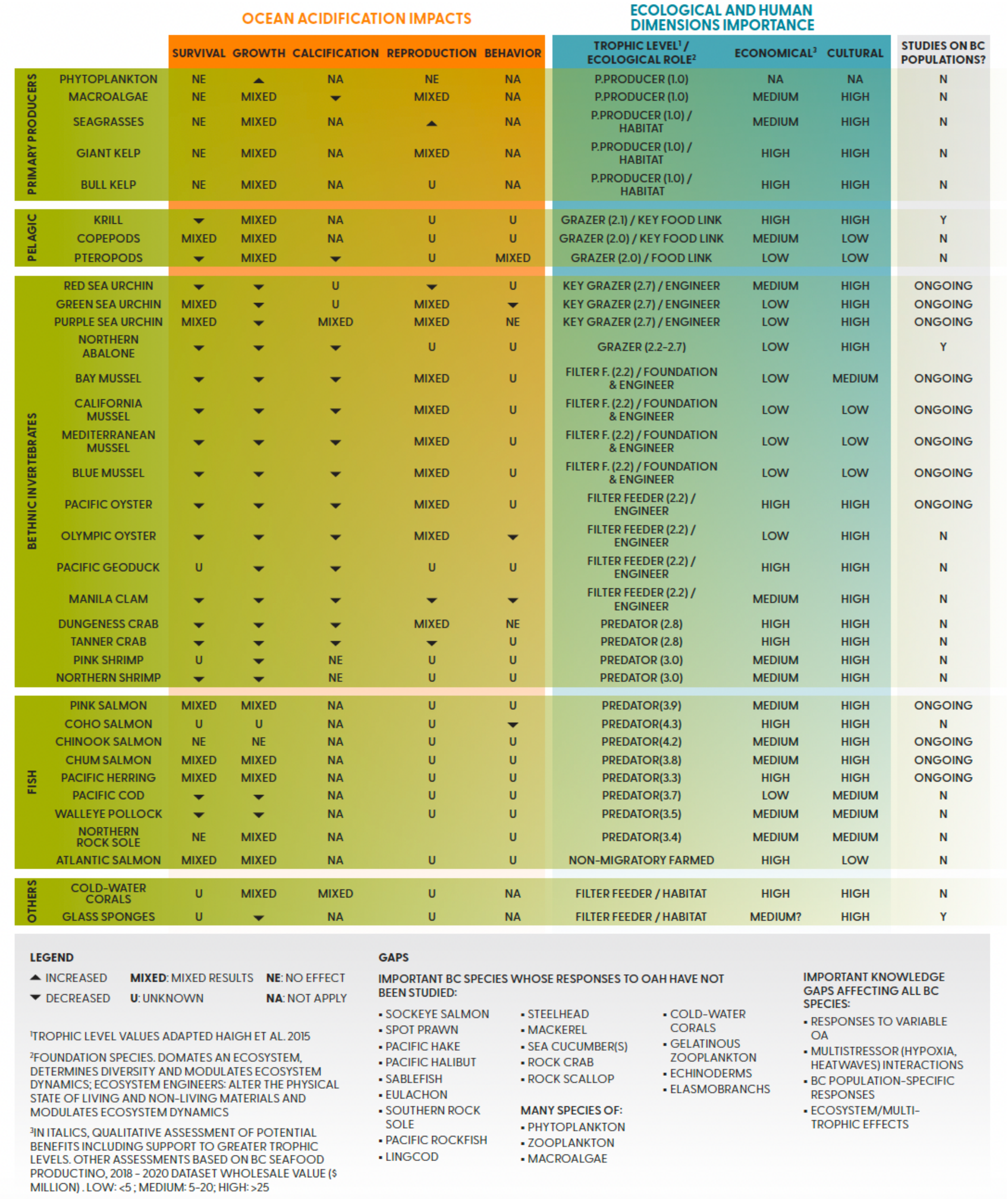
Biological Impacts of OAH in British Columbia

The first attempt to summarize and contextualize potential effects of OA on BC marine organisms and ecosystems was carried out by Haigh et al. (2015). The authors identified shellfish species as particularly vulnerable to OA, though highlighted many knowledge gaps on species and ecosystem responses, including indirect effects on species through increased production of toxins (HABs) and changes to trophic relationships. We have built on this effort, with guidance from others (Alaska Ocean Acidification Network, California Ocean Trust, West Coast OAH Science Panel and the Oregon Coordinating Council on OAH), and collated and organized published literature to date (Appendix 2) while also eliciting expert opinion on ongoing OAH research regarding the potential effects of OA and hypoxia on BC marine species and ecosystems (Figures 14 and 15).

Based on the current state of the knowledge, OA can adversely affect ecologically, commercially and culturally important BC species (Figure 14), where laboratory studies reveal most evidence of potential negative effects on invertebrate calcifying species. Shellfish species such as clams, mussels and oysters, as well as sea urchins, shrimps and crabs could potentially be severely affected by persistent corrosive conditions. In addition, OA can negatively impact zooplanktonic organisms such as krill and pteropods, key prey species for higher trophic levels in BC coastal ecosystems. Though significant gaps in knowledge remain, primary producers and vertebrates including fish seem relatively more tolerant to OA. In turn, persistent hypoxic events can disproportionately affect important fish species like multiple species of salmon, and certain invertebrates including sea urchins, and mussel and clam species (Figure 15).

Though there are many modes of action for OAH to affect marine organisms, for our synthesis we have focused on five key biological processes: survival, overall growth, calcification (OA) / physiology (hypoxia), reproduction, and behaviour. Classifying the type of effect on most processes is intuitive as, for instance, a decrease in survival is an obvious adverse effect. The understudied behaviour category, however, encompasses many types of non-intuitive responses including, but not limited to, prey avoidance, settlement behaviour, swimming patterns, or stress-related responses like bivalve gaping. For the purpose of this synthesis, a decrease in behaviour responses is associated with negative biological consequences, though the overall population effects of individual behaviour responses are hard to predict. Many marine organisms have complex life cycles that include larval and sessile life-stages, albeit most experimental research on OAH effects has focused on single life-stages. For most organisms, sensitivity to OAH stress is life-stage dependent, and frequently early larval stages or early post-larval stages (juveniles post-metamorphosis) have been identified as the most vulnerable stages to OAH. In our effort to collate available data, we have classified species as having negative effects if adverse responses have been observed in at least one life-stage even if other life-stages are not highly sensitive. On the other hand, when multiple laboratory results show contradictory results, the overall effect is characterized as mixed.

The ecological, economic and cultural importance of BC species affected by OAH was considered through a combination of qualitative and quantitative methods. Trophic level was determined using qualitative descriptors of trophic role within food webs and quantitative classification following Haigh et al. (2015). Some species play key roles within the ecosystem including serving as key food web links across trophic levels (*e.g.*, dominant zooplankton groups such as copepods and krill species), acting as ecosystem engineers by providing and modifying structural habitat and ecosystem dynamics (*e.g.*, oyster or clam beds), or by acting as foundational species by dominating and modulating an ecosystem and its diversity (*e.g.*, mussels on rocky intertidal shores). The economic importance of non-commercial species was estimated based on their role in supporting higher trophic level commercial fisheries (*e.g.*, krill and copepods) or emerging industries (*e.g.*, kelp farming), though we acknowledge that this approach underestimates potential indirect commercial value for some species. For commercial species, the 2018-2020 wholesale landing value was used and grouped under three categories: Low: <\$5; Medium: \$5-\$20; High: >\$25 (in CAD millions). Assigning cultural value to species is contingent on consultation with First Nations, coastal communities and diverse groups of stakeholders. The descriptors provided here are our best estimates to date.



		OCEAN ACIDIFICATION IMPACTS					ECOLOGICAL AND HUMAN DIMENSIONS IMPORTANCE			
		SURVIVAL	GROWTH	CALCIFICATION	REPRODUCTION	BEHAVIOR	TROPHIC LEVEL[1] / ECOLOGICAL ROLE[2]	ECONOMICAL[3]	CULTURAL	STUDIES ON BC POPULATIONS?
PRIMARY PRODUCERS	PHYTOPLANKTON	NE	▲	NA	NE	NA	P.PRODUCER (1.0)	NA	NA	N
	MACROALGAE	NE	MIXED	▼	MIXED	NA	P.PRODUCER (1.0)	MEDIUM	HIGH	N
	SEAGRASSES	NE	MIXED	NA	▲	NA	P.PRODUCER (1.0) / HABITAT	MEDIUM	HIGH	N
	GIANT KELP	NE	MIXED	NA	MIXED	NA	P.PRODUCER (1.0) / HABITAT	HIGH	HIGH	N
	BULL KELP	NE	MIXED	NA	U	NA	P.PRODUCER (1.0) / HABITAT	HIGH	HIGH	N
PELAGIC	KRILL	▼	MIXED	NA	U	U	GRAZER (2.1) / KEY FOOD LINK	HIGH	HIGH	Y
	COPEPODS	MIXED	MIXED	NA	U	U	GRAZER (2.0) / KEY FOOD LINK	MEDIUM	LOW	N
	PTEROPODS	▼	MIXED	▼	U	MIXED	GRAZER (2.0) / FOOD LINK	LOW	LOW	N
BETHNIC INVERTEBRATES	RED SEA URCHIN	▼	▼	U	▼	U	KEY GRAZER (2.7) / ENGINEER	MEDIUM	HIGH	ONGOING
	GREEN SEA URCHIN	MIXED	▼	U	MIXED	▼	KEY GRAZER (2.7) / ENGINEER	LOW	HIGH	ONGOING
	PURPLE SEA URCHIN	MIXED	▼	MIXED	MIXED	NE	KEY GRAZER (2.7) / ENGINEER	LOW	HIGH	ONGOING
	NORTHERN ABALONE	▼	▼	▼	U	U	GRAZER (2.2-2.7)	LOW	HIGH	Y
	BAY MUSSEL	▼	▼	▼	MIXED	U	FILTER F. (2.2) / FOUNDATION & ENGINEER	LOW	MEDIUM	ONGOING
	CALIFORNIA MUSSEL	▼	▼	▼	MIXED	U	FILTER F. (2.2) / FOUNDATION & ENGINEER	LOW	LOW	ONGOING
	MEDITERRANEAN MUSSEL	▼	▼	▼	MIXED	U	FILTER F. (2.2) / FOUNDATION & ENGINEER	LOW	LOW	ONGOING
	BLUE MUSSEL	▼	▼	▼	MIXED	U	FILTER F. (2.2) / FOUNDATION & ENGINEER	LOW	LOW	ONGOING
	PACIFIC OYSTER	▼	▼	▼	MIXED	U	FILTER FEEDER (2.2) / ENGINEER	HIGH	HIGH	ONGOING
	OLYMPIC OYSTER	▼	▼	▼	MIXED	▼	FILTER FEEDER (2.2) / ENGINEER	LOW	HIGH	N
	PACIFIC GEODUCK	U	▼	▼	U	U	FILTER FEEDER (2.2) / ENGINEER	HIGH	HIGH	N
	MANILA CLAM	▼	▼	▼	▼	▼	FILTER FEEDER (2.2) / ENGINEER	MEDIUM	HIGH	N
	DUNGENESS CRAB	▼	▼	▼	MIXED	NE	PREDATOR (2.8)	HIGH	HIGH	N
	TANNER CRAB	▼	▼	▼	▼	U	PREDATOR (2.8)	HIGH	HIGH	N
	PINK SHRIMP	U	▼	NE	U	U	PREDATOR (3.0)	MEDIUM	HIGH	N
	NORTHERN SHRIMP	▼	▼	NE	U	U	PREDATOR (3.0)	MEDIUM	HIGH	N
FISH	PINK SALMON	MIXED	MIXED	NA	U	U	PREDATOR(3.9)	MEDIUM	HIGH	ONGOING
	COHO SALMON	U	U	NA	U	▼	PREDATOR(4.3)	HIGH	HIGH	N
	CHINOOK SALMON	NE	NE	NA	U	U	PREDATOR(4.2)	MEDIUM	HIGH	ONGOING
	CHUM SALMON	MIXED	MIXED	NA	U	U	PREDATOR(3.8)	MEDIUM	HIGH	ONGOING
	PACIFIC HERRING	MIXED	MIXED	NA	U	U	PREDATOR(3.3)	HIGH	HIGH	ONGOING
	PACIFIC COD	▼	▼	NA	U	U	PREDATOR(3.7)	LOW	MEDIUM	N
	WALLEYE POLLOCK	▼	▼	NA	U	U	PREDATOR(3.5)	MEDIUM	MEDIUM	N
	NORTHERN ROCK SOLE	NE	MIXED	NA		U	PREDATOR(3.4)	MEDIUM	MEDIUM	N
	ATLANTIC SALMON	MIXED	MIXED	NA	U	U	NON-MIGRATORY FARMED	HIGH	LOW	N
OTHERS	COLD-WATER CORALS	U	MIXED	MIXED	U	NA	FILTER FEEDER / HABITAT	HIGH	HIGH	N
	GLASS SPONGES	U	▼	NA	U	NA	FILTER FEEDER / HABITAT	MEDIUM?	HIGH	Y

LEGEND

▲ INCREASED	**MIXED**: MIXED RESULTS	**NE**: NO EFFECT
▼ DECREASED	**U**: UNKNOWN	**NA**: NOT APPLY

[1] TROPHIC LEVEL VALUES ADAPTED HAIGH ET AL. 2015

[2] FOUNDATION SPECIES. DOMATES AN ECOSYSTEM, DETERMINES DIVERSITY AND MODULATES ECOSYSTEM DYNAMICS; ECOSYSTEM ENGINEERS: ALTER THE PHYSICAL STATE OF LIVING AND NON-LIVING MATERIALS AND MODULATES ECOSYSTEM DYNAMICS

[3] IN ITALICS, QUALITATIVE ASSESSMENT OF POTENTIAL BENEFITS INCLUDING SUPPORT TO GREATER TROPHIC LEVELS. OTHER ASSESSMENTS BASED ON BC SEAFOOD PRODUCTINO, 2018 - 2020 DATASET WHOLESALE VALUE ($ MILLION) . LOW: <5 ; MEDIUM: 5-20; HIGH: >25

GAPS

IMPORTANT BC SPECIES WHOSE RESPONSES TO OAH HAVE NOT BEEN STUDIED:

- SOCKEYE SALMON
- SPOT PRAWN
- PACIFIC HAKE
- PACIFIC HALIBUT
- SABLEFISH
- EULACHON
- SOUTHERN ROCK SOLE
- PACIFIC ROCKFISH
- LINGCOD
- STEELHEAD
- MACKEREL
- SEA CUCUMBER(S)
- ROCK CRAB
- ROCK SCALLOP
- COLD-WATER CORALS
- GELATINOUS ZOOPLANKTON
- ECHINODERMS
- ELASMOBRANCHS

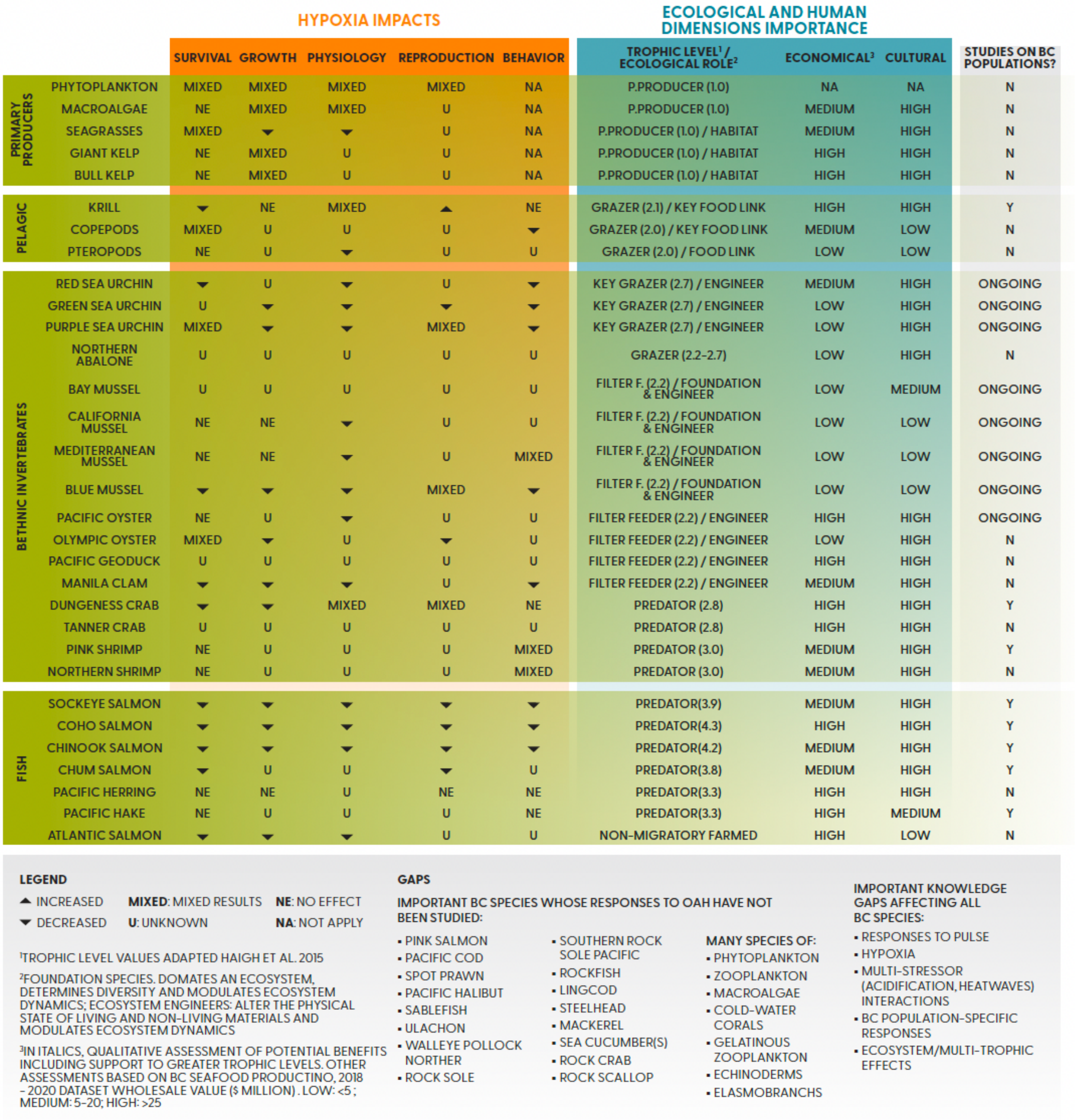
MANY SPECIES OF:

- PHYTOPLANKTON
- ZOOPLANKTON
- MACROALGAE

IMPORTANT KNOWLEDGE GAPS AFFECTING ALL BC SPECIES:

- RESPONSES TO VARIABLE OA
- MULTISTRESSOR (HYPOXIA, HEATWAVES) INTERACTIONS
- BC POPULATION-SPECIFIC RESPONSES
- ECOSYSTEM/MULTI-TROPHIC EFFECTS

Figure 14: Summary of biological impacts of ocean acidification on important marine species found in British Columbia. Credit: Iria Gimenez/Hakai Institute for content and Katana for design.



		HYPOXIA IMPACTS					ECOLOGICAL AND HUMAN DIMENSIONS IMPORTANCE			
		SURVIVAL	GROWTH	PHYSIOLOGY	REPRODUCTION	BEHAVIOR	TROPHIC LEVEL[1] / ECOLOGICAL ROLE[2]	ECONOMICAL[3]	CULTURAL	STUDIES ON BC POPULATIONS?
PRIMARY PRODUCERS	PHYTOPLANKTON	MIXED	MIXED	MIXED	MIXED	NA	P.PRODUCER (1.0)	NA	NA	N
	MACROALGAE	NE	MIXED	MIXED	U	NA	P.PRODUCER (1.0)	MEDIUM	HIGH	N
	SEAGRASSES	MIXED	▼	▼	U	NA	P.PRODUCER (1.0) / HABITAT	MEDIUM	HIGH	N
	GIANT KELP	NE	MIXED	U	U	NA	P.PRODUCER (1.0) / HABITAT	HIGH	HIGH	N
	BULL KELP	NE	MIXED	U	U	NA	P.PRODUCER (1.0) / HABITAT	HIGH	HIGH	N
PELAGIC	KRILL	▼	NE	MIXED	▲	NE	GRAZER (2.1) / KEY FOOD LINK	HIGH	HIGH	Y
	COPEPODS	MIXED	U	U	U	▼	GRAZER (2.0) / KEY FOOD LINK	MEDIUM	LOW	N
	PTEROPODS	NE	U	▼	U	U	GRAZER (2.0) / FOOD LINK	LOW	LOW	N
BETHNIC INVERTEBRATES	RED SEA URCHIN	▼	U	▼	U	▼	KEY GRAZER (2.7) / ENGINEER	MEDIUM	HIGH	ONGOING
	GREEN SEA URCHIN	U	▼	▼	▼	▼	KEY GRAZER (2.7) / ENGINEER	LOW	HIGH	ONGOING
	PURPLE SEA URCHIN	MIXED	▼	▼	MIXED	▼	KEY GRAZER (2.7) / ENGINEER	LOW	HIGH	ONGOING
	NORTHERN ABALONE	U	U	U	U	U	GRAZER (2.2-2.7)	LOW	HIGH	N
	BAY MUSSEL	U	U	U	U	U	FILTER F. (2.2) / FOUNDATION & ENGINEER	LOW	MEDIUM	ONGOING
	CALIFORNIA MUSSEL	NE	NE	▼	U	U	FILTER F. (2.2) / FOUNDATION & ENGINEER	LOW	LOW	ONGOING
	MEDITERRANEAN MUSSEL	NE	NE	▼	U	MIXED	FILTER F. (2.2) / FOUNDATION & ENGINEER	LOW	LOW	ONGOING
	BLUE MUSSEL	▼	▼	▼	MIXED	▼	FILTER F. (2.2) / FOUNDATION & ENGINEER	LOW	LOW	ONGOING
	PACIFIC OYSTER	NE	U	▼	U	U	FILTER FEEDER (2.2) / ENGINEER	HIGH	HIGH	ONGOING
	OLYMPIC OYSTER	MIXED	▼	U	▼	U	FILTER FEEDER (2.2) / ENGINEER	LOW	HIGH	N
	PACIFIC GEODUCK	U	U	U	U	U	FILTER FEEDER (2.2) / ENGINEER	HIGH	HIGH	N
	MANILA CLAM	▼	▼	▼	U	▼	FILTER FEEDER (2.2) / ENGINEER	MEDIUM	HIGH	N
	DUNGENESS CRAB	▼	▼	MIXED	MIXED	NE	PREDATOR (2.8)	HIGH	HIGH	Y
	TANNER CRAB	U	U	U	U	U	PREDATOR (2.8)	HIGH	HIGH	N
	PINK SHRIMP	NE	U	U	U	MIXED	PREDATOR (3.0)	MEDIUM	HIGH	Y
	NORTHERN SHRIMP	NE	U	U	U	MIXED	PREDATOR (3.0)	MEDIUM	HIGH	N
FISH	SOCKEYE SALMON	▼	▼	▼	▼	▼	PREDATOR(3.9)	MEDIUM	HIGH	Y
	COHO SALMON	▼	▼	▼	▼	▼	PREDATOR(4.3)	HIGH	HIGH	Y
	CHINOOK SALMON	▼	▼	▼	▼	▼	PREDATOR(4.2)	MEDIUM	HIGH	Y
	CHUM SALMON	▼	U	U	▼	U	PREDATOR(3.8)	MEDIUM	HIGH	Y
	PACIFIC HERRING	NE	NE	U	NE	NE	PREDATOR(3.3)	HIGH	HIGH	N
	PACIFIC HAKE	NE	U	U	U	NE	PREDATOR(3.3)	HIGH	MEDIUM	Y
	ATLANTIC SALMON	▼	▼	▼	U	U	NON-MIGRATORY FARMED	HIGH	LOW	N

LEGEND

▲ INCREASED	**MIXED**: MIXED RESULTS	**NE**: NO EFFECT
▼ DECREASED	**U**: UNKNOWN	**NA**: NOT APPLY

[1] TROPHIC LEVEL VALUES ADAPTED HAIGH ET AL. 2015

[2] FOUNDATION SPECIES. DOMATES AN ECOSYSTEM, DETERMINES DIVERSITY AND MODULATES ECOSYSTEM DYNAMICS; ECOSYSTEM ENGINEERS: ALTER THE PHYSICAL STATE OF LIVING AND NON-LIVING MATERIALS AND MODULATES ECOSYSTEM DYNAMICS

[3] IN ITALICS, QUALITATIVE ASSESSMENT OF POTENTIAL BENEFITS INCLUDING SUPPORT TO GREATER TROPHIC LEVELS. OTHER ASSESSMENTS BASED ON BC SEAFOOD PRODUCTINO, 2018 - 2020 DATASET WHOLESALE VALUE ($ MILLION) . LOW: <5 ; MEDIUM: 5-20; HIGH: >25

GAPS

IMPORTANT BC SPECIES WHOSE RESPONSES TO OAH HAVE NOT BEEN STUDIED:

- PINK SALMON
- PACIFIC COD
- SPOT PRAWN
- PACIFIC HALIBUT
- SABLEFISH
- ULACHON
- WALLEYE POLLOCK NORTHER
- ROCK SOLE
- SOUTHERN ROCK SOLE PACIFIC
- ROCKFISH
- LINGCOD
- STEELHEAD
- MACKEREL
- SEA CUCUMBER(S)
- ROCK CRAB
- ROCK SCALLOP

MANY SPECIES OF:

- PHYTOPLANKTON
- ZOOPLANKTON
- MACROALGAE
- COLD-WATER CORALS
- GELATINOUS ZOOPLANKTON
- ECHINODERMS
- ELASMOBRANCHS

IMPORTANT KNOWLEDGE GAPS AFFECTING ALL BC SPECIES:

- RESPONSES TO PULSE
- HYPOXIA
- MULTI-STRESSOR (ACIDIFICATION, HEATWAVES) INTERACTIONS
- BC POPULATION-SPECIFIC RESPONSES
- ECOSYSTEM/MULTI-TROPHIC EFFECTS

Figure 15: Summary of the biological impacts of hypoxia on important marine species found in British Columbia. Credit: Iria Gimenez/Hakai Institute for content and Katana for design.

Key knowledge gaps on OAH impacts

Our ability to accurately predict the fate of BC marine organisms and ecosystems when faced with near and long-term OAH conditions is severely limited by many knowledge gaps. Perhaps the most important one is the lack of basic experimental data on responses to OAH for many BC marine organisms (see Figures 14 and 15), including many ecologically, commercially and culturally important species such as salmon, herring, abalone, and hake. Given the variability of sensitivities among closely related species (Bednaršek et al. 2019; Kroeker et al. 2013), filling this knowledge gap is crucial to limit the reliance on analogues to predict species' fate to future OAH conditions. Organismal responses to OAH are also life-stage dependent but most studies to date focus on single life-stages despite observed carry-over (within one generation) and positive and negative transgenerational (across generations) effects in a handful of marine species. Accurate assessments of species' vulnerability to OAH requires improved understanding of intra- and trans-generational effects of OAH exposure, as effects may be cumulative or create bottlenecks for population abundances and stability.

Recent work reveals population-specific responses to OAH stress yet there are very few laboratory or field studies conducted on BC populations or in different locations. Corrosive and hypoxic conditions naturally occur at certain times of the year at some BC locations, creating hotspots of exposures. Therefore, it is possible that some BC populations have developed evolutionary adaptation strategies or, at the very least, are somewhat acclimated to tolerate transient unfavourable OAH conditions. Recent and preliminary work in BC suggest that Pink salmon (Frommel et al. 2020), juvenile herring (Frommel pers. comm.), and larvae from mussels and naturalized Pacific oysters (Gimenez; pers. comm.) show decreased vulnerability to OA when compared to populations from other North Pacific regions (Villalobos et al. 2020; Waldbusser et al. 2015a; Waldbusser et al. 2015b). Similarly, studies on effects of hypoxia in BC populations of several species of fish and crustaceans reveal different sensitivity thresholds when compared to other Atlantic or Pacific populations (Chu and Tunnicliffe 2015; Chu and Gale 2017; Tunnicliffe et al. 2020).

As stated in previous sections, marine carbonate chemistry and oxygen concentrations vary significantly across multiple time-scales in BC's dynamic coastal environments. Most of the currently available experimental data on organismal OA sensitivity and, to a lesser extent, hypoxia, rely however on exposure to constant concentrations of elevated pCO_2 or reduced O_2. In addition, regional data may be poor leading to global predictions being used in experimental exposures, rather than what may be environmentally relevant for BC species. Thus, there are significant gaps in our understanding of organisms, population and community responses to environmental OAH variability, despite limited evidence suggesting that organismal, population and ecosystem-level responses to OAH can vary significantly when environmental variability is incorporated into laboratory experiments (Boyd et al. 2016; Gobler et al. 2017; Kapsenberg et al. 2018; Ostrowski et al. 2022).

Scaling results from laboratory experiments on individual organisms to better predict responses on populations, communities and ecosystems is a significant challenge and the focus of numerous global research initiatives (*e.g.*, Page et al. 2022). A suite of complementary approaches are needed to bridge the gap between lower and higher levels of ecological organization, including: identifying mechanisms of OAH sensitivity in keystone and foundational species that dominate ecosystems and are crucial to their functioning and stability; elucidating community- and ecosystem-level responses using mesocosms within laboratory settings and through long-term field observations and manipulations, and; better integration of laboratory results into ecological theory and modeling that incorporates multi-stressor sensitivity and how environmental change can affect interactions within and across trophic levels (Kroeker et al. 2017). We have identified significant gaps in all three strategies that require ongoing research efforts.

OAH stress does not occur in isolation but in conjunction with other environmental and non-environmental stressors so incorporating multi-stressors in laboratory experiments and models is key to improve our ability to forecast vulnerability and resiliency of BC marine populations to future climate scenarios. In particular, understanding the interactions between OAH, rising temperatures, and potential increases in frequency and magnitude of marine heatwaves is key given the potential for synergistic effects and the overall modulating role of temperature in physiological processes. OAH interactions with additional stressors such as increases in abundance and virulence of pathogens (*e.g.*, *Vibrio* spp) or toxins from HABs and changes in food quality and abundance should also be examined.

A complementary approach to laboratory studies to explore OAH effects on BC marine biological systems is through biological monitoring of *in situ* effects, which can help to better determine population and ecosystem-level responses to OA that are hard to evaluate under controlled laboratory experiments (Page et al. 2022). Though there are many biological pelagic and benthic monitoring programs throughout BC, there are very few *in situ* observations of OAH effects on BC marine organisms or populations (Chu and Tunnicliffe 2015; Chu et al. 2018), particularly in benthic ecosystems. There is a clear need to identify suitable OAH stress indicator species for several habitats and ecosystems and for the integration of biological monitoring within existing programs that investigate and document OAH in BC coastal environments.

Understanding the effects of ocean acidification and hypoxia on the species that First Nations rely on can be facilitated by including these marginalized communities in scientific research starting at the development phase. Observing and harvesting wild species from one area over many lifetimes gains these groups a unique position to observe changes over time. Developing timelines for hypoxia and acidification and respectful consultation approaches and collaborative partnerships with First Nations and other small communities who have been heavily interacting with potentially vulnerable species over time is critical. This consultation and collaboration must be meaningful and considerate of First Nations knowledge and culture. Developing and refining our predictions for the impacts of OAH on BC marine organisms and ecosystems requires filling multiple knowledge gaps and incorporating TEK that comprises First Nations' observations and expertise.

Adaptation and Mitigation of OAH

The increasing occurrences of ocean acidification and hypoxia due to global climate change have important regional implications (Chan et al. 2019), for which adaptation and mitigation approaches may serve to reduce severity and increase resiliency (Cooley et al. 2016; Whitefield et al. 2021). In addition to rapid and deep reductions in fossil fuel emissions, various approaches may serve to address different aspects of these threats. Enhancing education and awareness, both for the public and government agencies, are key aspects of adapting to and mitigating OAH. This step is critical for making OAH science actionable. It is noteworthy that capacity issues for stakeholders and rights-holders were identified during two workshops (*BC Seafood Harvester and Producer Perspectives on OAH*, *BC Coastal Communities' Perspectives on OAH*), which need to be addressed in order to enable equitable engagement and resiliency to OAH. This was particularly true for coastal First Nations that must be part of the co-development of research products as well as the decision-making process for sustainably managing coastal resources.

Ocean acidification has already been identified as a major threat through the *Preliminary Strategic Climate Risk Assessment for British Columbia*, however, as has been discussed, hypoxia and ocean acidification are co-occurring stressors that are metabolically linked (Figure 9) as well as are challenges that span the jurisdictions of Federal, Provincial, and First Nation Governments; thus, requiring a coordinated effort to develop policies and practices that address their manifestation in BC. This topic was introduced during the *Policy and Governance Considerations for BC's OAH Action Plan* workshop but requires further careful consideration by a body tasked with implementing the BC OAH Action Plan. These levels of government together can facilitate discussions around solutions that are necessary as OAH will continue to intensify in BC for years to decades even after global climate targets are met due to lags stemming from CO_2 equilibration timescales (Jones et al. 2014) and ocean circulation patterns (Feely et al. 2008; Joos et al. 2011).

Solutions deployable over the decade to help mitigate OAH and enhance adaptive capacity were first introduced during the *State of the Science of OAH Research in BC* workshop and included select key measures. Firstly, the role of traditional ecological knowledge (TEK) has been grossly under-appreciated, despite the power in bridging western science and TEK to enhance ocean observing (Proulx et al. 2021) and achieve better management of coastal resources (Ban et al. 2018). Bridging TEK and western science can help expand our understanding of OAH impacts by identifying shifting patterns in species distributions and helping to prioritize species- and ecosystem-level assessments of OAH impacts. Adaptation can also be enhanced by the development of frameworks to modernize fisheries and aquaculture sectors, as the slow permitting process was identified as an area that hampers the industry's ability to adapt to climate change, including the occurrence of extreme events (Raymond et al. 2022). As highlighted above, marine calcifiers are particularly vulnerable and the BC shellfish industry needs support to develop best practices for adaptation approaches in order to thrive as coastal waters continue to acidify. In addition to evaluating the permitting process, examinations are needed into restorative aquaculture and methods to mitigate OAH within aquaculture settings. Increasing adaptive capacity can also be achieved by bolstering research into Vancouver Island University's Selective Breeding Programs, which seeks to select for individuals in a species (*i.e.*, Pacific oyster) that have a greater tolerance to anticipated ocean acidification levels in the future. A careful evaluation is also needed on the interaction between manifestations of OAH and other emerging climate-related threats, for instance interactions with the increasing frequency and intensity of atmospheric rivers (Gillett et al. 2022) or heat domes (Philip et al. 2022). Finally, there is an intensifying focus on climate mitigation through atmospheric and marine CO_2 removal, with proposed marine approaches having potential to alter biogeochemical cycles in ways that impact the manifestation of OAH. Approaches could either mitigate or intensify OAH, and research into these avenues must proceed in a careful, open, coordinated and responsible manner (Loomis et al. 2022). We considered some interactions with OAH in more detail below.

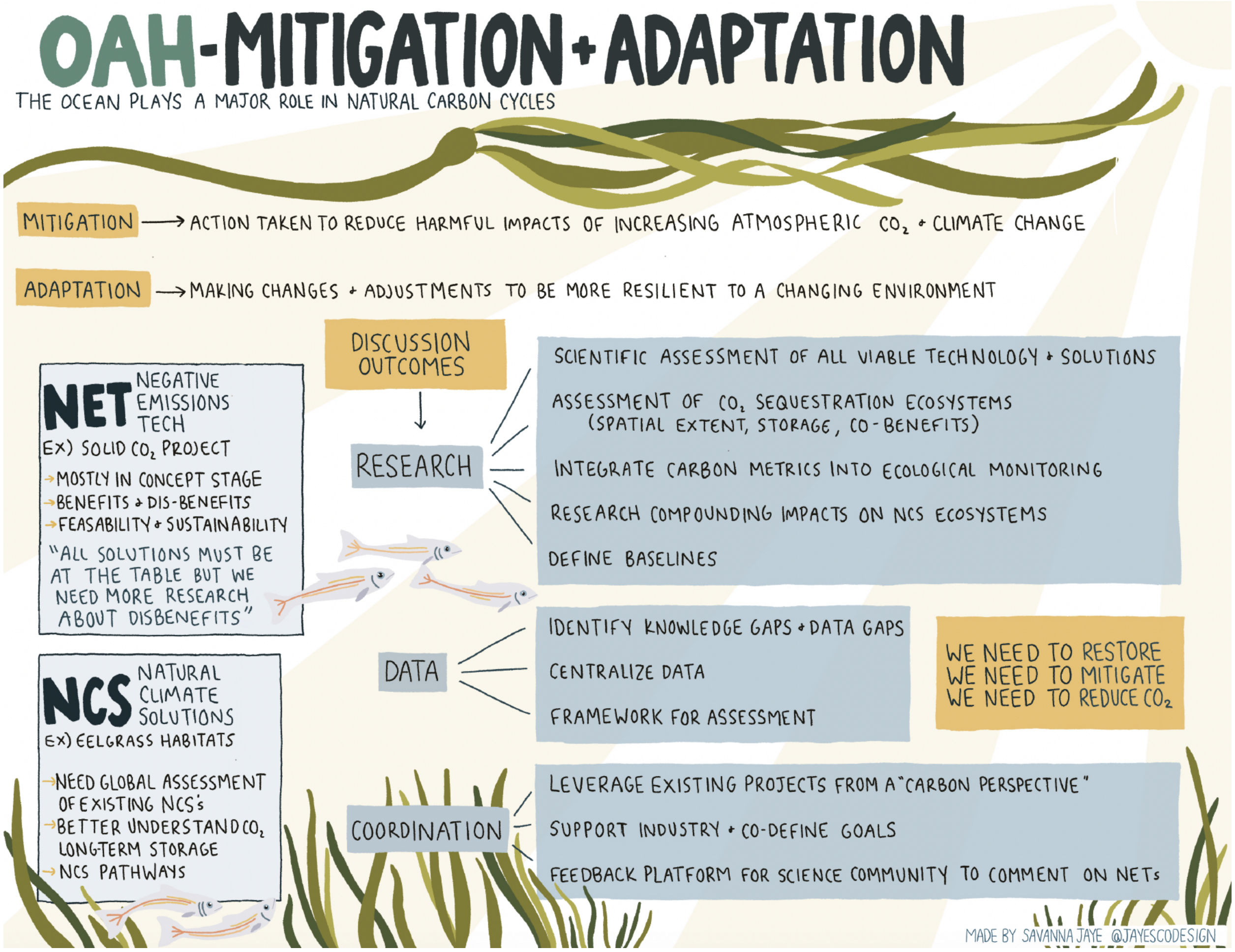
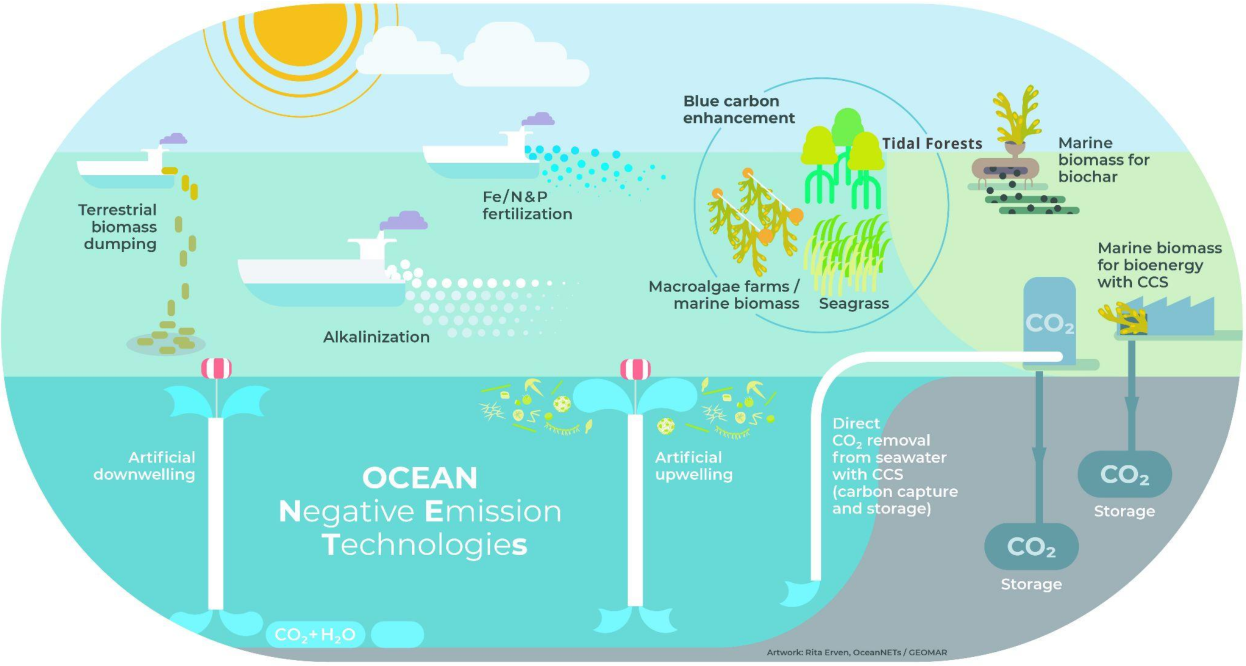


Figure 16: Graphic describing elements of OAH mitigation and adaptation.

Linkages between OAH and proposed approaches for marine carbon dioxide removal

To reach internationally agreed upon climate goals (UNFCC 2015) and constrain the harmful impacts of climate change, it is widely acknowledged that in addition to rapid and deep emission reductions, major efforts will be necessary to remove CO_2 from the atmosphere (Riahi et al. 2022). Government organizations, research communities, and developing industries are exploring a wide range of CO_2 removal (CDR) approaches under the broad category of negative emission technologies (NET). In BC's *Roadmap to 2030*, NET was identified as potentially playing an important role in helping BC reach its climate targets. Given the ocean covers 70% of the surface of the planet and currently sequesters 2.8 GtC per year (Friedlingstein et al. 2022), it is widely considered that the ocean can have a greater role in mitigating climate change. However, as detailed in a recent U.S. National Academies of Sciences, Engineering, and Medicine report (National Academies of Sciences 2022), there are common challenges to the proposed methods for enhancing the ocean's role in marine CDR that include frameworks for monitoring, reporting, and verification (MRV), potential impacts and risks to the marine environment, as well as high costs associated with these technologies to achieve levels of sequestration that are at the scale of the problem. It is essential that marine CDR activities implemented in BC waters be assessed, regulated, and managed to ensure maximal environmental and community benefit, while minimizing any negative or detrimental environmental, economic, or societal effects, including exacerbating OAH conditions.

The present suite of marine CDR approaches can be grouped into three main categories: a) enhanced biological carbon fixation, b) ocean alkalinity enhancement, and c) direct carbon capture and storage in the deep ocean or seabed (Figure 17). For both biological carbon fixation and ocean alkalinity enhancement, alterations to natural processes are confined to surface waters, where photosynthesis and direct exchange with the atmosphere are integral to atmospheric carbon dioxide removal (Figure 17). Many areas where proposed alterations are being investigated are in coastal regions, which are inherently complex and with dynamic carbon cycling, such that longer duration storage (*e.g.*, > 100 years) is achieved through active burial or transport to the deep ocean to depths exceeding 1000 m (Krause-Jensen and Duarte 2016; Siegel et al. 2021). Deep ocean carbon storage may have longer term sequestration potential, but is likely the most technically challenging and cost prohibitive approach.



Artwork: Rita Erven, OceanNETs / GEOMAR

Figure 17: Ocean negative emission technologies (NET). Also referred to as marine carbon dioxide removal (CDR). These approaches are part of a growing climate action effort to scale-up

CDR and carbon capture and storage (CCS) initiatives. Shown here are a range of marine CDR approaches being assessed. Image adapted from Rita Erven/GEOMAR.

The 2022 National Academies for Science, Engineering, and Medicine (National Academies of Sciences 2022) report assessed the research needs to close knowledge gaps for various marine CDR approaches, including: ocean fertilization, artificial up- and down-welling, seaweed cultivation, recovery of critical coastal ecosystems, ocean alkalinity enhancement, and electrochemical approaches. These approaches were assessed on the basis of the existing knowledge base, their potential CDR efficiency, the scalability and durability of the approach, the environmental risk and any co-benefits, and the social considerations and costs in terms of scale-up, carbon accounting, and environmental monitoring. Apart from the potential for marine CDR through the recovery and protection of critical marine blue carbon ecosystems (BCEs; Macreadie et al. 2021; Macreadie et al. 2019), which had few drawbacks but limited scalability and variable efficiency, all other approaches assessed had medium to high levels of environmental risk. Of particular concern are approaches that propose major changes to parts of the ocean system, without a full understanding of the complete consequences and efficiency of any CO_2 removal activity. An emerging view is that a portfolio of approaches operating on different scales may be required to effectively utilize marine CDR to achieve sequestration rates with magnitudes equal to or exceeding 1 GtC per year (Riahi et al. 2022). For instance, for seaweed cultivation to remove 0.1 GtC per year (~100x less than current annual emissions), (National Academies of Sciences 2022) estimated that a 100-m wide continuous belt of coastline extending 730,000 km would need to be cultivated. This represents 63% of the global coastline and is clearly not possible due to the availability of suitable areas for cultivation, and competition with other uses (Duarte et al. 2017). However, this highlights that some combination of approaches will be needed to reach CDR levels that appreciably remove atmospheric CO_2 at the timescales needed, in combination with rapid and deep fossil CO_2 emissions reductions, in order to reach our climate goals. What is needed is a clear BC-centric framework for assessing the effectiveness of marine CDR approaches (*i.e.,* MRV) that builds on recommendations from the international community. This should include evaluations of the scientific, socio-cultural and economic co-benefits and 'dis-benefits' of different CDR approaches tested in BC waters. This should be accomplished by leveraging and aligning existing and international efforts (*e.g.*, Pacific Coast Collaborative's Climate Resilience Working Group).

The recent National Academies for Science, Engineering, and Medicine assessment, together with other rigorous reports of marine CDR strategies (*e.g.*, Gattuso et al. 2021; Gattuso et al. 2018), considers both natural and cultivated marine vegetation as feasible CDR pathways to explore. Marine vegetation has a high photosynthetic capacity and rapid turnover time, which potentially leads to CO_2 drawdown in seawater and subsequent CO_2 exchange between the ocean and atmosphere. The biomass of marine vegetation is then subsequently buried locally within sediments or exported, potentially to the deep sea (Figure 2). The potential role of marine vegetation in carbon sequestration stems from reports of relatively high fractions (~11%) of macroalgal net primary production comprising BCEs being exported to the deep sea (Krause-Jensen et al. 2018), but this paradigm can be complicated when considering the impact of microalgal and calcareous components of BCEs that contribute to the net ecosystem production of these systems (Filbee-Dexter et al. 2022; Gallagher et al. 2022) and the role of methane production (Roth et al. 2023). Careful evaluation of all components of BCEs including organic subsidies to these ecosystems needs to be considered in order to accurately gauge their mitigation potential (Gallagher et al. 2022), as well as data that is specific to the BC coastline and not extrapolations from other regions. Reports of BCE carbon storage in BC are limited to a few studies in seagrass (Douglas et al. 2022; Postlethwaite et al. 2018; Prentice et al. 2019) and marsh ecosystems (Chastain et al. 2022; Douglas et al. 2022; Gailis et al. 2021). These trends suggest that carbon storage potential associated with these habitats is variable but on par with other northern temperate ecosystems (*e.g.*, Prentice et al. 2020; Röhr et al. 2018; Ward et al. 2021). Another proposal being considered is the sinking of macroalgae biomass in the deep ocean that was produced within BCEs or at aquaculture sites, however, significant research into the efficacy and environmental impacts of such an approach is needed (Ocean Visions and Monterey Bay Aquarium Research Institute 2022; Ricart et al. 2022). Finally, biomass that is produced within BCEs may be used to offset CO_2 emissions associated with other human uses. For example, seaweed biomass used as biofuel and food (for both humans and livestock) is an active area of research, where the life cycle costs of seaweed use are being evaluated with respect to traditional high intensity CO_2 emission activities (Duarte et al. 2017). Globally, these natural climate solutions can have the potential to contribute substantially to CO_2 emission reductions, on the order of 3% of the global emissions for 2020 (Macreadie et al. 2021; Seddon et al. 2020).

Because of their photosynthetic capabilities, marine vegetation that form BCEs may also impact the marine carbonate system where they grow in ways that can be beneficial for other species vulnerable to OA (Ricart et al. 2021a). While using dissolved inorganic carbon to produce organic matter during photosynthesis (Figure 2), marine vegetation can mitigate local adverse pH and saturation state conditions and provide refugia for vulnerable species (Kapsenberg and Cyronak 2019; Nielsen et al. 2018). For example, amelioration of adverse pH conditions in upwelled water on the coast of California has been reported during summer months associated with high seagrass productivity (Ricart et al. 2021b). However, marine vegetation creates biologically and hydrodynamically complex habitats which also mediate the direct effects of photosynthesis on ocean biogeochemistry (Van Dam et al. 2019; Van Dam et al. 2021). Physical factors, such as tides, currents, waves, water residence time, light, temperature and salinity, influence seawater conditions, and have the potential to counteract or augment biogeochemical changes associated with photosynthesis (Doo et al. 2020). Furthermore, macrophytes exhibit seasonal variability, often increasing their growth rates and biomass in spring and summer months. So, understanding of the potential mitigation of OA associated with macroalgal-related photosynthesis demands research that quantifies the net effects of observed changes throughout the year, and between locations with different biological and physical characteristics.

Similar to British Columbia, other province and state-level reviews of research and monitoring along the west coast of North America (Washington Marine Resources Advisory Council 2017; Nielsen et al. 2018) have highlighted the need for advancing our understanding of where and when BCE habitats ameliorate OA. Overall, research and case studies from other locations show that BCEs hold great promise as contributors to climate mitigation and to the resiliency of coastal areas in the face of OA and other stressors. However, little research has explored the interlinkages between these different functional attributes (*i.e.*, ecosystem services) of macrophyte-dominated habitats (except see Ravaglioli et al. 2019). Greater coming together of the research communities studying BCE and OAH is needed in order to critically assess the true promise of these habitats, drawing on expertise in the fields of ecology, biogeochemistry and oceanography. This is especially important for management considerations as there are different timescales and costs/considerations associated with different ecosystem services. For example, the timescales for carbon sequestration, on the order of a century, differs hugely from OA alleviation, which may be more pronounced seasonally when macrophyte biomass is high (Nielsen et al. 2018). In British Columbia, pilot projects for CO_2 removal via BCEs (*i.e.*, habitat restoration, enhancement and preventative loss) and studies of natural analogue environments (*e.g.*, refugia locations where low pH conditions are ameliorated) could be used as focal studies of these interactions.

Management pathways that explicitly consider restoration of blue carbon ecosystems, or means to reduce their ongoing, or projected declines, are considered 'blue carbon enhancements' (Figure 17). BC's *Roadmap to 2030* specifically highlights blue carbon enhancements as a strategy in the portfolio of approaches being used to reach BC's climate goals. In order to plan for, and account for these strategies so that they meet international standards (*e.g.*, Verified Carbon Standards for global carbon markets), a suite of research and implementation actions are needed to fill existing data and knowledge gaps to quantify and assess GHG removals as: real, measurable, permanent, and additional to the status quo. Major data and knowledge gaps include quantifying the spatial distribution of BCEs (including the temporal and spatial patterns in distribution, the carbon storage and emissions offset potential, and the management actions that can influence carbon sequestration), understanding the interaction between blue carbon enhancement and climate change, and understanding the full spectrum of benefits from BCEs and natural climate solutions, including their market and non-market values.

The Main Goals of the BC OAH Action Plan

The BC OAH Action Plan identified 5 goals to enhance understanding and awareness of ocean acidification and hypoxia, and to build stronger resilience with approaches to increase collaboration and measures to enhance mitigation and adaptation. Each goal contains one or more objectives, and each objective contains 1 or more actions needed to successfully reach the goal. Sixty-two actions are recommended within the BC OAH Action Plan. We describe below the elements of each goal, and point the reader to the BC OAH Action Plan document for the recommended actions associated with each goal.

Goal 1 of the BC OAH Action Plan aims to build and strengthen collaborations related to OAH science and engagement. Enhancing collaborations is a critical aspect of the BC OAH Action Plan. A task force appointed by the Province of British Columbia will enable stronger collaboration and engagement, define metrics of success and track the progress made in carrying out actions recommended by the BC OAH Action Plan over the coming years. Following appointment by the Province, the OAH task force would be responsible for developing a communications platform as well as a registry for the research community, First Nations, seafood industry partners, and coastal communities engaging in or concerned about OAH. The OAH task force will also work to grow and sustain the collaborations already in place along the Northeast Pacific, which includes planning and organizing an annual workshop for the BC OAH community.

Goal 2 of the BC OAH Action Plan aims to increase public awareness and understanding of OAH. Elevating the awareness and understanding of OAH for the public, as well as for decision makers from the highest levels of government to stakeholders making day-to-day operational decisions, is essential for increasing resilience. Greater awareness and understanding leads to better decision making that enables communities and industries potentially impacted by OAH to become more robust. Part of this process includes connecting to and building relationships with coastal communities, and cataloging concerns from these communities related to OAH. Also important in this process is identifying and promoting positive steps forward, as positive messaging can help inspire engagement. Some existing programs, such as the Master of Disaster: Youth emergency preparedness classroom program, can be utilized to build OAH messaging into the BC school system.

Figure 18: Overview graphic of BC OAH Action Plan goals and objectives.

Goal 3 of the BC OAH Action Plan aims to advance scientific understanding of OAH. A number of key scientific advancements must be made to increase the understanding of OAH in BC. Central to this is coordination between research entities such that rapid and holistic information can be generated on trajectories and impacts. Bridging TEK and western science in ways to better define shifts in biodiversity and species range will be critical for characterizing the breadth of biological impacts from OAH, as well as setting priorities for evaluating species where are unknown. BC lacks model forecast capacity on management-relevant time scales (*i.e.*, months to seasons), and is missing biological and chemical measurements in many regions. Supporting the advancement of scientific understanding of OAH in BC is directly in line with facilitating a more resilient future for BC as outlined by the *Climate Preparedness and Adaptation Strategy: Actions for 2022-2025*.

Goal 4 of the BC OAH Action Plan targets the interaction between potential marine CO_2 removal approaches and OAH. BC's *Roadmap to 2030* and the recent Intergovernmental Panel on Climate Change Assessment Report (2022) highlight the need to enhance atmospheric CO_2 removal, in addition to rapid and deep reductions in fossil fuel emissions, to reach climate targets. Proposed marine CO_2 removal approaches remain exploratory, largely untested, and present a myriad of potential risks for the welfare of coastal ecosystems and communities. Significant research must be undertaken to evaluate the efficacy and permanence of these approaches, and the risks they may pose in terms of enhancing the manifestations of OAH.

Finally, goal 5 of the BC OAH Action Plan aims to enhance mitigation, adaptation, and resilience to OAH. Important actions can be taken to mitigate adverse marine carbonate chemistry conditions, increase adaptive capacity, and build stronger resilience to current and future manifestations of OAH. The recommended actions are in addition to deep and rapid reductions in fossil fuel emissions, and should be considered "short-range" recommendations. OAH presents challenges that span Provincial, Federal, and First Nations Government Jurisdictions, and therefore a coordinated inter-governmental approach is needed to develop long-range solutions for BC.

The path forward in the "Ocean Decade"

The United Nations declared 2021-2030 as a Decade of Ocean Science for Sustainable Development, or "The Ocean Decade", to ensure that ocean science can support the global community to achieve the 2030 Agenda for Sustainable Development. The 2030 Agenda for Sustainable Development includes a global goal to address "*life below water*" (SDG 14) that targets a number of areas of degradation in the marine environment including ocean acidification (SDG 14.3). The United Nations Sustainable Development Goal 14.3 specifically calls to "*minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels*". Through the development of this OAH action plan, British Columbia is taking a landmark step forward along this path as the first Canadian province to recommend actions needed to understand and minimize the impacts of ocean acidification and hypoxia within the province's coastal waters. Enacting the recommendations provided in the BC OAH Action Plan will take a coordinated approach that involves federal, provincial, and community-level engagement; all hands will need to be on deck to successfully enact these recommendations. BC's OAH Action Plan is a shining example of how provincial leadership is thinking globally about the world-wide problem of increasing ocean acidification and hypoxia but acting locally to enhance the resilience of BC to these threats.

The authors of this report envision that the implementation of the BC OAH Action Plan will span the coming 5 years and be orchestrated by a provincially-appointed OAH task force. The OAH task force should comprise key science experts as well as community and government leaders. The vision for our future involves strong coordination and collaboration between research groups, stakeholders, and coastal communities, enhanced ocean observing that has addressed the key gaps outlined in this report, a clearer and more holistic understanding of the responses to OAH across species and ecosystems, predicted ocean conditions over timescales important for resource managers and decision-makers, a clear BC-focused view of the implications of marine CDR on OAH manifestations as well as impacts on biodiversity and equitable deployment, and ultimately a more resilient ocean environment that brings to realization for BC the sustainability goals of the Ocean Decade.

Metrics of Success

The Province of British Columbia has recently released a *Climate Preparedness and Adaptation Strategy: Actions for 2022-2025* that defines the development of this action plan as one of a group focused on "enhancing the resiliency of species and ecosystems through improved understanding of the impacts of climate change on key species, habitats and ecosystems" (Pathway 3). The tides have been turning on a history of inaction by BC with regard to addressing OAH, and the growing focus and momentum will drive the successful implementation of this plan. What that success looks like, in terms of how aspects of the BC OAH Action Plan are implemented, should be gauged by a provincially-appointed OAH task force, and ideally through an open review and evaluation of the actions implemented and information gained over the coming years. BC's *Climate Change Accountability Act* provides some avenues for this through the comprehensive re-assessment of climate risks on a 5-year basis and through the annual Climate Change Accountability Reports. What success ultimately looks like is a sustained and coordinated focus on OAH, with investment into strengthening the understanding of OAH including adaptation and mitigation approaches, that sets us on the path toward enhanced resiliency in BC.

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Appendices

Appendix 1: Joint OAH Monitoring Task Force Inventory

In 2018 the Joint OAH Monitoring Task Force established by the Pacific Coastal Collaborative and the U.S. federal Interagency Working Group on Ocean Acidification completed an inventory of OAH monitoring assets along the North America west coast from California to Alaska. This was a comprehensive inventory of activities related to physical, chemical, and biological monitoring efforts along the coast. This is an ideal product for the BC research community to build on, with support from the Canadian Integrated Ocean Observing System, to incorporate information addressed in the actions of this report, and utilize this as a "living platform" to facilitate collaboration and information exchange.

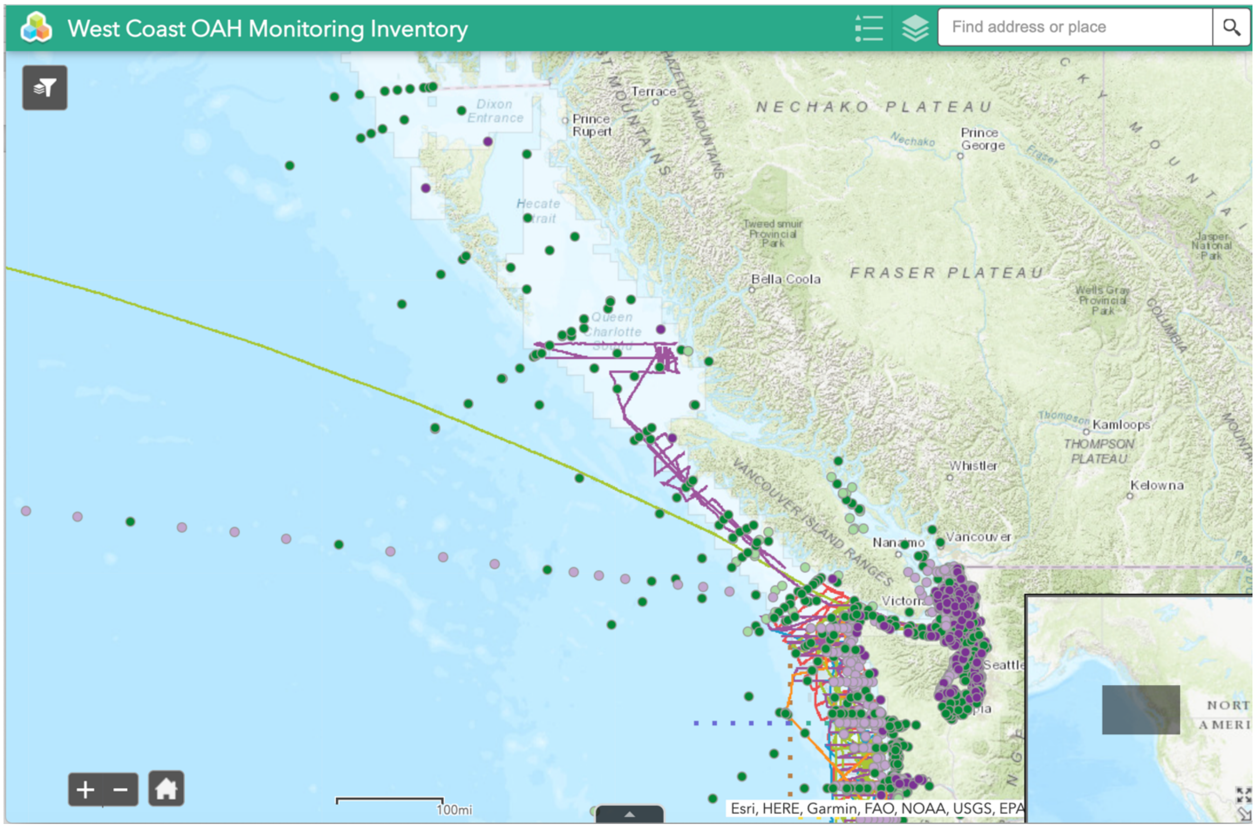

Figure A.1: Image of the West Coast OAH Monitoring Inventory completed in 2018.
https://www.arcgis.com/apps/webappviewer/index.html?id=a8b5c0ecfbe7451e950def767c55335e

Appendix 2: Reference list for biological impact infographic

BC coastal phytoplankton communities are diverse but generally dominated by diatoms and dinoflagellates. Although there are many gaps in knowledge regarding individual species' direct responses to OAH, most BC phytoplankton species might be relatively unaffected by OA or show slight positive effects in growth. By contrast, hypoxia effects on survival, growth and reproduction of BC phytoplankton species are mixed, as some laboratory results show positive effects whereas other studies showed slight negative effects. Though negative responses to OA have been documented for some species of calcifying coccolithophores, their contribution to overall primary production in most BC environments is relatively small, despite their occasional coastal blooms and presence in offshore surface environments. Indirect effects of OAH on phytoplankton communities are harder to predict and quantify, although there is potential for community composition changes that could affect higher trophic levels. There is also evidence that at least some phytoplankton species that can generate Harmful Algal Blooms (HABs) might increase their growth rate and toxin production under future OA, although responses are species and strain-specific and may be modulated by light, temperature and nutrient availability, warming and higher light levels. The potential synergistic effects of OAH and other stressors on phytoplankton communities, ecosystem functioning and dynamics, and HABs are not well understood.

OAH effects on other primary producers such as macroalgae, including kelp, and seagrasses, have been less studied. Currently available results reveal mixed responses to OA for most macroalgal and seagrasses. Effects of OA on calcifying species are adverse overall and hypoxia generally results in negative responses in various species of macroalgae and seagrasses. The ecological implications of disruptions to ecosystems sustained by these primary producers are currently poorly understood despite changes in community structure likely to be expected as species less sensitive to OAH stress could potentially outcompete and displace vulnerable ones.

Despite their importance in sustaining higher trophic levels as common prey for many species of fish, including salmon and herring, BC zooplankton responses to OA and hypoxia are not well studied, particularly for microzooplankton and gelatinous species. Among important Calanoid copepods, OAH responses are species-specific and vary from relative resilience to moderate OA and mild hypoxia for locally dominant *Calanus pacificus*, to heightened sensitivity in other common copepod species (*Pseudocalanus spp., Acartia spp.*). Pteropods are particularly vulnerable to OA, but their responses to hypoxia are not well understood. OAH impacts on krill are also not well understood but the dominant krill *Euphasia pacifica* is sensitive to OA and hypoxia, with potentially some positive responses on reproductive output but negative impacts on overall survival. Responses of other krill species commonly found in BC are unknown. Changes in zooplankton communities as a result of direct and indirect effects of OAH exposure are expected but hard to predict.

Macroinvertebrate calcifying species including shellfish such as clams, mussels and oysters, as well as sea urchins, shrimps and crabs are most affected by OA, and though their responses to hypoxic events are less studied and more variable, some species will also likely be negatively impacted by persistent hypoxic events. Overall, growth, calcification and survival are negatively affected by OA for most studied benthic calcifiers including sea urchins, bivalves and crustaceans, albeit responses are species-dependent and life-stage dependent. For instance, bivalves are particularly sensitive during and juvenile stages, which play a key role in determining the stability of populations. Responses to hypoxia for these key biological processes are more mixed although less well-studied, with some species showing resilience and others vulnerability. Other physiological processes including respiration and feeding are also impaired under OA and hypoxia, potentially affecting some species' survival indirectly. For most studied macroinvertebrates, reproductive processes generally display mixed responses to OA and hypoxia, though the responses to the latter are not well-known. Similarly, most behavioural responses to OA and hypoxia are understudied and unknown in invertebrates, albeit this is a rapidly evolving area of research. Sea urchins and some bivalves display behavioural sensitivity to OA or persistent hypoxia, though responses are species-dependent. In contrast, Dungeness crab studied behaviours are resilient to both.

In general, vertebrates including fish are not as vulnerable to OA as calcifiers, though early life stages of some fish show reduced survival and growth as a response to increased pCO_2. Mixed responses to OA have also been found in multiple fish species, whereas, in a few cases, BC populations have shown more resiliency than other NE Pacific populations. Conversely, many species of fish show high vulnerability to transient and moderate hypoxia. Overall, survival and growth are severely affected in salmon species, but other processes including reproduction, cellular physiology, and behavioural responses can also be negatively impacted.

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Appendix 3: Workshop Agendas

British Columbia Ocean Acidification & Hypoxia Action Plan

Workshop 1: State of the Science
Date: Nov 2-4
Website: https://quadracentre.org/meetings/bc-fisheries-oah

Aim: To produce an environmental scan of what we know and what we need to know related to patterns, trajectories, and impacts of ocean acidification and hypoxia along the British Columbia coastal margin.

Outcomes: A synthesis with recommendations from the research community to address what we need to know with regard to ocean acidification and hypoxia to develop regionally relevant mitigation and adaptation strategies to support B.C. fisheries and aquaculture sectors. To effectively achieve a thorough environmental scan, we need to consider 4 key themes: (1) observing, (2) modeling, (3) biological impact, (4) mitigation and adaptation.

DAY 1:

Session 1: OAH Frameworks & Gaps in Our Knowledge: (**2 hours; 09:30-12:00**)

1. Myron Roth: Intro & Opening Remarks (**10 mins**)
2. Eric Peterson: Hakai linkages and CIOOS (**10 mins**)
3. Helen Gurney-Smith: MEOPAR OA Community of Practice (**10 mins**)
4. Jan Newton: Lessons learned from the Washington and California plans, coordination from regional to global, and an exemplary vulnerability assessment (**30 mins**)
   15 Minute Question Period
   15 Minute Break
5. Richard Feely: A basin scale perspective of OA and hypoxia with linkages, and an example gap analysis based on the OAH inventory (**30 mins**)
   15 Minute Question Period

Session 2: OAH Observing: (**2.5 hours; 1300-1600**)

1. Synthesis Speaker 1: Patterns from Marine CO_2 Observations on the British Columbia Margin (Wiley Evans) (**20 mins**)
2. Synthesis Speaker 2: Observed patterns of marine hypoxia in British Columbia waters (Jen Jackson) (**20 mins**)
3. Synthesis Speaker 3: CIOOS: A National Ocean Data Portal (Richard Dewey) (**20 mins**)
4. Synthesis Speaker 4: State of the Technology, and technology transfer (Patrick Duke) (**20 mins**)

15 Minute Break

- Question-oriented break-out session (**30 mins; example questions below**)
    - How can we ensure coordination across the research community and therefore optimize the effectiveness of our observing network?

  - Is there alignment between the physical, chemical, and biological monitoring efforts related to identifying OA and hypoxia impacts?
  - Are we missing key areas where biological processes are important that we aren't characterizing biogeochemical patterns?
  - Does our current observing framework support the needs of decision makers?
- Report back from break-out discussions and larger group discussion (**30 mins**)

DAY 2:

Session 3: OAH Modeling: (**< 2 hours; 1000-1200**)

1. Synthesis Speaker 5: Modelling (Jim Christian) (**30 mins**)

- Question-oriented break-out session (**30 mins; example questions below**)
  - What are the key uncertainties across the various modeling efforts?
  - How does model uncertainty impact our mechanistic understanding?
  - What is needed to develop forecasting capacity over seasonal and sub-seasonal timescales?
  - How can collaborations be enhanced between the modeling and observing communities?

- Report back from break-out discussions and larger group discussion (**30 mins**)

Session 4: Biological Impacts from OAH: (**< 2 hours; 1300-1500**)

1. Synthesis Speaker 6: Biological Impacts of ocean acidification and hypoxia on British Columbian Marine Life (Iria Gimenez) (**20 mins**)
2. Synthesis Speaker 7: Traditional Ecological Knowledge, Science, and Policy Change (Jennifer Walkus) (**20 mins**)

- Question-oriented break-out session (**30 mins; example questions below**)
  - What are the important gaps in terms of species and ecosystems?
  - What approaches are suitable for understanding biological impacts?
  - How can we enhance the ability of organisms and ecosystems to cope?
  - What is the interplay between emerging threats (forest fires, heat domes, etc) and OAH and how do these influence marine species and ecosystems?

- Report back from break-out discussions and larger group discussion (**30 mins**)

DAY 3:

Session 5: Mitigation & Adaptation: (**< 2.5 hours; 09:30-12:30**)

1. Synthesis Speaker 8: Linking BC's OAH Action Plan and the Roadmap to 2030 (Wiley Evans) (**10 mins**)
2. Synthesis Speaker 9: Natural Climate Solutions: GHG Mitigation Potential by Nearshore Benthic Habitats (Margot Hessing-Lewis) (**15 mins**)
3. Synthesis Speaker 10: Ocean-based carbon removal and sequestration (Richard Dewey) (**15 mins**)
4. Synthesis Speaker 11: Genetic Tools and Mitigating Hatchery Practices (Tim Green) (**20 mins**)

15 Minute Break

- Question-oriented break-out session (**30 mins; example questions below**)
  - How can we assess the effectiveness of regional mitigation strategies?
  - Are there opportunities for other mitigation strategies in BC?

- Report back from break-out discussions and larger group discussion (**30 mins**)

15 Minute Break

Session 6: Discussion and Concluding Remarks (**30 hr**)

BC OAH Action Plan

BC Seafood Harvester and Producer Perspectives on OAH
January 27 - 28, 2022
Quadra Centre for Coastal Dialogue/Zoom

Rev: January 11, 2022

Summary:
The second in a series of workshop to inform the BC Fisheries & Aquaculture Ocean Acidification and Hypoxia (OAH) Action Plan, the BC Seafood Harvesters and Producers Workshop on OAH will be hosted virtually by the Quadra Centre for Coastal Dialogue on January 27th and 28th. This workshop will review the key themes and recommendations from the first workshop on the State of the Science on OAH Research in BC and give an opportunity for BC's commercial harvesters, food-fish harvesters and aquaculture producers to share their perspectives. The outcome of this workshop will consist of a synthesis with recommendations from harvesters and producers in support of the development of regionally relevant mitigation and adaptation strategies for BC's fisheries and aquaculture sectors.

DAY 1:

Session 1: Introduction/Overview (10:00-12:00)

1. Myron Roth (10:00-10:45)
    - Welcome and Opening Remarks [15 min]
    - The importance of OAH Action Planning to the Seafood Sector [30 min]
2. Wiley Evans & Iria Giménez (10:45-11:30)
    - Overview of Ocean Acidification & Hypoxia [10 min]
    - Review/Outcomes of the State of the Science Workshop/Biological & Socio-Economic Impacts [35 min]

3. OAH & State of the Science – Q&A: (11:30-12:00)

Lunch Break: 12:00 – 13:00

Session 2: Seafood Sectoral Perspectives (13:00-15:30)

1. Christina Burridge, BC Seafood Alliance (13:00-13:20)
    - Commercial Fishing Industry Perspective
2. Andy Olson, Native Fishing Association (13:20 – 13:40)
    - Traditional & Commercial First Nations Perspectives
3. Kennedy Nikel & Jordan Hawkswell (13:40-14:00)
    - Seaweed Industry Perspectives

Coffee Break: 14:00-14:20

4. Breakout: 14:20-15:00
5. Group discussion: 15:00-15:30

DAY 2

Session 3: Seafood Perspectives (9:00-11:30)

1. Wenche Gronbrekk, Seafood Business for Ocean Stewardship (SeaBOS)/ UN Global Compact-Ocean Stewardship Coalition: Sustainable Ocean Business (9:00 – 9:30)
    - Seafood Producers/Food Systems Perspective
2. Linda Sams, Cermaq Canada (9:30-9:50)
    - Salmon Farming Perspective
3. Alex Munro, Fanny Bay Oysters (9:50 – 10:10)
    - Shellfish Farming Perspective

Coffee Break: 10:10-10:30

1. Break Out Sessions 10:30-11:00
2. Group Discussion: 11:00-1130

Lunch: 11:30 – 12:30

Session 4: Adaptation/Mitigation (12:30 – 15)

1. Richard Dewey (12:30-13:00)
    - Mitigation - Offshore
2. Margot Hessing-Lewis (13:00 – 13:30)
    - Mitigation - Nearshore
3. Darah Gibson, BC Ministry of Agriculture, Food & Fisheries (13:30 – 13:50)
    - Adaptation & Mitigation Considerations for Commercial Fishing
4. Tim Green (13:50 – 14:10)
    - Adaptation Strategies for Shellfish Farming

Coffee Break: 14:10 – 14:25

5. Break Out Groups: 14:25 – 15:00
6. Group Discussion: 15:00-15:30

Session 5: Wrap-Up (15:30 – 16:00)

BC OAH Action Plan

Coastal Communities' Perspectives on OAH
February 15-16, 2022
Quadra Centre for Coastal Dialogue/Zoom

DAY 1:

Session 1: Introduction/Overview (9:00-11:55)

1. Myron Roth/Wiley Evans (09:00-09:30)
    - Welcome and Opening Remarks [30 min]
2. Sarah Cooley (09:30-10:45)
    - Getting Action on Ocean Acidification [30 min]
    - Q&A and Discussion [45 min]

Coffee Break (10:45-11:00)

3. Wiley Evans
    - OAH Overview & BC OAH Action Plan Workshop Series [40 min]
    - Q&A And Discussion [15 min]

Lunch Break: (12:00-13:00)

Session 2: Community Observations, Concerns and Needs (13:30-15:30)

1. Myron/Kathryn (13:30-13:45)
    - Welcome back, introduction of the Ocean Decade Collaborative Center [15min]

- **Breakout**: (13:45-15:00)
- **Group discussion:** (15:00-15:30)

DAY 2

Session 3: Adaptation, Mitigation and Solutions (9:00-10:45)

1. Myron Roth (09:00-09:15)
    - Welcome and Opening Remarks [15 min]
2. Richard Dewey (09:15-09:35)
    - Mitigation – Offshore [20 min]
3. Margot Hessing-Lewis (09:35-09:55)
    - Mitigation – Nearshore [20 min]
4. Sally Cargill, MaPP Stakeholder advisory committee (9:55-10:15)
    - Local communities coming together to tackle complex issues [20 min]
5. Q&A and Discussion (10:15-10:45)

Coffee Break: (10:45-11:00)

Session 4: BC OAH Action Plan: Draft Recommendations (11:00-12:30)

1. Wiley Evans (11:00-11:25)
    - Presentation of Draft Recommendations [25 min]
2. Q&A and Discussion (11:25-12:30)

Lunch: (12:30-13:30)

Session 5: Wrap-Up (13:30-14:30)

- **Group Discussion:** (13:30-14:30)

BC Ocean Acidification & Hypoxia Action Plan
Policy & Governance Workshop
Date: March 15, 13:00 – 16:00
Venue: Quadra Centre for Coastal Dialogue

AGENDA		
Time	**Topic / Activity**	**Presenter**
1:00 – 1:10	Welcome / Introductions 1 - Provide agenda for the day 2 - Discuss rationale & objectives	Myron Roth (AFF)
1:10 – 1:40	OAH Workshops defining the need 1- State of the Science 2- Harvesters & Producers Perspectives 3 - Coastal Communities Perspectives	Wiley Evans (Hakai)
1:40 – 2:00	Questions & Answers	All Myron Roth (Moderator)
2:00 – 2:10	BREAK	
2:10 – 2:20	The path forward: Action Plan Goals, Objectives & Actions	Wiley Evans (Hakai)
2:20 – 2:40	Questions & Answers	All Myron Roth (Moderator)
2:40 – 3:10	Roundtable Discussion 1 *How does this work align with your portfolio/mandate priorities?*	All Myron Roth (Moderator)
3:10 – 3:30	Roundtable Discussion 2: *How do we address/coordinate the jurisdictional complexity surrounding OAH between the various governments, local, provincial, federal, Indigenous involved?*	All Myron Roth (Moderator)
3:30 – 3:50	Roundtable Discussion 3: *Do you see any policy or legislated outcomes from the actions we are proposing?*	All Myron Roth (Moderator)
3:50 – 4:00	Wrap Up & Thank You	Myron Roth

Appendix 4: Organisations that participated in and contributed to the BC OAH Action Plan Workshop Series

1. Aboriginal Aquaculture Association
2. Alutiiq Pride Marine Institute
3. Area A Crab Association
4. BC Centre for Aquatic Health Sciences
5. BC Ministry of Agriculture, Food & Fisheries
6. BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development
7. BC Salmon Farmers Association
8. BC Seafood Alliance
9. British Columbia Shellfish Growers Association
10. Canadian Kelp Resources
11. Cedar Coast Field Station
12. Central Coast Indigenous Resource Alliance
13. Centre for Marine Applied Research
14. Cermaq Canada Ltd
15. City of Vancouver
16. Commercial fisherman
17. Council of the Haida Nation
18. Creative Salmon Company Ltd.
19. DB Schenker of Canada
20. Elanco Canada
21. Fisheries And Oceans Canada
22. Golden Eagle Sablefish
23. Grieg Seafood BC
24. Gwaii Haanas Parks Canada
25. Hakai Institute
26. Hatfield Consultants
27. Heiltsuk First Nation
28. International Alliance to Combat Ocean Acidification
29. Island sea farms
30. Jayes Co Design
31. Kitsumkalum Indian Band
32. Kyuquot Chekleseth First Nations
33. Mairiculture Consulting
34. Malahat First Nation
35. Marine Plan Partnership
36. Merck
37. Mowi Canada West
38. Naas Foods
39. Native Fishing Association
40. Nature United

41. North Coast Skeena First Nations Stewardship Society
42. North Island College
43. National Oceanic and Atmospheric Administration
44. North Pacific Kelp Wild Foods Inc.
45. Nuxalk Nation
46. Ocean Acidification Canadian Community of Practice
47. Ocean Networks Canada
48. Okeover Organic Oysters
49. Omega Pacific Hatchery & Seafarms
50. Pacific Seaweed Industry Association
51. Pacific Urchin Harvesters Association
52. Parks Canada
53. Phibro Animal Health Corp.
54. Project Watershed
55. Province of BC
56. Radicle
57. RBR Ltd.
58. Salish Sea Foods LP
59. Sawmill Bay Shellfish Company Ltd
60. ScaleAQ North America
61. SeaBOS/ UN Global Compact
62. Secretariat of the Haida Nation
63. Simon Fraser University
64. Skaiakos Point Oysters Inc.
65. Taylor Shellfish Canada
66. Terraforma Environmental Ltd.
67. TRI-GEN Fish Improvement Ltd.
68. T'Sou-ke Nation
69. Tula Foundation/Ocean Decade Regional Collaborative Center
70. University of Dar es Salaam
71. Underwater Harvesters Association
72. University of British Columbia
73. University of Calgary
74. University of Victoria
75. University of Washington
76. Vancouver Island University
77. Washington State Department of Ecology
78. West Coast Reduction Ltd
79. Zoetis Canada