1 Introduction

The IMBeR Eutrophication Study Group (ESG) was established in 2022 and is co-chaired by Professor Dongyan Liu from East China Normal University and Professor Peter Thompson from the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia. The ESG currently consists of 22 scientists from 11 countries (Table 1). The ESG focuses on eutrophication related topics affecting the coastal ecosystem and environmental policy, including *(1) the diversity of eutrophication and the response of marine ecosystem on eutrophication, (2) nutrient reduction policy and its effects in different countries, (3) how to consider climate-driven effects on nutrient reduction policy and (4) what is our expectation on after-eutrophication?*. From 2022 to 2025, the ESG held regular online meetings, discussing the eutrophication status, underlying mechanisms, and management strategies in coastal and estuarine ecosystems, as well as its intricate connections with climate change and environmental policies. In 2024, the ESG launched a global expert survey based on IMBeR network, titled "*A Global Expert Survey on Nutrient Reduction Policies and Their Consequential Effects on the Eutrophication/Oligotrophication Status of Coastal Water Bodies*". In this chapter, the knowledge from case studies and the information from global survey were described for readers.

Table 1 ESG Personnel List

Name	Affiliations	Country	
Dongyan Liu	East China Normal University	China	Co-Chairs
Peter Thompson	CSIRO	Australia	
Nina Bednaršek	The Jožef Stefan Institute	Slovenia	Members
Jacob Carstensen	Aarhus University	Denmark	
Bingzhang Chen	University of Strathclyde	UK	
James Cloern	USGS	USA	
Masahiko Fujii	The University of Tokyo	Japan	
Ricardo Giesecke	Universidad Australde Chile	Chile	
Haifeng Gu	Third Institute of Oceanography, Ministry of Natural Resources, PRC	China	
James D. Hagy III	United States Environmental Protection Agency	USA	
Noreen E. Kelly	Fisheries and Oceans Canada	Canada	
Kun Lei	Chinese Research Academy of Environmental Sciences	China	
Keqiang Li	Ocean University of China	China	
Senjie Lin	University of Connecticut	USA	
Hongbin Liu	The Hong Kong University of Science and Technology	China	
Abigail McQuatters-Gollop	University of Plymouth	UK	
Alice Newton	University of Algarve	Portugal	
Hans Paerl	UNC-CH Institute of Marine Sciences	USA	
Tae Gyu Park	National Institute of Fisheries Science, South Korea	South Korea	
Ed Sherwood	Tampa Bay Estuary Program	USA	
Juying Wang	National Marine Environmental Monitoring Center, China	China	
Chongran Zhou	East China Normal University	China	

2 Case Studies

A dozen major case studies spanning North America, Europe, East Asia, and Oceania were shared during ESG meetings, covering estuaries, coastal bays in the temperate and subtropical seas (Fig. 1). The main research themes center on the intertwined impacts of climate change, human nutrient enrichment, and mitigation efforts on eutrophication dynamics.

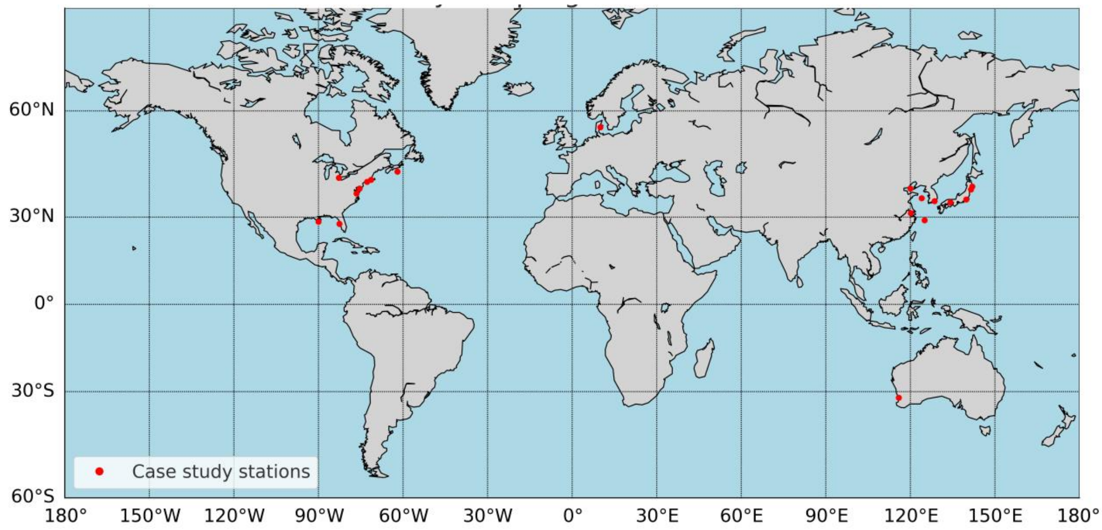


Figure 1 Spatial distribution of Case Studies in the temperate and subtropical seas

Case-1: Danish Coastal Waters (Baltic Sea)

Presenter: Jacob Carstensen

Jacob Carstensen provided a comprehensive review of nearly fifty years of eutrophication management in Danish coastal waters and the western Baltic Sea. Denmark has implemented ambitious national policies, resulting in a 50% reduction of nitrogen (N) inputs and an 80% reduction in phosphorus (P) inputs to the marine environment since 1990. However, despite these significant input reductions, ecological improvements were less dramatic than expected. During 1990 to 2010, the average standing stock of chlorophyll-a (Chl-a), a key indicator of phytoplankton biomass, decreased only modestly; and water clarity from Secchi disk data showed slight improvement (Fig. 2). The ratios between total nitrogen (TN) and Chl-a were found to be highly variable within single water bodies and only weakly patterned across different systems, highlighting the complexity of ecosystem responses.

Danish model was applied to examine the interactions among stratification, temperature, dissolved oxygen, wind speed, and nutrient–phytoplankton relationships. The findings showed that rising temperatures and decreasing wind speeds—both influenced by climate change—strengthened water column stratification, decreased ventilation and oxygen solubility, and promoted more frequent low-oxygen events in bottom waters. This, in turn, increased the release of nutrients from sediments during summer, potentially supporting greater phytoplankton growth for a given input of dissolved inorganic nitrogen (DIN). The legacy period for nitrogen in Danish estuarine sediments is less than a decade, while phosphorus legacy in the Baltic Sea can persist for decades.

Jacob also highlighted biological changes associated with eutrophication and management. There has been a decline in eelgrass, due to combined effects of nutrient enrichment, trawling, and warming; a strong decline in filter feeders such as mussels; and an increase in benthic macroalgae and detritivore communities. Overall, the

Baltic case illustrated the need to consider both external nutrient reductions and the modifying effects of climate-driven environmental changes when assessing and managing eutrophication in coastal ecosystems.

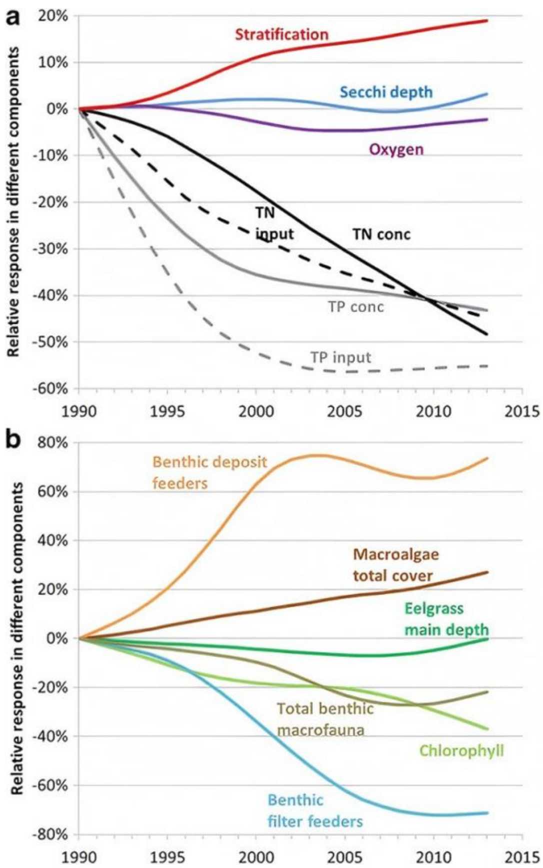


Figure 2 Synthesis of trends in Danish coastal waters (From Jacob's presentation)

Main references:

- *Carstensen, J., Sánchez-Camacho, M., Duarte, C. M., et al. (2011). Connecting the dots: responses of coastal ecosystems to changing nutrient concentrations. Environmental Science & Technology, 45(21), 9122-9132.*

- *Duarte, C. M., Conley, D. J., Carstensen, J., et al. (2009). Return to Neverland: shifting baselines affect eutrophication restoration targets. Estuaries and Coasts, 32, 29-36.*

- *Riemann, B., Carstensen, J., Dahl, K., et al. (2016). Recovery of Danish coastal ecosystems after reductions in nutrient loading: a holistic ecosystem approach. Estuaries and Coasts, 39, 82-97.*

Case 2: Sishili Bay, Yellow Sea, China

Presenter: Dongyan Liu

Dongyan Liu shared the studies on eutrophic history, cause and ecological trend in the Sishili Bay, located in Yantai on the northeast coast of the Shandong Peninsula. Sishili Bay is a typical example of a temperate bay in northern China to serve marine aquaculture function. The study revealed that eutrophication in this region has experienced two distinct periods: a slow phase from the 1970s to 1990s and a much more rapid development after 2000, coinciding with China's economic development.

By integrating the data of palaeoecological reconstruction and ocean observations, a clear shift in the dominant phytoplankton regime was identified. Historically, the bay was characterized by diatom dominance (specifically *Paralia sulcata*) in winter and spring, and then shifted toward non-diatom dominance in the summer as a result of dissolved silicate limitation. The transition point for this regime shift was determined to be between 1975 and 1980, closely aligned with increased fertilizer usage.

Analysis of sediment cores confirmed that *Paralia sulcata* abundance had a strong, significant correlation with increased nitrogen levels. Additional laboratory experiments showed that ammonia (NH_4^+), which now accounts for over 30% of total nitrogen emissions due to human activities, has a much greater effect on diatom miniaturization, chlorophyll-a reduction, and silicification than nitrate (Fig. 3). The findings indicate that the form of nitrogen, not just the concentration, plays a crucial role in phytoplankton community structure and biogeochemical cycles in Sishili Bay.

The evolution of eutrophication in Sishili Bay reflects a broader impacts on diatoms. The case highlights the importance of considering nitrogen speciation and the coupling between nitrogen and silicon in both scientific research and the development of national and global nutrient management policies.

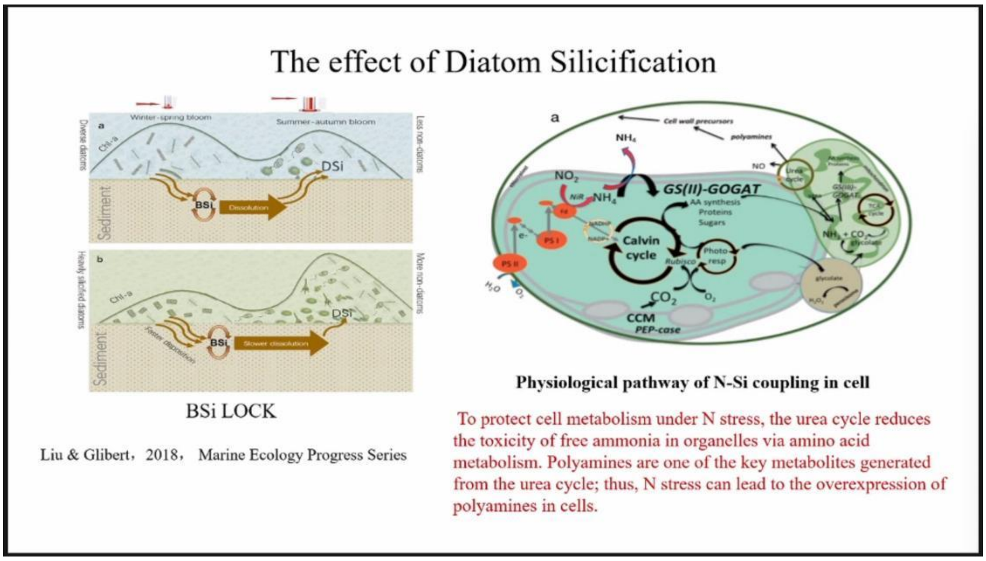


Figure 3 Schematic diagrams of diatom structure and metabolic pathways (from Dongyan's presentation)

Main references:

- *Di, B., Liu, D., Wang, Y., et al. Diatom and silicoflagellate assemblages in modern surface sediments associated with human activity: a case study in Sishili Bay, China. Ecological indicators, 24, 23-30.*
- *Liu, D., Glibert, P. M. (2018). Ecophysiological linkage of nitrogen enrichment to heavily silicified diatoms in winter. Marine Ecology Progress Series, 604, 51-63.*
- *Liu, D., Shen, X., Di, B., et al. (2013). Palaeoecological analysis of phytoplankton regime shifts in response to coastal eutrophication. Marine Ecology Progress Series, 475, 1-14.*

Case 3: Tampa Bay, Florida, USA

Presenter：Ed Sherwood

Ed shared a comprehensive overview of the long-term efforts to manage and restore Tampa Bay, a shallow estuary in western Florida. Historically, Tampa Bay experienced severe water quality degradation from the 1950s to the 1980s, primarily due to rapid urban expansion and associated increases in nitrogen loads. These nutrient increases resulted in the loss of nearly half the bay’ s seagrass coverage and widespread ecological decline. In response, a regional estuary program was established in 1991 as part of a national initiative, aiming to restore and protect the bay through a coordinated, science-driven management approach (https://tbep.org/).

This program implemented 39 specific actions and 166 strategies organized under three main priorities: Clean Waters & Sediments, Thriving Habitats & Abundant Wildlife, and Informed, Engaged & Responsible Community. Central to the recovery was the formation of a regional nitrogen management consortium, which coordinated the allocation of nitrogen load responsibilities among public and private partners. Through targeted reductions in point-source (such as wastewater) and non-point source nutrient contributions, nitrogen loads were significantly reduced. This led to a steady improvement in seagrass coverage, which by 2014 had surpassed both the 1950s baseline and the restoration goal set by the program.

However, new challenges have emerged. In recent years, the bay has experienced persistent blooms of *Pyrodinium bahamense* (a dinoflagellate), primarily in Old Tampa Bay, even as nitrogen loads remain below targets (Fig. 4). Other emerging issues include sustained and increasing nitrogen contributions from non-point sources such as stormwater runoff, likely exacerbated by climate change, and significant industrial events such as the 2021 discharge of 814 million liters of phosphate mining wastewater from a major facility into lower Tampa Bay. These events have disrupted nutrient cycling and may impact water quality for several years.

In response, the program has expanded its management strategies to include public education (such as encouraging residents not to fertilize during the summer rainy season), infrastructure upgrades, ecosystem restoration (including oyster and clam bioremediation to control algal blooms), construction of new water channels for improved tidal circulation, and real-time monitoring of temperature and water quality. It was emphasized that while significant ecological recovery has been achieved, ongoing vigilance and adaptive management are required to address the combined impacts of legacy nutrients, non-point source pollution, and climate-driven changes such as increased stormwater inputs and warming.

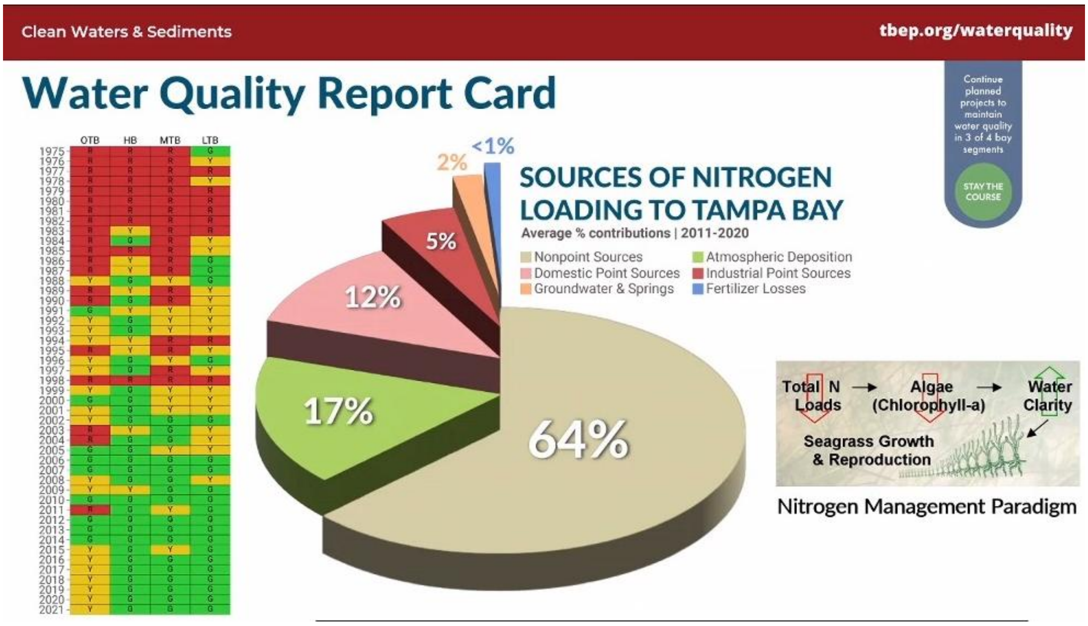


Figure 4 Contribution of nitrogen from different sources in Tampa Bay (from Ed's presentation)

Main references:

- *Beck, M. W., Altieri, A., Angelini, C., et al. (2022). Initial estuarine response to inorganic nutrient inputs from a legacy mining facility adjacent to Tampa Bay, Florida. Marine Pollution Bulletin, 178, 113598.*
- *https://tbep.org/about-the-bay/state-of-the-bay/*
- *https://drive.google.com/file/d/1UlH0QcWy_acrqOV2on7fff7oMtJAnwmg/view*

Case 4: U.S. Estuaries

Presenter: James D. Hagy III

James Hagy shared a comparative analysis of eutrophication and hypoxia management in several major U.S. estuaries, highlighting the varied outcomes driven by differences in policy, nutrient sources, and local implementation (Fig. 5). The discussion began with Narragansett Bay, where strong regulatory action and technical upgrades in wastewater treatment facilities resulted in a 63% reduction in nitrogen loads. This outcome was achieved by combining plant upgrades, strict permit limits, and a balanced approach between supporting fisheries and maintaining water quality, leading to marked improvements in ecological health.

Tampa Bay was presented as another successful case where coordinated local government actions and regulatory frameworks enabled both point and non-point source nutrient reductions. Through comprehensive management, Tampa Bay restored its seagrass coverage to 1950s levels by 2014, an outcome also attributed to effective monitoring and clear regulatory targets.

In Long Island Sound, the impact of the U.S. Clean Water Act led to a mandatory, region-wide nitrogen reduction plan adopted in 2000. This plan required upgrades at 79 wastewater treatment plants, resulting in a 42% decline in point-source nitrogen loads, even as the local population grew. However, the effectiveness of such actions was context-dependent: areas with focused, mandatory interventions saw faster and more pronounced improvements.

Chesapeake Bay' s experience contrasted with the above cases. Despite decades of effort, only a 17% reduction in nitrogen was achieved, primarily due to reliance on voluntary best management practices in agriculture and the political reluctance to impose mandatory controls. Non-point source pollution, especially from agriculture, remains a critical challenge, and the lack of robust regulation has slowed water quality recovery.

Finally, in the Gulf of Mexico, nitrogen loads from the Mississippi River basin have stabilized, but large-scale hypoxia ("dead zone") persists. Efforts have been hampered by insufficient regulatory progress on agricultural runoff and the scale of nutrient legacies.

It was emphasized that the pace and extent of estuarine recovery in the United States have depended heavily on the presence of mandatory, locally-focused regulations, effective nutrient reduction strategies, and strong political commitment. Where these elements were weak or absent, improvements have been slow and water quality problems persist. Further use of scientific modeling (such as Generalized Additive Models, GAMs) and long-term monitoring was recommended to better link nutrient controls to ecological outcomes and guide adaptive management.

N Loading Reductions Caused Improvement in Principal Eutrophication Effects

Estuary	Dominant N Source	Management	N Loading Trends	Effects of Eutrophication	Response Trends
Narragansett Bay	Sewage	Local Mandate, Dedicated Agency	Large/Fast Decrease	Hypoxia, Harmful Algae, Seagrass Loss	Hypoxia and Chl-a decreased
Tampa Bay	Sewage	Local Mandate, Dedicated Agency	Large/Fast Decrease	Algal Blooms, Seagrass Loss, Harmful Algae	Chl-a decreased, Seagrass recovered
Long Island Sound	Sewage	Regulation, Federal Law, Dedicated Agency	Decrease	Hypoxia, Seagrass Loss, Harmful Algae	Hypoxia, Chlorophyll-a decreasing
Delaware River	Sewage	Regulation, Federal Law, Dedicated Agency	NH_4 Decrease	Hypoxia	Hypoxia decreased
Chesapeake Bay	Sewage / Agriculture	Regulation, Federal Law, Dedicated Agency	Small Decrease	Hypoxia, Seagrass, Harmful Algae	Limited hypoxia decrease, Partial seagrass recovery
Northern Gulf of Mexico	Agriculture	Non-Regulatory, Incentives	Minimal or No Decrease	Hypoxia	No improvement

EPA Office of Research and Development

Figure 5 Nitrogen loading reductions improve principal eutrophication effects in U.S. estuaries (from James's presentation)

Main references:

- *Greene, R. M., Lehrter, J. C., Hagy, J. D. (2009). Multiple regression models for hindcasting and forecasting midsummer hypoxia in the Gulf of Mexico. Ecological applications, 19(5), 1161-1175.*

- *Hagy, J. D., Boynton, W. R., Keefe, C. W., et al. (2004). Hypoxia in Chesapeake*

Bay, 1950–2001: long-term change in relation to nutrient loading and river flow. Estuaries, 27, 634-658.

- *Hagy, J. D. (2024). Quantifying Dissolved Oxygen Thresholds for Growth and Survival of Juvenile Atlantic Sturgeon in the Tidal-Fresh Delaware River using a Bioenergetic Modeling Approach. EPA/600/R-24/002.*

Case 5: Atlantic Canada (Scotian Shelf)

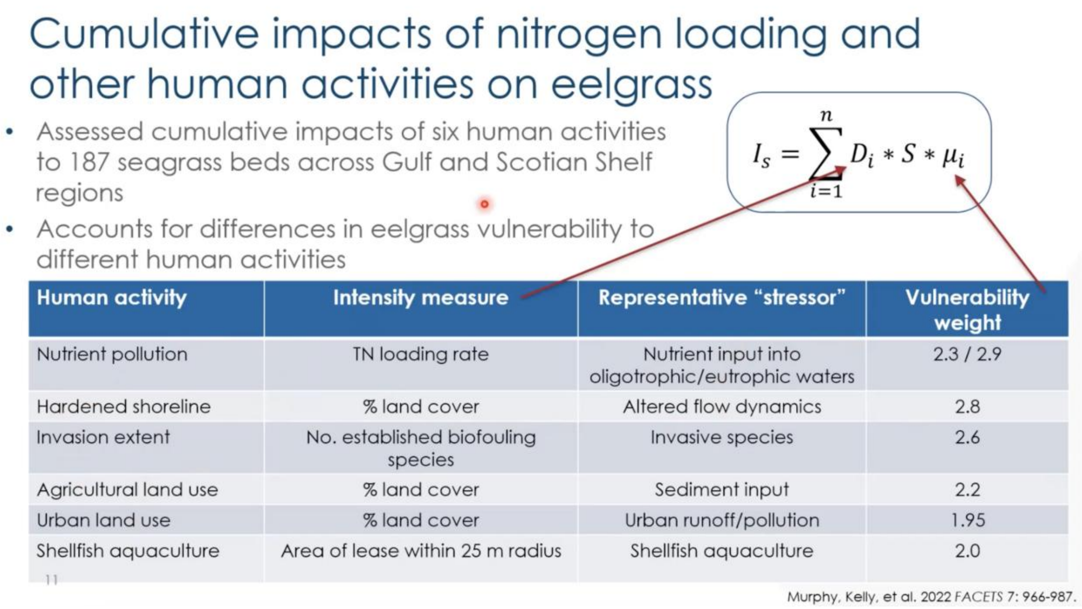
Presenter: Noreen E. Kelly

Noreen Kelly shared a report centered on the impacts of nitrogen loading on coastal ecosystems in Atlantic Canada, with a particular focus on eelgrass (*Zostera marina*) meadows. Eelgrass beds are ecologically important along the Atlantic coast, providing essential habitat and preventing shoreline erosion. However, their populations have declined by 90% since the 1930s, primarily due to increased wastewater discharge, turbidity, and changes in current regimes. Eelgrass also has a high minimum light requirement, making it especially vulnerable to declining water quality.

Potato agriculture was identified as the largest contributor to nitrogen loading in the region, owing to excessive fertilizer use. Sea cage aquaculture was found to increase annual nitrogen input by 14.4%. Atmospheric deposition is now the largest overall source of nitrogen, reflecting the influence of industrial areas and precipitation patterns.

To assess risk, a nitrogen loading model suitable for rural and suburban watersheds was applied. The ΔN indicator (load: dilution) was introduced, with a value above 0.06 signaling the likelihood of anoxic events. While ΔN in most embayments was below this threshold, some low-tide areas exceeded known limits associated with eelgrass loss. Additionally, a cumulative impact score (Is) was developed based on six human activities (Fig. 6); 49 eelgrass beds exceeded the Is threshold of 3.2, with 86% of these beds facing more than three pressures above this level.

A long-term study on marine harmful algal events in Canada was also referenced, identifying *Pseudo-nitzschia*, *Alexandrium*, and *Dinophysis* as the main phytoplankton groups causing annual paralytic shellfish toxin events since 2000. The report underscored the need for continued baseline monitoring and multi-factor risk assessment, especially as climate change, agriculture expansion, and new aquaculture activities intensify cumulative impacts on Atlantic Canada’ s coastal habitats.



Human activity	Intensity measure	Representative “stressor”	Vulnerability weight
Nutrient pollution	TN loading rate	Nutrient input into oligotrophic/eutrophic waters	2.3 / 2.9
Hardened shoreline	% land cover	Altered flow dynamics	2.8
Invasion extent	No. established biofouling species	Invasive species	2.6
Agricultural land use	% land cover	Sediment input	2.2
Urban land use	% land cover	Urban runoff/pollution	1.95
Shellfish aquaculture	Area of lease within 25 m radius	Shellfish aquaculture	2.0

Figure 6 A new indicator used to calculate the cumulative impacts of nitrogen loading and other human activities (from Noreen’s presentation)

Main references:

- *Kelly, N. E., Guijarro-Sabaniel, J., & Zimmerman, R. (2021). Anthropogenic nitrogen loading and risk of eutrophication in the coastal zone of Atlantic Canada. Estuarine, Coastal and Shelf Science, 263, 107630.*
- *McKenzie, C. H., Bates, S. S., Martin, J. L., et al. (2021). Three decades of Canadian marine harmful algal events: Phytoplankton and phycotoxins of concern to human and ecosystem health. Harmful Algae, 102, 101852.*
- *Murphy, G. E., Kelly, N. E., Lotze, H. K., et al. (2022). Incorporating anthropogenic thresholds to improve understanding of cumulative effects on seagrass beds. FACTS, 7, 966-987.*

Case 6: Cockburn Sound, Western Australia

Presenter: Chongran Zhou

Chongran Zhou shared a report focused on the historical development and recovery of eutrophication in Cockburn Sound, a semi-enclosed embayment near Perth, Western Australia. In the 1980s, Cockburn Sound was severely impacted by nutrient inputs from multiple anthropogenic sources. Groundwater leakage was heavily contaminated with nitrate from industrial waste, and the discharge of sewage added to the overall nutrient load. The construction of a causeway to Garden Island dramatically increased the water residence time from about 7 days to approximately 16 days, which promoted water stagnation and intensified eutrophication. As a result, nearly all seagrass beds in the eastern bay were lost during this period.

Sediment core analysis was used to reconstruct the ecological history of Cockburn Sound. The cores revealed the abundance patterns of three main groups of phytoplankton: dinoflagellates, diatoms, and haptophytes/coccolithophorids. Diatoms generally dominated during the period of severe eutrophication, which was attributed in part to shifts in the ammonium to nitrate (NH4:NO3) ratio in nutrient inputs. The cores also indicated increasing abundances of the harmful silicoflagellate *Dictyocha* and *Chaetoceros* species, signifying continued water quality concerns even after efforts at recovery.

Statistical analysis showed that temperature changes explained 50.0% of the observed variation in phytoplankton groups, while salinity accounted for 24.6%. This indicates that, although nutrient management remains important, climate variables such as temperature and salinity—potentially influenced by climate systems like ENSO and the Indian Ocean Dipole—have become strong drivers of phytoplankton dynamics in Cockburn Sound. These findings highlight the complexity of ecosystem recovery, demonstrating that both legacy effects of past nutrient loading and ongoing climate variability shape the current state and future prospects of the bay (Fig. 7).

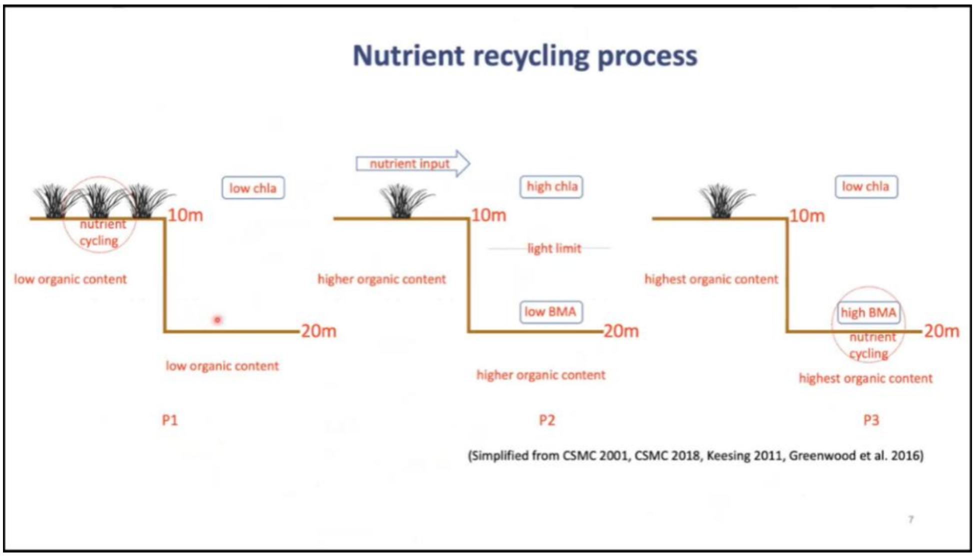


Figure 7 Nitrogen cycling processes at different stages of eutrophication in Cockburn Sound

(From Chongran's presentation)

Main references:

- *Helleren, S. (2016). The diatom Chaetoceros spp. as a potential contributing factor to fish mortality events in Cockburn Sound, November 2015. Dalcon Environmental Report, 1-29.*
- *Kendrick, G. A., Aylward, M. J., Hegge, B. J., et al. (2002). Changes in seagrass coverage in Cockburn Sound, Western Australia between 1967 and 1999. Aquatic Botany, 73(1), 75-87.*
- *Zhou, C., Liu, D., Keesing, J., et al. (2024). Microalgal assemblages response to water quality remediation in coastal waters of Perth, Australia. Environmental Pollution, 351, 124017.*

Case 7: Bohai Sea, China

Presenter: Keqiang Li

Keqiang Li shared a presentation addressing the worsening eutrophication situation in the Bohai Sea, a semi-enclosed sea with one of the highest population densities in China. Over the past seventy years, dissolved inorganic nitrogen (DIN) in the Bohai Sea has doubled, while phosphate and silicate concentrations have remained relatively stable. This imbalance has caused the nitrogen to phosphorus (N/P) ratio to rise sharply from less than 5 to over 60. Since the 1990s, chlorophyll-a concentrations have increased, and the phytoplankton community has shifted from diatom dominance to a co-dominance of diatoms and dinoflagellates, indicating a clear response to changing nutrient regimes.

A Compound Eutrophication Index (CEI) was introduced, based on pressure elements (such as TN, TP, DO), ecological elements (including DIN, PO4-P, SiO3-Si, SST), and oceanographic elements (reclamation area, residual current). The CEI was found to have a strong linear relationship with chlorophyll-a, making it a robust metric for eutrophication assessment. Further, an Ecological Risk Index (ERI) derived from CEI was used to evaluate both spatial and temporal risk patterns. Analysis showed that the ERI in the Bohai Sea increased from level II (low risk) in 1980 to level IV (high risk) by 2012, with the highest risk (level V) occurring in summer and in coastal areas compared to deeper waters.

Anthropogenic factors were identified as the largest contributors to eutrophication risk, accounting for 91% of the ERI. To guide pollution control, a 3D biogeochemical-hydrodynamic model was used to calculate total maximum allocated loads (TMALs) for the Bohai Rim, resulting in values of 1.05×10^5 tons/year for total nitrogen (TN), 1.10×10^5 tons/year for total phosphorus (TP), and 1.95×10^6 tons/year for chemical oxygen demand (COD). Comparison between China's 13th and 14th Five-Year Plans showed that the proportion of pollution reduction from area and non-point sources has increased significantly, from 17% and 14% to 42% and 28% respectively (Fig. 8).

The conclusion was that, despite implementation of three major environmental protection plans since 2001, eutrophication in the Bohai Sea remains severe and is intensifying. It was emphasized that future control strategies must focus more on reducing anthropogenic nutrient inputs, especially from area and non-point sources, and that the approach and indices developed in this research provide important references for policy and management in this ecologically sensitive region.

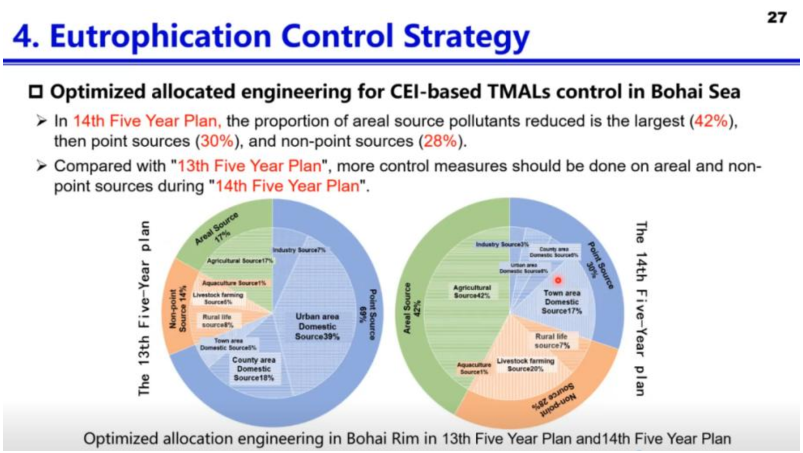


Figure 8 Allocation optimization for pollution source control in the Bohai Rim under the 13th and 14th five-year plans (from Keqiang's presentation)

Main references:

Dai, A., Li, K., Ding, D., et al. (2015). Total maximum allocated load calculation of nitrogen pollutants by linking a 3D biogeochemical–hydrodynamic model with a programming model in Bohai Sea. Continental Shelf Research, 111, 197-210.

Lin, G., Xu, X., Wang, P., et al. (2020). Methodology for forecast and control of coastal harmful algal blooms by embedding a compound eutrophication index into the ecological risk index. Science of the Total Environment, 735, 139404.

Wang, Y., Li, K., Li, Y., et al. (2018). Assessing the total maximum allocated load of jurisdiction petroleum pollutants in the Bohai Sea. Ocean & coastal management, 151, 150-164.

Case 8 Jinhae Bay, South Korea

Presenter: Tae Gyu Park

Tae Gyu Park shared a presentation detailing a decade-long study (2011–2022) on harmful algal blooms caused by *Alexandrium* species in Jinhae Bay, a major estuary in South Korea. By isolating thirty *Alexandrium* strains and using LSU rDNA sequencing, four dominant species were identified: *A. fraterculus*, *A. affine*, *A. catenella*, and *A. pacificum*. Quantitative PCR (qPCR) methods were used for precise species-level quantification, with results compared to traditional microscopy-based cell counts.

The research showed that each *Alexandrium* species exhibited unique ecological and seasonal preferences. Notably, A. catenella reached high cell densities and caused strong paralytic shellfish poisoning (PSP) events when surface water temperatures were low (10–16°C), with blooms terminating as temperatures rose above 18°C. A. pacificum contributed to longer PSP event durations. Laboratory and field data further revealed that cold stress (rapid temperature drops) increased saxitoxin gene expression and overall toxin production, while heat stress reduced total toxin but increased toxin diversity (Fig. 9).

Grazing experiments showed that predation by copepods (*Acartia* spp.), ciliates (*Strombidinopsis* spp.), and dinoflagellates (*Polykrikos* spp.) was generally low, except at low *Alexandrium* cell densities. The study concluded that rapid temperature fluctuations, especially sudden cooling events, are key triggers for *Alexandrium* bloom formation and elevated toxicity in Jinhae Bay. Nutrient levels and grazing played lesser roles compared to the dominant effect of temperature dynamics.

Overall, the report highlighted the importance of climate variability—specifically temperature changes—in driving harmful *Alexandrium* blooms and PSP risk, underscoring the need for continuous temperature and bloom monitoring in Korean estuarine environments.

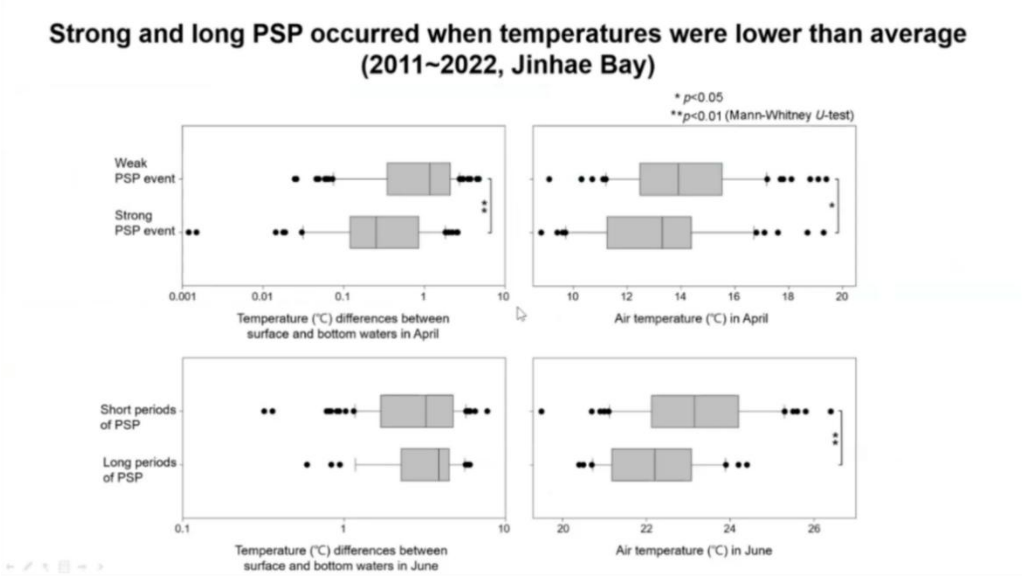


Figure 9 Lower-than-average temperatures promote strong and prolonged PSP events (Jinhae Bay, 2011–2022, from Tae Gyu's presentation)

Main references:

- *Kim, H. S., Kim, T., Park, J., et al. (2024). Development of saxitoxin biosynthesis gene sxtB-targeted qPCR assay for the quantification of toxic dinoflagellates Alexandrium catenella (group I) and A. pacificum (group IV) occurring in the Korean coast. Harmful Algae, 134, 102603.*
- *Kwon, H. K., Kim, G., Lim, W. A., et al. (2020). Conditions of nutrients and dissolved organic matter for the outbreaks of Paralytic Shellfish Poisoning (PSP) in Jinhae Bay, Korea. Marine pollution bulletin, 158, 111381.*
- *Lee, H., Kim, G., Baek, C., et al. (2024). Biogeochemical conditions controlling the intensity of paralytic shellfish poisoning (PSP) outbreak caused by Alexandrium blooms: Results from 6-year field observations in Jinhae-Masan Bay, Korea. Science of the total environment, 950, 175236.*

Case 9: Japan Coastal Bays (Miyako, Tokyo, Shizugawa, Hinase)

Presenter: Masahiko Fujii

Masahiko Fujii shared a presentation focused on the impacts of climate change and human activities on several types of Japanese coastal bays, including Miyako Bay (oligotrophic), Tokyo Bay (eutrophic), and two important oyster farming areas, Shizugawa and Hinase. Field observations were combined with high-resolution modelling using the PISCES biogeochemical model and the ROMS-based CROCO v1.1 model, with future projections based on IPCC AR5 scenarios (including changes in CO_2, alkalinity, dissolved oxygen, and carbon).

For Miyako Bay, a relatively undisturbed and oligotrophic system, the models accurately simulated rainfall-driven salinity drops but underestimated dissolved oxygen levels, likely due to sensor fouling. In contrast, Tokyo Bay receives significant nutrient and freshwater inputs from urban sewage and factory discharges—approximately half of the total—resulting in persistent hypoxia and large fluctuations in pH and aragonite saturation (Ωarag). These environmental stresses threaten key aquaculture species, particularly Pacific oyster larvae, which require a minimum Ωarag threshold for survival and shell formation (Fig. 10).

Future scenario modelling indicated that by 2090, under high-emission RCP 8.5, Hinase Bay will permanently fall below the Ωarag threshold suitable for oyster larvae, and Shizugawa Bay will experience unsuitable conditions for most of the oyster spawning period. Additionally, heavy rainfall and increased freshwater inputs under climate change are expected to intensify stratification, hypoxia, and acidification.

The findings highlighted that effective adaptation and mitigation strategies will require stricter management of organic matter and nutrient inputs, improvements in aquaculture techniques, and possibly adjusting farming locations or practices. The report underlined the importance of combining physical, chemical, and biological models with long-term monitoring to address the complex, multi-stressor impacts of climate change and human activities on Japanese coastal ecosystems.

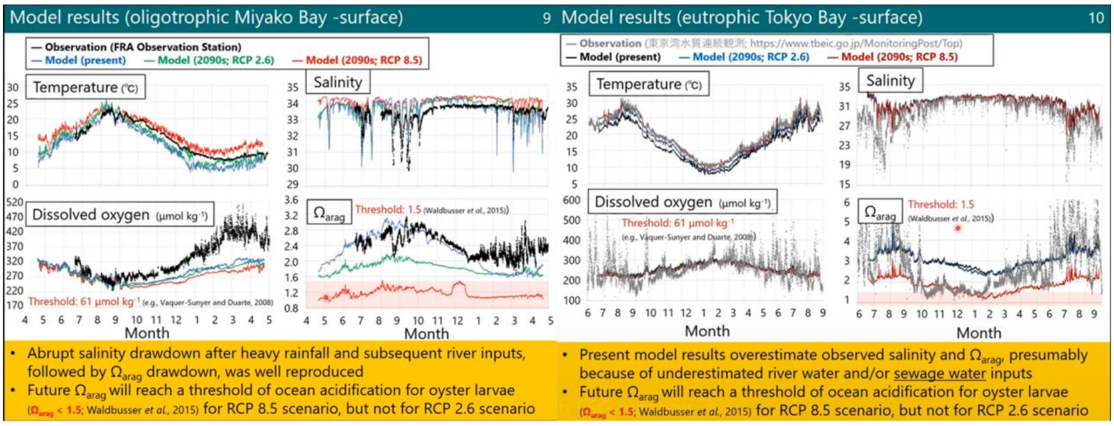


Figure 10 Comparison of Modeled and Observed Surface Water Properties in Miyako Bay and Tokyo Bay under Different Climate Scenarios (from Masahiko's presentation)

Main references:

- *Fujii, M., Hamanoue, R., Bernardo, L. P. C., et al. (2023). Assessing impacts of coastal warming, acidification, and deoxygenation on Pacific oyster (Crassostrea gigas) farming: a case study in the Hinase area, Okayama Prefecture, and Shizugawa Bay, Miyagi Prefecture, Japan. Biogeosciences, 20(22), 4527-4549.*

- *Fujii, M., Takao, S., Yamaka, T., et al. (2021). Continuous monitoring and future projection of ocean warming, acidification, and deoxygenation on the subarctic coast of Hokkaido, Japan. Frontiers in Marine Science, 8, 590020.*

- *Yamamoto-Kawai, M., Ito, S., Kurihara, H., et al. Ocean acidification state in the highly eutrophic Tokyo Bay, Japan: controls on seasonal and interannual variability. Frontiers in Marine Science, 8, 642041.*

Case 10: Freshwater and Marine Cyanobacterial Harmful Algal Blooms

Presenter: Hans Paerl

Hans Paerl shared a presentation focused on the growing problem of cyanobacterial harmful algal blooms (CyanoHABs) as a symptom of both human activities and climate change in aquatic environments. Population growth, urban and agricultural expansion have increased both nitrogen and phosphorus loads into waterways, directly promoting cyanobacterial blooms. Additionally, hydrological changes and climate variables play important roles in bloom intensity and distribution. CyanoHABs are not only a freshwater issue but are increasingly found in marine and brackish systems as well.

The "players" in CyanoHABs can be grouped into three types: (1) coccoid cyanobacteria (e.g., *Microcystis*) which rely on external nitrogen inputs, (2) filamentous non-heterocystous cyanobacteria that may form colonies but mostly do not fix nitrogen, and (3) filamentous heterocystous types that do fix nitrogen. Early studies showed that salinity is not necessarily a barrier to cyanobacterial proliferation, and nutrient availability, especially high nitrogen and phosphorus, is the key driver (Fig. 11). Other promoting factors include warmer water temperatures and increased stratification, both of which are enhanced by climate change.

Several specific examples were given. In Lake Taihu (China), three decades of rapid population growth caused a shift from a diatom-dominated oligotrophic lake to a mesotrophic, cyanobacteria-dominated system. Nutrient addition experiments showed that both phosphorus and nitrogen contribute to higher chlorophyll concentrations, and their combined addition has the strongest effect regardless of season. In Lake Erie (USA), earlier reductions in phosphorus loads successfully suppressed blooms, but in recent decades blooms have returned, now dominated by non-nitrogen-fixing cyanobacteria, suggesting an increasing role for nitrogen.

The influence of climate was also emphasized: cyanobacteria grow better at higher temperatures compared to diatoms and chlorophytes, and syntheses of data from 143 lakes in Europe and South America confirmed that cyanobacterial percentage in phytoplankton communities is a function of both water temperature and nutrient levels. Hydrology also matters; for example, in Brazilian coastal lagoons and North Carolina estuaries, extreme rainfall events and tropical storms deliver more nutrients and promote blooms, while longer low-flow periods allow cyanobacteria to form persistent blooms.

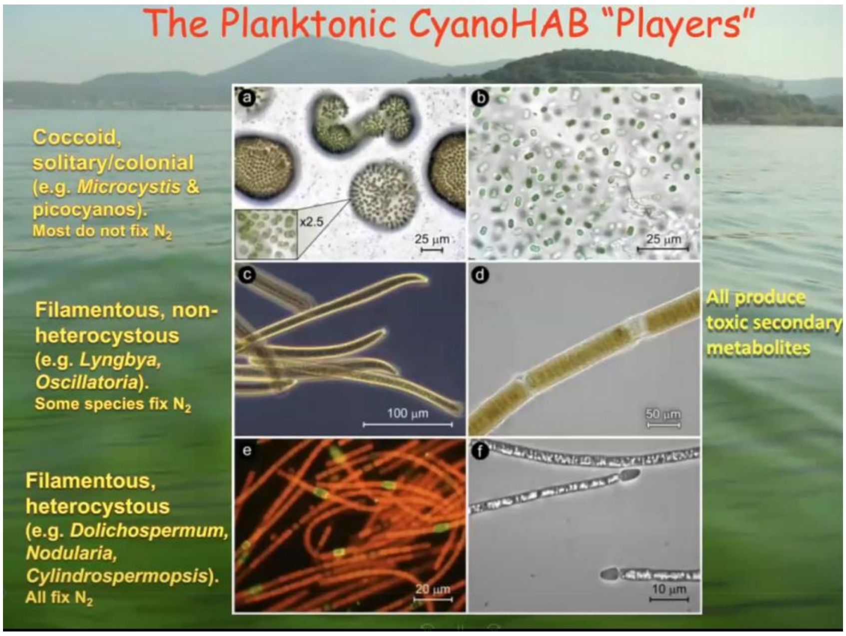


Figure 11 Key planktonic Cyanobacteria types ('Players') in CyanoHABs and their toxicity (from Hans's presentation)

Dual nutrient reduction strategy—reducing both nitrogen and phosphorus by over 30%—especially under warmer and stormier conditions was recommended. Year-round restrictions on nutrient inputs were advocated, and in systems where hydrology can be managed, reducing residence time was suggested as a way to benefit diatom populations. Technical interventions such as hydrogen peroxide application for bloom control were discussed, along with the potential use of floating solar collectors to limit light, though with important caveats.

Overall, the report highlighted that CyanoHABs are driven by the combined effects of human nutrient enrichment and climate change. Effective management requires integrated approaches that address both nitrogen and phosphorus, anticipate more frequent extreme weather events, and consider the physiological and ecological traits that allow cyanobacteria to dominate under current and future environmental conditions.

Main references:

- *Paerl, H. W., Gardner, W. S., Havens, K. E., et al. (2016). Mitigating cyanobacterial harmful algal blooms in aquatic ecosystems impacted by climate change and anthropogenic nutrients. Harmful algae, 54, 213-222.*
- *Paerl, H. W., Hall, N. S., Calandrino, E. S. (2011). Controlling harmful cyanobacterial blooms in a world experiencing anthropogenic and climatic-induced change. Science of the total environment, 409(10), 1739-1745.*
- *Paerl, H. W., Huisman, J. (2008). Blooms like it hot. Science, 320(5872), 57-58.*

Case 11: Harmful algal blooms in East China Sea

Presenter: Senjie Lin

Senjie Lin shared a presentation addressing the complex relationships between nutrient ratios, chemical forms, and the occurrence of harmful algal blooms (HABs) in the East China Sea and adjacent waters. Research supported by both field observations and laboratory molecular work revealed that an increased nitrogen-to-phosphorus (N:P) ratio is strongly associated with a higher frequency of HABs in Chinese coastal waters. However, the chemical form of nutrients—such as ammonium versus nitrate—can significantly influence which species dominate a bloom and its ecological effects.

Using the example of a major 2014 bloom in the East China Sea, a 48-fold increase in the expression of the proton pump rhodopsin (PPR) gene was observed, suggesting that light energy harvesting mechanisms are crucial for bloom formation and persistence. Different HAB species, such as Alexandrium catenella, P. shikokuense, and certain diatoms, exhibit unique strategies for nutrient utilization: diatoms were shown to use ammonium and organic nitrogen most efficiently, while P. shikokuense could utilize ammonium, nitrate, and even engage in phagotrophy (feeding on other phytoplankton), as indicated by gene expression data.

Further research demonstrated that some harmful algal species have advanced defense strategies, such as expressing genes for antimicrobial peptides, and complex sexual reproduction mechanisms, all contributing to bloom dynamics. These findings support a conceptual “ENDS” model (Energy, Nutrients, Defense, Sex) for understanding the ecological success of HAB species (Fig. 12).

The report concluded that the management of coastal eutrophication and HABs requires not just controlling the total amounts of nutrients, but also paying attention to their chemical forms and the specific ecological traits of bloom-forming species.

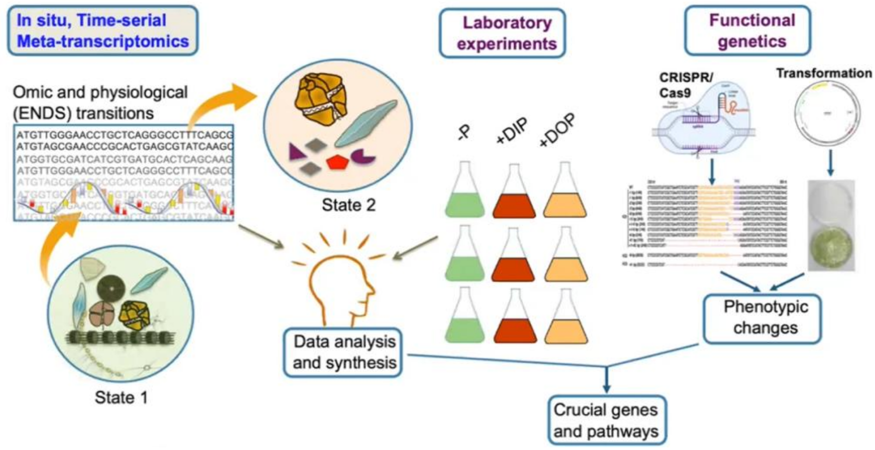


Figure 12 A multi-layered workflow: From in situ meta-transcriptomics to functional genetics in aquatic microbial responses (from Senjie's presentation)

Main references:

- *Guo, C., Li, L., Lin, S., et al. (2023). Species-dependent effects of seawater acidification on alkaline phosphatase activity in dinoflagellates. Journal of Phycology, 59(6), 1347-1352.*
- *Li, H., Li, L., Yu, L., et al. (2021). Transcriptome profiling reveals versatile dissolved organic nitrogen utilization, mixotrophy, and N conservation in the dinoflagellate Prorocentrum shikokuense under N deficiency. Science of The Total Environment, 763, 143013.*
- *Lin, S., Litaker, R. W., Sunda, W. G. (2016). Phosphorus physiological ecology and molecular mechanisms in marine phytoplankton. Journal of Phycology, 52(1), 10-36.*

3 Summary

The ESG highlights the complex and evolving nature of aquatic eutrophication worldwide. Case studies demonstrate that while nutrient reduction policies are fundamental, ecological responses are strongly influenced by climate change and other environmental conditions. Effective management depends on coordinated regulations, long-term monitoring, and adaptive strategies that integrate both scientific insights and policy action. In future, it is important to consider an interdisciplinary approach to address the effects of anthropogenic activity and climate change to sustain the health of marine ecosystem.