Developing Best Practices to Address Coastal Marine Oxygen Loss in APEC Economies for Improving the Management of Marine Living Resources

Project Summary Report

APEC Ocean and Fisheries Working Group

August 2025

Asia-Pacific
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APEC Project: OFWG 201 2023

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CONTENTS

1. Introduction

Ocean deoxygenation is one of the major threats for marine biodiversity and is caused by global warming and coastal pollution, so that there is a critical need to properly assess its trends, particularly along the coastal waters, whereby its impacts on ecosystem services can be significant. Despite that measurement of dissolved oxygen concentrations is one of the oldest monitoring activities related to the status of marine ecosystem health, in many exclusive economic zones (EEZs), there is an insufficient information on monitoring protocols and data availability, particularly in the less developed economies (Garçon et al., 2019). These gaps compromise the ability to provide science-based policies and measures to mitigate the local natural and anthropogenic drivers of coastal hypoxia, and its detrimental impact on marine fisheries and aquaculture.

In that context, the OFWG 201 2023 project "Developing best practices to address coastal marine oxygen loss in APEC economies for improving the management of marine living resources" was developed by the Peruvian Institute of Marine Research (IMARPE), aiming to build capacities for the adoption of good and innovative practices for marine coastal dissolved oxygen monitoring, involving biological indices related to coastal hypoxia, and to improve the collaboration to implement or sustain local environmental observatories of coastal oxygen loss, in the Asia-Pacific economies. Outputs of the project included a workshop with theoretical-practical sessions on good and innovative practices for the collection, analysis, quality control and data processing of coastal dissolved oxygen; and a diagnosis of current situation in APEC economies through the results of a pre-workshop assessment survey. The second output was the delivery of a Technical Report with a roadmap that emphasized fostering collaboration among APEC economies to address coastal oxygen loss through scientific partnerships and capacity building.

As the third project's output, this summary report is addressed to policy makers and stakeholders from organizations with fishery and aquaculture expertise. Thus, this document provides theoretical basis of coastal deoxygenation effects on biodiversity and marine living resources, highlights the relevance of fishery and aquaculture in the Pacific region and their potential vulnerability to oxygen loss, and emphasizes the roadmap content relevant for policy and regulatory advances. In order to reach a wider audience, this document is written in plain language.

2. The relevance of fishery and aquaculture in the Pacific region

While global fishery production has been fluctuating since late 1980s between 86 and 94 million tons per year, with a peak of 96 million tons in 2018, coinciding with the exceptionally high catches of 'anchoveta' (*Engraulis ringens*) reported by Chile and Peru in that year, global aquaculture has grown significantly during the same period, and since 2022, aquaculture production is higher than capture fisheries production (FAO, 2024).

Asian economies produced 70% of the total output of aquatic animals, followed by Latin America, the Caribbean and Europe economies producing 9% each. In terms of the FAO Major Fishing Areas, 41% of the total production was harvested in the Pacific Ocean, greater than other areas such as Atlantic, Indian and Southern Oceans, as well as continental inland waters (Figure 1). China remained the major producer followed by other APEC economies such as Indonesia; Peru; Russia; USA; and Viet Nam, among others.

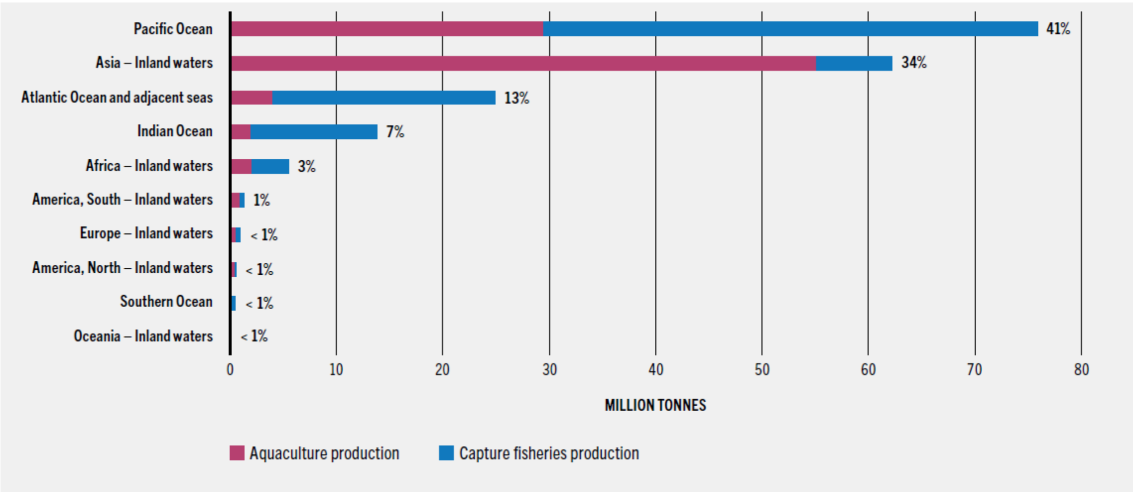


Figure 1. World fisheries and aquaculture production of animals by area, and relative shares for 2022 (FAO, 2024).

As mentioned, world aquaculture production in 2022 achieved a record of 130.9 million tons, and it was the first time in history that global aquaculture production of animal species surpassed capture production, estimated at 91 million tons. Marine and coastal aquaculture provides livelihoods and employment, and facilitates economic development among coastal communities, particularly within the APEC economies, which are the most important representatives of the global aquaculture production (Figure 2).

Although 731 species items are known for aquaculture —composed by algae, finfish, crustacean, mollusks, and other animals— about 17 farmed species represent 60% of global aquaculture production. However, these can have positive economic effects since they provide the largest share of employment, approximately 22 million people globally, mainly in Asia and Latin America; and some of them, such as the non-fed farm species like bivalves and seaweed, even have a lower carbon footprint than others (FAO, 2024).

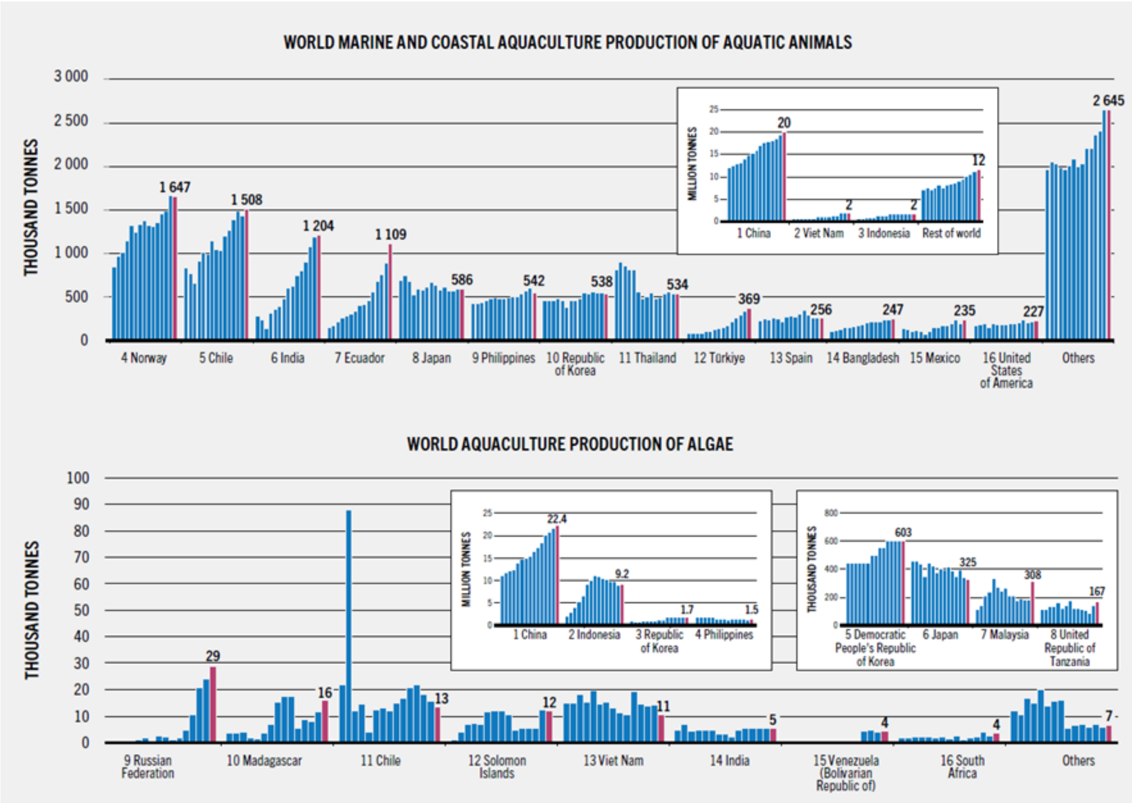


Figure 2. World aquaculture production of aquatic animals and algae from 2008 to 2021 (blue bars) and 2022 (red bar) with the first 16 most important economies (FAO, 2024).

Fisheries and aquaculture in the Pacific Ocean and its coastal zones are highly vulnerable to natural and climate-related phenomena due to the region's ecological sensitivity and dependence on marine resources. Events such as cyclones, El Niño-Southern Oscillation (ENSO) fluctuations, rising sea temperatures, and deoxygenation significantly disrupt marine ecosystems and species population dynamics. In particular, deoxygenation can lead to shifts in species distribution, reduced fish stocks, and increased mortality in farmed aquatic species. Coastal zones, often home to vital nursery habitats and aquaculture operations, are particularly at risk, which can damage economical activities, infrastructure and displace communities (Bell et al., 2018, Roman et al., 2024).

3. Theoretical synthesis

Deoxygenation in aquatic food-producing coastal zones

While the excess nutrients entering the coastal ocean, mainly through watershed and river runoff, fuels algal blooms that increase oxygen demand and develop hypoxic coastal zones, the absorption of excess heat —due to greenhouse gas induced warming— by the ocean causes the decrease of oxygen solubility and changes in ventilation and ocean mixing that reduce the oxygen supply to deeper coastal waters (Breitburg et al., 2018).

Finfish and shellfish undergo negative effects in oxygen-depleted waters and their vicinity, ranging from altered trophic interactions to mortality. The evidence of negative effects of deoxygenation on finfish and shellfish, in scale of populations and fisheries, comes from systems with large hypoxic zones, riverine portions of estuaries that receive nutrient loads or raw sewage, and areas with multiple stressors or degraded habitats (Breitburg et al., 2009).

Deoxygenation can affect fisheries through negative and complex effects on reproduction, growth, and survival affecting biomass and fish movement affecting their availability to harvest. The extent of these effects is expected to increase because of deoxygenation is expanding to coastal regions that support high fisheries production, and the effects can become amplified when hypoxia is combined with other stressors (Rose et al., 2019), as coastal pollution or eutrophication. The effects may be most impactful on artisanal fisheries and aquaculture facilities, which often have little capacity to relocate as hypoxia grows in space and time (Roman et al., 2024).

Despite there are known effects on development, reproduction, metabolism, growth and behavior on certain species, the understanding of consequences of hypoxia on aquaculture is still limited and focused mainly in commercial finfish. Broader surveys on more species are needed to clarify the profound consequences of hypoxia. The physiological adaptations of some species to hypoxia responds to molecular mechanisms that are not fully elucidated yet. Research is needed to develop aquaculture species with strong hypoxia tolerance and economical potential (Zhan et al., 2023).

Some aquatic organisms exhibit an evolved tolerance to low concentrations of oxygen. This ability to cope with hypoxic concentrations depends on their metabolism and capacity to extract oxygen from water and transport it to tissues. These physiological characteristics set a critical oxygen partial pressure (P_c, oxygen critical point), strongly related to species-specific historical exposure, below which aerobic metabolism is limited. In coastal regions, decreasing oxygen concentrations in shallow waters, due to eutrophication or climate change, would push organisms beyond their evolved oxygen critical point affecting growth and survival, and restricting distributions and abundances of living resources. Hypoxia tolerance can only be determined through measured response of live animals to a range of oxygen concentrations and at specified temperatures (see Box 1) (Seibel & Wishner, 2019).

Finally, organismal and fisheries effects are at the heart of the coastal hypoxia issue, but subtle regime shifts and trophic interactions that can be triggered by coastal hypoxia are also cause for concern, particularly for the benthic communities (Rabalais et al., 2014).

The role of aquaculture and fishery on coastal deoxygenation

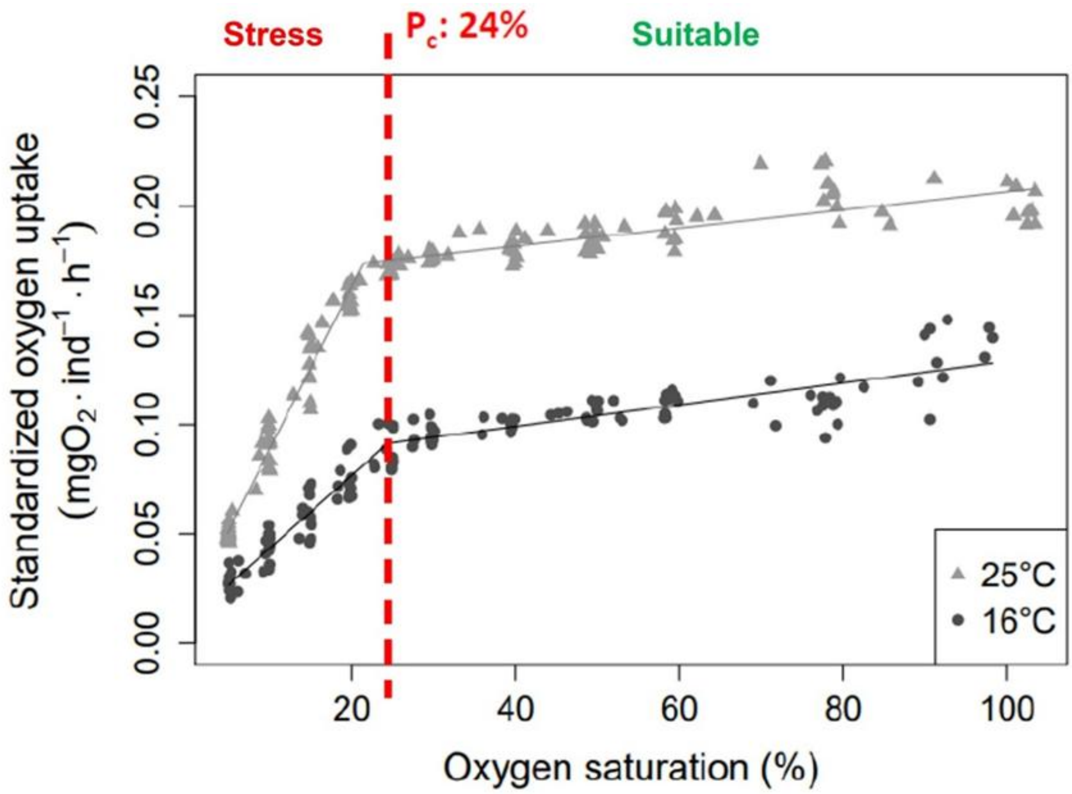
Aquaculture can lead to deoxygenation in coastal areas by increasing the oxygen uptake for respiration by both farm fauna and microbes that decompose excess food and feces. When this increased respiration and insufficient water flow occur at the same time, oxygen concentrations can decline until causing death of farm animals and consequently producing economic losses and threats to food security (Rice 2014). Unable to escape from harmful low-oxygen conditions, dying animals in aquaculture pens and cages compromise human livelihoods and can directly harm human health when low incomes and severe food insecurity force the consumption of fish killed by hypoxic conditions (Breitburg et al., 2018).

Fisheries are not usually identified as an anthropogenic driver of deoxygenation in coastal areas. The Changjiang estuary undergoes seasonal hypoxia driven by eutrophication linked to nutrient loading arriving with the Yangtze River flow (Box 2). The demand for high trophic economic fishes probably altered the coastal ecosystem structure, leading to the increase of benthic macroinvertebrates. This enhances the flux of carbon to bottom waters and might be one of the key processes exacerbating seasonal hypoxia in the estuary (Xu et al. 2024). In Peru, Walsh (1981) postulated that a decline of anchoveta (*Engraulis ringens*) grazing pressure by overfishing led to increases in plankton biomass, and in carbon loading and respiration over the Peruvian continental shelf. This was suggested as the origin of a decline in oxygen and nitrate contents in the water column during a period after overfishing (1976-1979) compared to more oxygenated conditions in the before-overfishing period (1966-1969).

Box 1. The oxygen critical point of coastal living resources

The oxygen critical point is a concept used to characterize the physiological response of aquatic fauna to hypoxic conditions. It is defined as the oxygen level below which organisms lose their ability to regulate their oxygen uptake and have an abrupt decrease in respiration rate (Prosser 1973). This means they turn from oxyregulators to oxyconformers when exposed to a certain low oxygen level in a deoxygenation event.

The farming of the scallop *Argopecten purpuratus*, a major species for Peruvian aquaculture, generates jobs and incomes for thousands of people in the coast of Peru and Chile (Kluger et al., 2019). Since 2012, at least eight mass mortality events were recorded in Peruvian farming areas and linked to deoxygenation events (Cueto-Vega et al., 2021), additional to seasonal hypoxic events that cause sublethal effects on the scallops in these areas, especially those farmed in bottom cultures (Igarza et al., 2024). The critical point (Pc) of *A. purpuratus* was determined experimentally for small (24-32 mm) individuals at 24% of oxygen saturation, exhibiting metabolic stress below this level (Aguirre-Velarde et al., 2016).

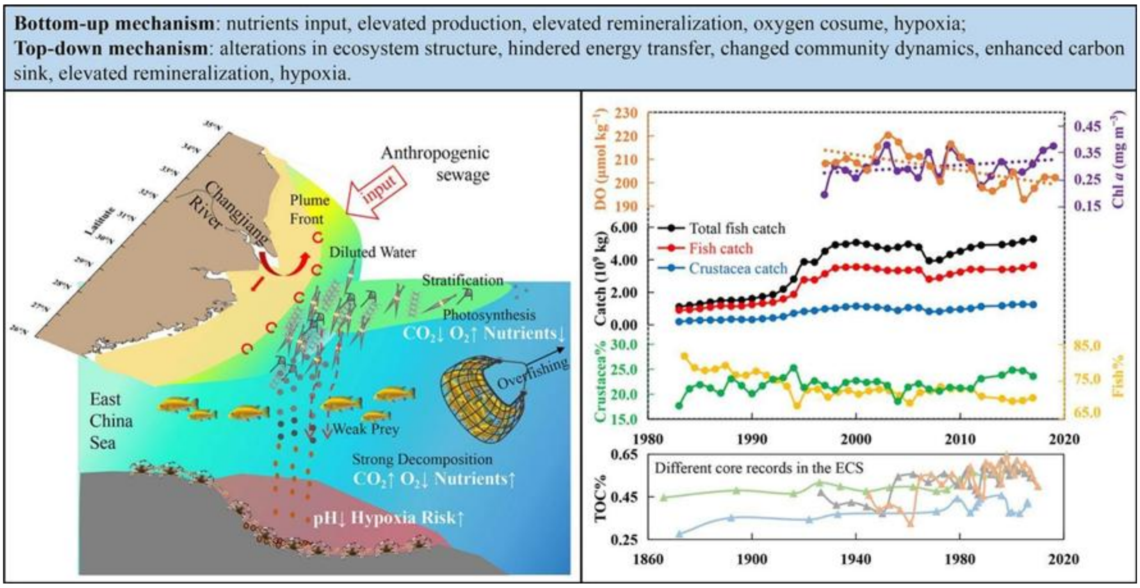


Box 1 Figure: Critical point of oxygen saturation for the scallop *Argopecten purpuratus* at two temperatures that characterize the range of its habitat variability (modified from Aguirre-Velarde et al., 2016).

Box 2. The Changjiang Estuary

The Changjiang estuary is a coastal area formed in the East China Sea by discharge of the Yangtze River that develops a large area of eutrophication-driven summer hypoxia. Since the second half of the twentieth century the extent of the hypoxic area off the estuary has been increasing. Strong water stratification and local degradation of organic matter are the main conditions triggering seasonal hypoxia in this coastal area (Zhu et al. 2011).

In the hypoxic zone, reduced fish diversity was detected as compared to adjacent waters, and fish with low economic value, small size, simple age structure, and low trophic level position predominated (Shan et al. 2010). Furthermore, seasonal hypoxia interacts with changes in fishing structure affecting the food web and might increase the risk of hypoxia. Fishing activities (top-down mechanism) hindered the control of phytoplankton biomass, which result in increased carbon export to the bottom, organic enrichment and ultimately hypoxia (Xu et al. 2024).



Box 2 Figure: Mechanisms of hypoxia control in the Changjiang Estuary and adjacent waters under eutrophication and fishing activities. Trends of deoxygenation, enhanced phytoplankton productivity (Chl *a*), fish catch, and organic enrichment (TOC) are shown (Xu et al. 2024).

Biological indicators: A key to monitoring and managing ocean deoxygenation

As oxygen levels in the ocean continue to decline, scientists are turning to marine and coastal animals themselves to help monitor the health of underwater ecosystems. These animals show clear signs of stress when oxygen gets too low. Young fish, oysters, and worms, for example, may grow more slowly or develop deformities when they do not get enough oxygen. Some species that can survive in very low-oxygen environments, such as certain clams or fish, are also helpful for scientists, since their presence can signal that oxygen conditions are especially poor (Roman et al., 2024).

Research has shown that many species start to struggle even before oxygen levels drop below traditionally used thresholds for hypoxia. In fact, fish and other sea life can become stressed or die at higher oxygen levels than once thought, meaning the damage may begin earlier than we realize. For instance, Deutsch et al. (2024) point out how these subtle biological responses, like shifts in where animals live or how many survive, are crucial clues in understanding the broader impacts of deoxygenation. Recognizing these features as biological indicators and developing indices related to physiological thresholds or exposure to hypoxia conditions, can also help us to develop tools to monitor, predict and respond to changes in coastal waters before the damage becomes irreversible (Box 3).

Low oxygen not only affect individual animals; it changes whole communities. Species that need a lot of oxygen start to disappear, while those that are tolerant to low oxygen take over, leading to less variety and fewer species overall. This shift is a strong sign that an ecosystem is under stress. Scientists also look at things like shrinking fish populations or reduced reproduction as red flags. By paying attention to these biological clues, researchers can better track where and how deoxygenation is happening. By combining local research with global efforts, like those promoted by the Global Ocean Oxygen Network (https://www.ioc.unesco.org/en/go2ne), we can better protect marine life and the vital resources it provides.

Long-term observations provide valuable insights into how benthic communities respond to sustained hypoxic conditions. Rabalais and Baustian (2020) examined historical shifts in benthic infaunal diversity in the northern Gulf of Mexico, documenting significant changes in community composition since the onset of seasonal hypoxia in the 1950s. Their research indicates a decline in species richness and a dominance of hypoxia-tolerant species, reflecting the ecosystem's adaptation to low-oxygen environments. These findings highlight the long-term ecological consequences of sustained oxygen depletion. Integrating such biological indicators into monitoring programs is crucial for detecting early warning signs, guiding mitigation efforts, and informing conservation strategies aimed at preserving marine biodiversity in the face of ongoing deoxygenation.

Why data matters: managing, controlling, and processing information to track deoxygenation

Tracking the loss of oxygen in coastal waters depends on collecting reliable data and making sure it's handled carefully. The Global Ocean Oxygen Database and Atlas (GO2DAT), outlined by Grégoire et al. (2021), brings together oxygen data from many different sources, such as research ships, underwater robots, and fixed ocean sensors, into one global system. What makes GO2DAT especially useful is its focus on quality: it checks and organizes the data to make sure it's accurate and easy to use for scientists around the world. With this well-organized data, researchers can create better maps and models to understand where and why the coastal ocean is becoming deoxygenated, and what that means for marine life and people.

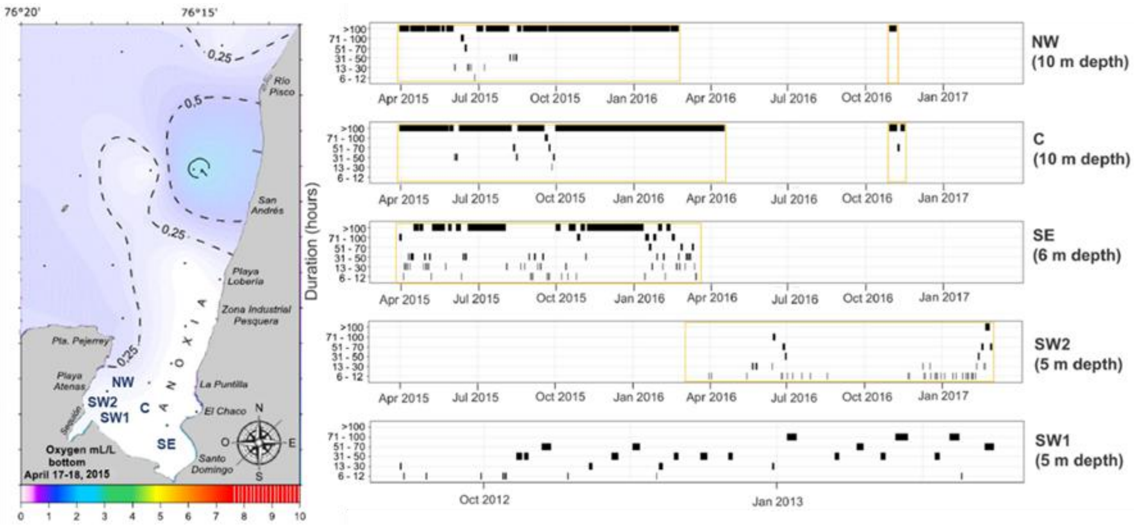
The VOICE project (Variability of the Oxycline and its Impact on the Ecosystem), described by Garçon et al. (2019), adds another important piece to the puzzle. It focuses on the "oxycline," the part of the ocean where oxygen levels drop sharply—a key zone that affects everything from ocean chemistry to fish behavior. VOICE combines different kinds of data, like ocean currents, water chemistry, and marine biology, in order to assess how changes in oxygen levels affect marine organisms and nutrient cycles in areas near naturally low-oxygen zones. The project also stresses the importance of shared standards and teamwork across scientific fields so that data is useful not just to researchers, but also to decision-makers who manage fisheries and coastal resources.

Developing early warning systems and risk assessments for coastal deoxygenation is becoming more important as oxygen levels in the ocean continue to decline, especially near heavily populated coastlines. These tools help scientists and decision-makers to detect changes before serious damage occurs to marine life, fisheries, and coastal communities. According to Grégoire et al. (2021), combining high-quality oxygen data with models and forecast tools can improve our ability to predict where and when oxygen might drop to dangerous levels. Early warning systems allow for faster responses, like changing fishing practices or triggering predefined protocols to protect marine cultures from hypoxic events, which can help to reduce additional impacts in the marine coastal systems and in the livelihoods of coastal communities.

Box 3. Paracas Bay: a case of development of hypoxia indices

The Paracas Bay is a small (surface of 35 km^2) and shallow (depth < 15 m) marine environment of the Peruvian coast that, despite being partially protected from winds and wave action, is an area of convergence of oxygen-low upwelling waters and oxygenated inshore waters. Moreover, port activities, industrial fishmeal and gas-derived fuel production, as well as recreational and tourist activities, are carried out in this coastal area (Pitcher et al., 2021).

The bay and the adjacent coastal waters are also a traditional finfish fishing and shellfish aquaculture area in which faunal mortality events associated with anoxic conditions occurr occasionally. Motivated by those events, several studies were carried out on the variability and distribution of surface and bottom dissolved oxygen content, on the main drivers of the hypoxic conditions, and for developing indices of hypoxia intensity and of hypoxia's biological effect on living resources such as the scallop "*Argopecten purpuratus*" (Igarza et al. 2024).



Box 3 Figure: Low oxygen event in the bottom waters of Paracas Bay and adjacent Pisco area in April 2015 (left, courtesy of A. Lorenzo – IMARPE, 2015). Time variability of hypoxic events (right, from Igarza et al. 2024), defined as oxygen records below 1.4 mL L^{-1} during at least six consecutive hours, in monitoring stations of the bay (SW1, SW2, NW, SE, and C) during 2012-2013 and 2015-2017.

4. Implications for policy and regulatory advances: strengthening fisheries and aquaculture in face of coastal oxygen loss

The roadmap for addressing coastal oxygen loss across APEC economies (Table 1) highlights the need for coordinated action—not only through science and partnerships, but also through clear, forward-looking policy and regulatory updates. Below are four key areas where policymakers and stakeholders can drive meaningful change to protect the sustainability and resilience of fisheries and aquaculture sectors.

Regulatory differences between aquaculture and fisheries

It is important to note that the management and regulatory aspects of fisheries and aquaculture are very different. Incorporating low oxygen issues with aquaculture is relatively straightforward because a facility can be viewed analogously as a point discharge. This is a two-way situation in that the facility can discharge and contribute to water quality problems as well as the operations of the facility requires water of a certain quality. The usual approach of water quality standards and regulations for discharges can be applied to aquaculture facilities. Similarly, regulatory mechanisms for siting and for ensuring water quality is adequate for operations can be adapted from existing water quality regulations. In general, the regulatory and policy infrastructure for water quality and point discharges can be adapted from or added to existing standards, monitoring, and enforcement approaches.

Incorporating oxygen considerations into fisheries management and policy is more challenging. Often, fisheries management and water quality monitoring and regulation are housed in different agencies of the government. More importantly, most fisheries management practices lack a direct method for incorporating oxygen considerations into assessments and management strategies. Fisheries management often has a periodic stock assessment step (e.g., every 1 to 5 years) that uses data and modeling to identify targets. The results of a stock assessment are then used in a management step in order to take actions to achieve the targets. Stock assessment relies on consistency over time and across species and rarely includes water quality variables such as oxygen in the analysis; changing the stock assessment model can be a major process involving review and stakeholder engagement. More often, such considerations are considered as background and in a qualitative manner. How to include oxygen in fisheries management will be ongoing challenge and probably best approached on a case-by-case basis (either for a species or for an area). What is important is to an agreed mechanism for including oxygen when it is appropriate.

Table 1. Summarized roadmap for addressing coastal oxygen loss across APEC economies.

Component	Timeline	Goal	Actions	Expected Outcome
A. Partnership among APEC economies for Coastal Oxygen Loss	1–2 years	Create a scientific partnership among APEC economies to address oxygen depletion in coastal areas and its effects on fisheries and aquaculture.	• Submit a letter of interest to establish the partnership through APEC's Ocean and Fisheries Working Group. • Develop a knowledge and data-sharing framework focused on oxygen monitoring in fisheries/aquaculture areas.	Joint proposal to international programs (e.g., GEF) under the UN Ocean Decade to raise funds for enhancing oxygen data management and application.
B. Scientific Communication and Ocean Literacy	1–2 years	Raise awareness about coastal deoxygenation's impact on ecosystems, food security, and well-being.	• Launch outreach initiatives (webinars, workshops, brochures). • Use co-production of knowledge to engage stakeholders.	Brochures and guidelines promoting ocean literacy and incorporating oxygen loss into fisheries management and policy.
C. Data Management	2–3 years	Enhance data access and integration for better management and responses to coastal deoxygenation.	• Align local data with FAIR principles. • Share data with global platforms like GO2DAT.	A standardized, integrated coastal oxygen database for APEC economies following "Findable, Accessible, Interoperable, and Reusable" principles.
D. Collaborative Research	2–3 years	Encourage transdisciplinary research on deoxygenation's effects.	• Conduct vulnerability and habitat suitability studies involving hypoxia. • Develop indices for hazards, exposure, and vulnerability of fisheries and farms.	A data portal summarizing insights on oxygen monitoring, and a workshop for developing strategies and metrics to quantify hazards, exposure, and vulnerability.
E. Early Warning and Risk Assessments	2–3 years	Develop risk assessments and early warning systems for low-oxygen and related extreme events (e.g., harmful algal blooms).	• Use oxygen data, satellite imagery, and modeling for forecasts. • Promote collaboration among scientists, government personnel, and stakeholders. • Collaborate with stakeholders for assessments, capacity building, and adaptive strategies.	A pilot program to test early warning options for coastal deoxygenation events in selected APEC regions.

Key areas for improvement

Key Area 1. Strengthen environmental standards and monitoring requirements

To safeguard fisheries and aquaculture from the growing threat of oxygen depletion (hypoxia), local and regional authorities should:

- Introduce mandatory oxygen monitoring in aquaculture farms and key fishery areas, especially those at risk of seasonal or recurring low-oxygen events, applying best practices from the data collection and management to information systems.
- Update environmental impact assessment guidelines to include oxygen-related risks, ensuring that all new projects consider hypoxia as a critical factor.
- Establish operational best practices (e.g. feed management, stocking density, sediment management) as enforceable standards to prevent local oxygen depletion caused by aquaculture waste.

Key Area 2. Improve site planning and location-based risk management

Policies should promote smarter, safer decisions about where aquaculture and fisheries activities are located.

- Use oxygen monitoring data and forecasts to guide site selection, prioritizing areas with stable oxygen conditions.
- Designate low-oxygen risk zones and time windows where aquaculture or fishing activities should be limited or paused during peak vulnerability, in order to prevent culture mortalities and overfishing, respectively.
- Explore dynamic zoning approaches, allowing flexible management of aquaculture areas based on real-time environmental data.
- Develop seasonal habitat maps that include oxygen as a factor for key life stages of fisheries species.

Key Area 3. Build early warning and risk response into regulation

As early warning systems and risk assessments become available through the roadmap, policymakers should ensure:

- Clear response protocols are developed and integrated into operational regulations. When low oxygen is forecasted or detected, stakeholders should know what actions are expected (e.g., moving stocks, aerating water, delaying harvest).

- Risk assessments are embedded in licensing processes for aquaculture facilities, requiring operators to demonstrate awareness of local deoxygenation risks and preparedness to respond.

Key Area 4. Promote regional coordination and regulatory alignment

Given the similar nature of coastal ecosystems, coordination across APEC economies is essential to:

- Support the development of a regional code of practice or shared policy guidelines on managing oxygen loss in fisheries and aquaculture.
- Facilitate data sharing agreements and regional data standards, ensuring that monitoring data is compatible, trusted, and usable across borders.
- Develop shared protocols for coordinated communication of real-time and projected low oxygen events occurring in fisheries grounds.
- Share lessons learned from implementing Key Areas 1-3.

Proactive, science-based policy is essential to keep fisheries and aquaculture systems productive and resilient. By integrating the roadmap's guidelines into local and regional frameworks, APEC economies can reduce risks, strengthen food security, and become leaders in sustainable ocean management. With actions such as better monitoring, smarter regulation, collaborative research and capacity building, awareness-raising among the stakeholders, and sustained support for innovation, we can mitigate the effects of coastal deoxygenation and secure a healthier future for the ocean and coastal communities.

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