Ocean Acidification

Its Causes, Impacts, and Mitigation; A Report to the New York State Legislature

BY OCEAN ACIDIFICATION TASK FORCE, JULY 2023

For questions concerning ocean issues and the State's *Ocean Action Plan*, please contact NYSDEC's Division of Marine Resources at 631-444-0430.

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In Memory of Dr. Swanson

Ocean Acidification

OA

So, some say

Ocean acidification

A troubling situation

Declining pH

In too much haste

Seashells dissolving

Mitigation not evolving

To remediate

Need more carbonate

Reduce carbon dioxide

Worldwide

Raise pH to eight

The ocean's natural state

R. Lawrence Swanson
May 2020

Contents

continued on following page...

List of Figures

List of Tables

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List of Abbreviations

ANC	Acid-neutralizing capacity
BMP	Best management practices
DIC	Dissolved inorganic carbon
DO	Dissolved oxygen
DOS	New York State Department of State
EPA	Environmental Protection Agency
FOARAM	Federal Ocean Acidification Research and Monitoring
LINAP	Long Island Nitrogen Action Plan
LIRPC	Long Island Regional Planning Council
LIS	Long Island Sound
NOAA	National Oceanic and Atmospheric Administration
NRDC	Natural Resources Defense Council
NYC	New York City
NYS	New York State
NYSDEC	New York State Department of Environmental Conservation
NYSERDA	New York State Energy Research and Development Authority
OA	Ocean acidification
OATF	Ocean Acidification Task Force
PSA	Public Service Announcement
QAQC	Quality Assurance/Quality Control
SBU	Stony Brook University
SEQR	State Environmental Quality Review Act
SPDES	State Pollution Discharge Elimination System
STP	Sewage treatment plant
TMDL	Total Maximum Daily Load
USGS	U.S. Geological Survey
WTE	Waste-to-energy

Executive Summary

In 2016, the New York State Legislature established the Ocean Acidification Task Force (OATF) "to identify the causes and factors contributing to ocean acidification and evaluating ways of addressing the problem by applying the best available science as to ocean acidification and its anticipated impacts." One of New York State's most significant climate change impacts, ocean acidification (OA) has far-reaching, adverse impacts on marine living resources, altering ecosystems and the socioeconomic benefits derived from oceanic ecosystem services, including fishing, aquaculture, and coastline protection. In the coastal ocean, the carbonate system is strongly influenced by marine discharges of various acidic waters, such as fresh water, wastewater, and upwelling, as well as indirectly by excessive nutrient discharges driving coastal OA. Recommendations in this report are intended to reduce the impact of OA in the coastal waters of New York. Although the OATF embraces the broad global and national goals of reducing factors contributing to global carbon emissions and OA, efforts are centered in this report on identifying mitigation measures that are suitable to New York State's marine waters.

In this report, there are five categories, or pillars, of actions recommended for addressing the effects of coastal OA in New York's marine waters.

Pillar I: Mitigate by implementing measures to reduce the extent, magnitude, and impact of OA.

Coastal OA has a variety of drivers, such as carbon dioxide emissions, eutrophication, freshwater flows, marine discharges, and coastal upwelling. Mitigation measures can be directed at decreasing acidity directly or at utilizing and ameliorating the sources of nutrients or carbon dioxide that are causing OA. The ability of diverse natural systems, such as marshes, sea grasses, and seaweeds, to store blue carbon must be protected. One way to reduce OA is keeping active circulation in coastal waterbodies, thereby reducing residence times, nitrogen accumulation, occurrences of low dissolved oxygen (DO), and eutrophic conditions. Given that nitrogen is a driver of estuarine hypoxia and coastal OA, more stringent nitrogen water quality standards are recommended. Programs that use, recycle, or store nitrogen and carbon, such as shell-recycling and aquaculture, are to be encouraged to counteract the fundamental causes of OA. Land-use zoning may be the best tool available to balance land development and the protection of New York State's marine waters and their economically important marine resources. The State and its partners should assist zoning boards in planning for OA mitigation.

Pillar II: Educate to promote awareness of the occurrence of OA, its adverse impacts, and opportunities for mitigation.

Knowledge and awareness are essential for informing good policy and action. The OA community in New York should work with the extensive climate-change adaptation and resilience community to take advantage of existing educational opportunities and resources to create new avenues for outreach and engagement. In some cases, new legislation and changes in public policy will be necessary. New York State should regularly report on the status of coastal OA and how existing conditions and impacts are being mitigated once reasonable and sufficient monitoring has taken place.

Pillar III: Investigate through relevant OA research and monitoring.

The dynamic interactions and functioning of marine ecosystems are complex, and mitigating OA requires a broad understanding and continuing investigation of those systems. Research should focus on increasing the understanding of ocean carbonate chemistry and developing baseline data by monitoring the relevant chemical parameters, and the status of sentinel, shell-building marine organisms that are most sensitive to OA. Research must also identify appropriate remedial actions for each waterbody and OA mitigation best practices scalable to a level that results in significant environmental improvement and meaningful investment. Research efforts should include long-term monitoring of implemented measures for adaptive management and establishment of explicit marine environment targets for coastal OA in the major waterbodies in New York State's Marine and Coastal District.

Pillar IV: Engage, convene, and support efforts of businesses, industry, and all levels of governments to reduce or eliminate factors contributing to OA through the adoption of best management practices (BMPs).

Reducing the impact of OA on New York's coastal waters will require working closely with businesses, industry, and local governments to develop appropriate financial and other incentives for OA mitigation.

Pillar V: Legislate a regulatory action plan to set criteria; fund education, research, and monitoring; fund incentives for businesses and industry to implement BMPs; and fund implementation of mitigation measures.

Introduction

Ocean acidification (OA) is caused by the dissolution of excessive amounts of atmospheric carbon dioxide in marine waters, a global problem largely resulting from the burning of fossil fuels and the transformative changes in land use. OA is one of the many effects of anthropogenic (human-caused) climate change. This report will provide guidance to the New York State executive branch and Legislature in addressing the problem of OA. Successful implementation of appropriate recommendations will require hard work, ingenuity, financial and staff support, and extensive collaboration of all partners and stakeholders, including federal, state, and local governments; and nonprofit, academic, research, and private sector agencies and institutions.

This report recommends definitive actions the State and its partners[1] and stakeholders can undertake that will have measurable impacts for curbing and mitigating contributing factors to coastal OA. To identify the best actions for mitigating and reducing the contributing factors to coastal OA, specific marine environmental targets and mitigation measures should be identified for each waterbody that are scaled in time and space to achieve the targets. Targets might be based on specific life stages of key OA-sensitive species. New York State has several tools available to establish and enforce targets through the Federal Water Pollution Control Act (as amended, commonly referred to as the Clean Water Act) and the authorizations given to the states, including technology-based standards (Kelly and Caldwell, 2013).

Geographic Focus

This report identifies many of the New York State resources that are at risk in its Marine and Coastal District (Figure 1) and its neighboring waters in the New York Bight. The tidally influenced waters of the New York Marine and Coastal District consist of interconnected marine systems with distinct ecosystems. These systems include:

- The open Atlantic Ocean;
- South Shore Estuary Reserve, a series of shallow bar-built estuaries on the South Shore of Long Island, separated from the open Atlantic Ocean by barrier islands and connected by narrow inlets;
- The Hudson River Estuary system, running 233 km (145 mi) north to Albany from New York Harbor;
- The Long Island Sound (LIS), a large estuary shared with Connecticut; and
- The Peconic Estuary, located between the north and south forks of Long Island.

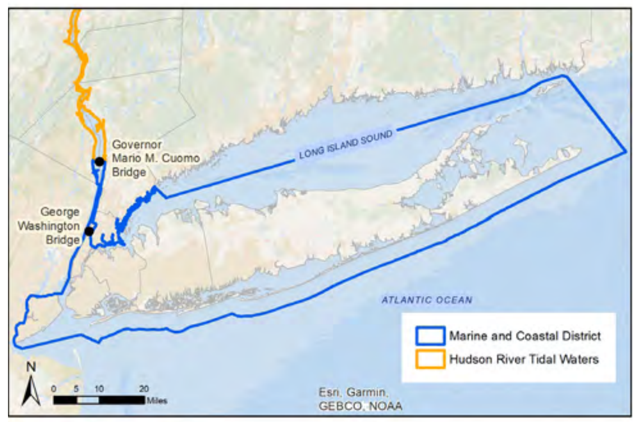

Figure 1. The Marine and Coastal District of New York State. Credit: https://www.dec.ny.gov/permits/95483.html

1 NYSDEC works closely with a broad coalition of partners, including the NYS Department of State, the Long Island Regional Planning Council (LIRPC), the region's National Estuary Programs, Suffolk and Nassau counties, federal government agencies, local governments, area scientists, numerous environmental organizations, nongovernmental organizations, and a cadre of consultant services.

Science of OA

To develop appropriate recommendations and appropriate policies for OA, it is essential to understand the basic science behind OA and how climate change and anthropogenic activities are contributing. Over the last 200 years, a measure of acidity known as pH[2] has declined on average by about 0.1 units throughout the world's oceans (Honisch, 2012; The Ocean Portal Team, 2018). This is about 50 times greater than the rate prior to the Industrial Revolution. The ocean is naturally slightly alkaline, with a normal average pH of 8.2. The ocean's average pH is now approximately 8.1. This decline translates into an increase in acidity of about 26% in the last two centuries, and ocean pH is expected to further decline 0.3–0.4 units by the end of the twenty-first century (The Ocean Portal Team, 2018).

On a global scale, the dissolution of atmospheric carbon dioxide in the ocean causes OA. When atmospheric carbon dioxide dissolves in seawater, the carbon dioxide is hydrated and forms carbonic acid that then separates into bicarbonate and carbonate, leaving hydrogen ions available in the water column (Figure 2). Marine organisms depend on carbonate ions in the form of calcium carbonate to create their shells. If the waters are too acidic, the carbonate ions will associate with excess hydrogen ions, decreasing the availability of calcium carbonate in the form of aragonite,[3] which is necessary for proper shell formation. This is what is referred to as global OA. In the coastal ocean, the carbonate system is strongly influenced by marine discharges of various acidic waters, such as freshwater and wastewater, upwelling (Rheuban et al., 2019), and stormwater and fertilizer inputs, all of which drive what is referred to as coastal OA (Wallace et al., 2014). In coastal OA, nitrogen from sewage and fertilizer seeps into coastal marine waters and stimulates excessive biological growth in the form of marine algae. As the excess algae die off and decompose, the process consumes DO every night and releases carbon dioxide into the water when excess organic matter decomposes. Nitrification, the process by which ammonia is oxidized to form nitrite and then is oxidized again to form nitrate, also contributes to acidification in nearshore waters. The relative contributions of both coastal OA and global OA to regional acidification conditions in New York State's waters have not yet been quantified, but coastal OA generally is thought to be the more immediate problem in New York's waters.

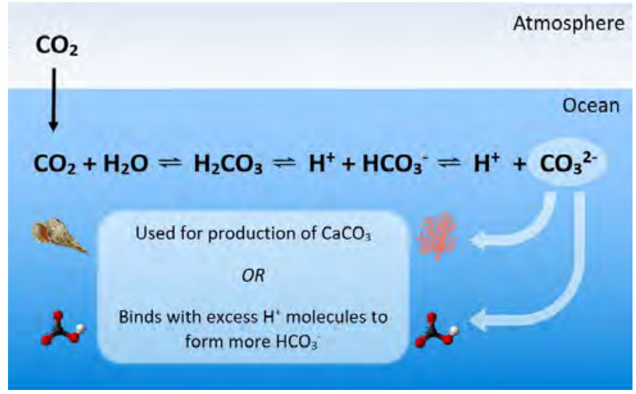

Figure 2. Reaction of carbon dioxide in water. When carbon dioxide dissociates in water it forms carbonic acid and carbonate ions and can either be used by calcifying organisms or taken up by excess hydrogen ions. Under acidic conditions, more carbonate ions react with hydrogen ions, making carbonate molecules unavailable to calcifying organisms. Credit: NYS OATF

Coastal eutrophic waters and hypoxia[4] can exacerbate acidic conditions as marine algae, phytoplankton, and microbes respire and release carbon dioxide to the water in a variety of marine environments reducing the buffering capacity of those environments (Cai et al., 2011; Cai et al. 2017). Locally, Baumann et al. (2015) have shown the wide daytime (diurnal) fluctuations of pH, DO, and the partial pressure of carbon dioxide[5] in Flax Pond (Baumann et al., 2015), a small, highly productive embayment of the LIS. The LIS experiences seasonal fluctuations in pH that occur together with low DO and high chlorophyll values (Wallace et al., 2014). The greatest fluctuations occur in bottom waters of the western LIS where the effect of high levels of partial pressure of carbon dioxide on the availability of aragonite would negatively impact many marine organisms (Kroeker et al., 2013). Large portions of the water column have low aragonite concentrations in summer months that can persist in the western LIS into the fall (Wallace et al., 2014). Hempstead Bay and Jamaica Bay (on the South Shore of Long Island) also display high levels of partial pressure of carbon dioxide (Wallace et al., 2014). Considerable marine resources, including coastal ecosystem services and assets, are potentially at risk from OA. Significant ecological and economic impacts have already affected the western LIS, Hempstead Bay, and Jamaica Bay (Wallace et al., 2014), where the acidity of marine waters has reduced growth and survival in early

2 pH, or potential of hydrogen, measures the concentration of hydrogen ions, that is, the acidity, of a liquid. A pH below 7 is acidic and above 7 is alkaline. pH is measured on a logarithmic scale where a 1 pH unit change is equivalent to a ten-fold change in hydrogen-ion concentration.

3 Aragonite, a calcium carbonate mineral, is secreted from water by animals to form a shell. Aragonite saturation state is a measure of the tendency of aragonite to form or dissolve.

4 Hypoxia is a condition of low levels of DO in the water (O_2 < 3 mg/L). Eutrophication is a process that occurs when there is an overabundance of nutrients in the water that leads to excessive growth of plants. When these plants die, bacteria use DO in the process of decomposition and this can lead to low levels of DO in the water.

5 The partial pressure of carbon dioxide is a measure of the concentration of carbon dioxide dissolved as a gas in the water.

life stages of both fish (Murray et al., 2014) and shellfish (Miller et al., 2009; Talmage et al., 2009; Kroeker et al., 2013).

OA is only one effect of global climate change, and the state of knowledge concerning OA is incomplete and rapidly evolving. Climate change impacts are considered to be threat multipliers because underlying stressors, like pollution, habitat destruction, and overexploitation, weaken the health and resilience of the marine ecosystem. Climate change impacts work synergistically to push ecosystems toward and beyond their limits (thresholds). As climate change continues to modify the chemistry, biology, and physical aspects of the already-stressed marine environment, actions taken to mitigate the effects of OA may not be as effective or even viable in the near future. For example, biogeographic zones of valued species in New York's waters may shift for reasons not directly caused by OA, but OA may make it impossible for those species to return to those zones even after habitat restoration projects are completed. Thus, it is imperative that the State's OA-management approach take into consideration current and future climate change conditions and how these impacts exacerbate existing stressors, and be readily adaptable to meet the changing environmental realities under climate change.

Climate Change Magnifies OA Impacts

Anthropogenic greenhouse gas emissions result in both climate change and ocean acidification, and ocean acidification has been referred to as "the other carbon dioxide problem" (Logan, 2010). Beyond their root causes, ocean acidification and climate change are often approached as distinct and separate problems. Recent research provides insights into a much more complex relationship, and demonstrates how unfolding physical effects and impacts of climate change are already exacerbating the impacts of ocean acidification and are projected to increase. In this way, climate change can be considered a threat- or risk-multiplier of ocean acidification.

Climate change has already resulted in significant physical effects and impacts and climate change projections have been developed for anticipated future climate changes. Average temperature increases have occurred every decade between 1901 and 2012 in all parts of NYS, with temperature increases ranging from 0.09–0.35 degrees Fahrenheit per decade (Horton et al., 2014). In the 2100s, New York City and Long Island temperatures are projected to be 12.1°F higher than baseline. Regional sea-surface temperatures have also risen more than 1.0°F over the course of the twentieth century, and future projections developed for the 2050s show substantial increases of 1.8–2.5°F above the 1980s baseline for regional nearshore waters (Buonaiuto et al., 2011). Projections for ocean waters over the Northeast Continental Shelf expect increased warming by up to 0.76°F per decade by the period 2070–2099, compared to 0.40°F per decade during the period 1976–2005 (Alexander et al., 2018).

Average annual precipitation has increased in New York City and Long Island by 0.76 inches per decade (1901–2012) (Horton et al., 2014). By 2080, the New York City area is projected to have an additional increase of 6–19% in average annual precipitation depending on carbon emissions levels (Horton et al., 2014).

Sea level along New York's ocean coast and in the Hudson River has already risen about 1.2 inches per decade, for a total of more than one foot since 1900 (Horton et al., 2014). New York State's official sea level rise projections, adopted under Title 6 of the New York Codes, Rules and Regulations (6 NYCRR Part 490), are shown in Table 1.

Table 1. New York State sea level rise projections (6 NYCRR Part 490)

Region	Long Island					NYC/Lower Hudson					Mid-Hudson				
	Inches of rise over baseline level, defined as the average level of the surface of tidal water over the years 2000-2004														
Descriptor	L	L-M	M	H-M	H	L	L-M	M	H-M	H	L	L-M	M	H-M	H
2020s	2	4	6	8	10	2	4	6	8	10	1	3	5	7	9
2050s	8	11	16	21	30	8	11	16	21	30	5	9	14	19	27
2080s	13	18	29	39	58	13	18	29	39	58	10	14	25	36	54
2100	15	21	34	47	72	15	22	36	50	75	11	18	32	46	71

L = Low, M = High; H=High; Baseline = "The average level of the surface of marine or tidal water over the years 2000–2004"

The number of days of extreme heat, with temperatures at or above 90°F, have been increasing since the 1970s. Total days of extreme heat, as well as both the number and duration of heat waves, are expected to increase in the coming decades. (Rosenzweig et al., 2011). Changes in future storm frequency is unclear, although it is expected that storm intensity will increase (Alexander et al., 2018). Average annual precipitation increases for New York City and Long Island were 0.76 inches per decade from 1901–2012 (Horton et al., 2014). Drought frequency in New York is projected to increase by the end of this century as increased rates of evaporation associated with warmer temperatures are expected to outweigh increases in precipitation (Horton et al., 2014). Projected changes to extreme weather in New York State as listed here, Table 2, were adapted from data in Horton et al., 2014.

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Climate Change Magnifies OA Impacts (continued)

Table 2. Projected changes to New York State extreme weather, 90th percentile				
Future Time Period	Extreme Heat (additional days above 90°F	Number of Heat Waves (# of additional periods of 3+ days of extreme heat) per year	Duration of Heat Waves (additional days)	Extreme Rain (additional days with more than 1 inch)
Baseline	0.3–18	0–2	3–4	5–13
2020s	1.7–15	0.2–3	0–1	1–3
2050s	9.7– 4	1–7	1–2	1–4
2080s	26.7–73	3–8	2–5	2–5

Climate change effects are already having and are expected to have increasingly compound, cumulative, and synergistic impacts on OA. Intense precipitation associated with tropical systems in late summer and fall have caused flooding to the state's larger riverine systems (Rosenzweig et al., 2011). Heavy rain events result in increased runoff and streamflow and reduced water quality (Dupigny-Giroux, 2018). Increases in precipitation are expected to alter the salinity of nearshore waters, impacting fish and shellfish (Alexander et al., 2018). Sea-surface temperature significantly influences the physiology, behavior, and phenology of temperate marine fish (Houde, 1989; Pepin, 1991; Nye et al., 2009). According to the National Oceanic and Atmospheric Administration (NOAA), "increased sea surface temperature in combination with runoff, sewage, and fertilizers may be interacting to alter the natural pattern of algal blooms, altering their frequency, spatial extent, species composition, and toxicity" (NOAA, n.d.). When climate change impacts such as thermal stress and hypoxia combine with OA, they can have a compound and synergistic effect that reduces the survival rate of larval fish (DePasquale et al., 2015; Gobler and Baumann, 2016). Atlantic fisheries are expected to experience "notable redistributions" under combined impacts of OA and warming waters from climate change by the end of the century (Wilson et al., 2020). Nutrient decreases coupled with warming temperatures may reduce phytoplankton biomass (Rose and Carron, 2007). Increasing temperatures, increasing ocean acidification, and reduced ocean food supplies, including phytoplankton, can work synergistically to reduce the survival and development of small fish in Atlantic estuaries (Gobler, et al., 2018). The combined effects of warming temperatures and OA threaten cold-water corals (Hoegh-Guldberg, et al., 2017). As climate change continues to intensify ocean acidification, "reductions in the survival, calcification, growth, development, and abundance of marine organisms" will become more likely (Mid-Atlantic Coastal Acidification Network, 2018).

Although there are still many uncertainties, and the dynamics of climate change and OA are not yet well understood, there is enough initial evidence to suggest that policies to address OA might be more robust if the current and projected physical effects and impacts of climate change were considered.

Establishment of the Ocean Acidification Task Force

Recognizing that the state's coastal waters are in distress, the New York Legislature enacted legislation establishing the Ocean Acidification Task Force (OATF; Laws of New York, 2016, Chapter 464). The OATF was charged with identifying "the causes and factors contributing to ocean acidification and evaluating ways of addressing the problem by applying the best available science as to ocean acidification and its anticipated impacts."

The legislation included several requirements:

- An assessment of the anticipated impacts related to OA;
- Recommendations related to mechanisms New York could establish to provide stronger, more protective standards, and the implementation and enforcement of such standards;
- Recommendations regarding adaptive measures that may be taken to respond to OA, including measures to:
  - Identify and monitor early effects of OA on marine life, animals, plants, and natural communities; and
  - Integrate OA mitigation and adaptation strategies into State environmental plans;
- Recommendations on State and local regulatory and/or statutory alterations to respond to the impacts of OA;
- Review of existing scientific literature and data on OA and how it has directly or indirectly affected or may potentially affect commercially harvested and grown species along the coast;
- Identification for monitoring the factors contributing to OA; and
- Recommendations to increase public awareness of OA.

To identify the best actions for mitigating and reducing the contributing factors to coastal OA, specific marine environmental targets and mitigation measures should be identified for each waterbody that are scaled in time and space to achieve the targets. Targets might be based on specific life stages of key OA-sensitive species. New York State has several tools available to establish and enforce such targets through the Federal Water Pollution Control Act and the authorizations given to the states including technology-based standards, the State Pollution Discharge Elimination System (SPDES), and Total Maximum Daily Loads (TMDLs) (Kelly and Caldwell, 2013).

Five Pillars

This report is divided into five pillars. Each pillar contains specific recommendations for addressing a different aspect of the OA issue. Collectively, the recommendations within the pillars have the potential to achieve measurable improvements in our coastal ocean and will also contribute to broader goals for OA reduction.

Pillar I: Mitigate – Identifying mitigation and resiliency measures to reduce the extent, magnitude, and impact of OA. These are intended to improve the conditions of New York State waters and their living marine resources. If implemented, these can not only reduce or help control New York's coastal OA but also be used in other states, increasing their impact.

Pillar II: Educate – Promoting awareness concerning the OA state of knowledge, its impacts, and opportunities for mitigation. Awareness of the importance of OA, particularly coastal OA, its consequences, and the potential for mediation is essential to develop the political will for its resolution.

Pillar III: Investigate – Undertaking relevant research and monitoring. There are many questions still surrounding the issue of OA. It is particularly important to identify remediation measures that have practical meaningful application, and not just implement aspirational measures that do not have a substantial quantitative effect. Remediation must be able to be scaled to a level that results in measurable environmental improvement. Long-term monitoring is a cornerstone of the adaptive management needed to ascertain that OA science is well founded and that New York State's remediation efforts are having the desired outcomes. Social sciences also have an important role in informing mitigation actions. Barriers to change within society must be anticipated if the consequences of OA are to be successfully mitigated.

Pillar IV: Engage – Engaging businesses and industry to invest in seeking solutions for OA impacts. The private sector should be inspired, and markets encouraged for marine products that can mitigate OA, such as kelp mariculture.

Pillar V: Legislate – In many cases, the primary way in which OA processes will be understood and appropriately monitored and remedial measures undertaken is through legislative action. Pillar V addresses the importance of the legislative process in setting standards; funding education, research, and monitoring; and requiring appropriate reporting. The legislative process can also provide incentives for businesses and industry to use BMPs and to invest in mitigation measures, perhaps by creating tax benefits.

Coordination and Collaboration with Partners

New York has a plethora of entities that have been and currently are working to address many water quality problems in the Marine and Coastal District. For example, in 2015, NYSDEC, the Long Island Regional Planning Council (LIRPC), and Suffolk and Nassau counties, with input from multiple partners and stakeholders, developed the Long Island Nitrogen Action Plan (LINAP), a multiyear initiative to reduce nitrogen in Long Island's surface and groundwaters. New York State DEC, Department of State (DOS), Energy Research and Development Agency (NYSERDA), and other state agencies have additional programs and initiatives that work on improving Long Island's water quality. Additionally, LINAP further partners with Long Island Sound Study to fund a Nutrient Bioextraction Coordinator to improve water quality. There are five estuary programs that are doing incredible work to assess and address water quality problems. On the federal level, the Environmental Protection Agency (EPA), NOAA, U.S. Geological Survey (USGS), and other agencies have led many successful water quality projects and initiatives. Local government, academic institutions, and nonprofit groups also work tirelessly to address water pollution in this area of the state.

Given limited staff and funding, and the far-reaching effects of OA, partnerships are critical to ensuring sustainable management of ocean resources to the benefit of all stakeholders. Since many of the recommendations in this report complement or expand on another group's activities, it will be most efficient and cost effective to collaborate with partners. By properly directing funding to supplement an existing program or project, leveraging will be maximized and thus ensure the most efficient and effective response to OA. At times, it will be essential for ocean stakeholders to collaborate and coordinate collectively to advocate for programs that advance shared goals.

Many partners have already added OA to the list of water-related priorities, and we look forward to partnering with them. The Task Force encourages others to also recognize and help address OA.

Marine Resources at Risk

OA is projected to have an adverse impact on marine fisheries, especially shellfishing. Adverse OA impacts to living marine resources are far-reaching, including impacts on physiology, population dynamics, and altered ecosystems (Doney et al., 2020). Societal benefits derived from oceanic ecosystem goods and services, including fishing, aquaculture, and coastline protection, are also jeopardized because of OA (Doney et al., 2020).

Consistent, negative, worldwide impacts of OA on survival, calcification, development (Figure 3), growth, and abundance in marine organisms have been identified (Kroeker et al., 2013). These impacts have been recognized from Maryland to Rhode Island (Maryland Task Force on OA, 2015; Ekstrom et al., 2015).

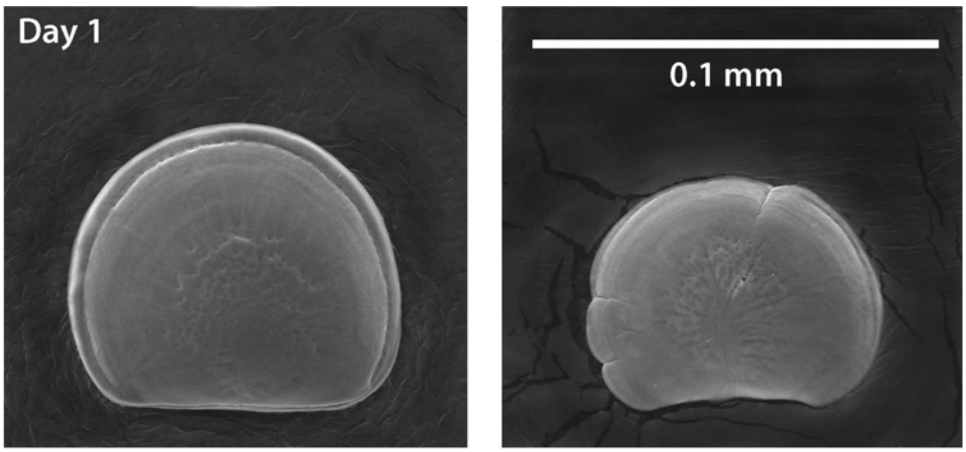


Figure 3. Effects of acidified water on shellfish larva development. This image shows one-day-old Pacific oyster larvae, both from the same parents, raised by the Taylor Shellfish Hatchery in natural waters of Dabob Bay, Washington. The larva on the left was reared in favorable carbonate chemistry; on the right, in unfavorable chemistry. The 0.1 mm scale bar is about the diameter of a human hair. (Credit: George Waldbusser and Elizabeth Brunner, Oregon State University, https://news.agu.org/press-release/ocean-acidification-killing-oysters-by-inhibiting-shell-formation/)

OA may produce adverse impacts on the physiology of many different types of organisms (Guinotte and Fabry, 2008). Numerous studies have overwhelmingly demonstrated reduced calcification, development, photosynthesis, growth, survivorship, and abundance of bivalves, with the magnitude of these effects varying across taxa (Kroeker et al., 2013). Lobsters, crabs, and shrimp have shown some initial ability to develop stronger shells in adaptation to OA (Ries et al., 2009), but these organisms may experience indirect negative impacts of OA on other physiological processes, like metabolism, growth, and reproduction.

While many shellfish are being and will be affected, it is unlikely that OA will impact all shellfishes equally. Understanding the various impacts will inform mitigation approaches. East Coast shellfish such as soft-shell clams and hard-shell clams (*Mya arenaria* and *Mercenaria mercenaria* respectively), blue mussels (*Mytilus edulis*), oysters (*Crassostrea virginica*), and bay scallops (*Argopecten irradians*) frequently have been identified as species at risk due to OA (Griffith and Gobler, 2017; White et al., 2013; White et al., 2014; Talmage and Gobler, 2009). Bay scallops (the official shellfish of New York State) are just starting to recover from reduced populations due to exposure to frequent harmful algal blooms, but they may now be in jeopardy again from OA, as well as from warming temperatures and other elements of climate change. Other economically important marine species potentially at risk due to impacts of OA include Atlantic surf clam (*Spisula solidissima*), longfin squid (*Loligo pealei*), and sea scallop (*Placopecten magellanicus*).

OA can also affect organisms without shells (finfish, jellyfish, plankton, etc.). Exposure of fish eggs and larvae to OA can reduce their growth and survivorship rates (Baumann et al., 2012a). OA-induced declines in growth and survival of shellfishes also reduced the biomass of upper trophic levels such as finfish (Fay et al., 2017). Simultaneously, there was an increased abundance of some jellyfish species, which could have a net negative impact on ecosystems because the jellyfish may then be able to outcompete other organisms for food (Guinotte and Fabry, 2008). The life stages of the sand lance (genus *Ammodytes*), a keystone forage fish for species such as humpback whales, sharks, and tuna, are particularly vulnerable to elevated partial pressure of carbon dioxide and increased temperatures, especially during their early life (Murray et al., 2019).

While the majority of OA research has focused on calcareous, shell-forming organisms, effects of OA on crustaceans with chitinous shells, such as lobsters, crabs, shrimp, and krill, have also been studied. American lobster (*Homarus americanus*) has already been locally decimated in the LIS by water temperature extremes (Wilson and Swanson, 2005) and may also be vulnerable to OA (Klymasz-Swartz et al., 2019; Tai et al., 2021; Waller et al., 2016). The blue crab, a recreationally important species in New York, seems to be increasing in abundance due to warming water temperatures. This species may be able to increase shell thickness in the presence of OA; however, the physiological costs of doing so are unknown. The horseshoe crab (*Limulus polyphemus*) is harvested locally for use in the biomedical industry and as bait (Sargent, 2002), but its shell-building ability could be threatened in changing ocean conditions. Additionally, the eggs of the horseshoe crab are the almost-exclusive food source for the migrating red knot (Sargent, 2002), a threatened shorebird species which is found along the salt meadows and mudflats of the South Shore of Long Island during its spring and autumn migrations (NYSDEC, 2014).

Some finfish species appear to be particularly affected by OA in their early life stages (Baumann et al., 2012b), although as they grow past the larval stage, they tend to confer resilience to OA (Cattano et al., 2018). Other fish species have been observed to be resilient under increased partial pressure of carbon dioxide, like the black sea bass (Meseck et al., 2022) and the Atlantic herring (Franke and Clemmesen, 2011). Little is known, however, about impacts on growth rates, blood buffering, age to maturity, sexual maturity, spawning, and homing instincts.

Alterations in the physiology of marine organisms could lead to reduced biodiversity impacting the entire marine food web. Calcareous phytoplankton that would normally sink rapidly instead tend to develop thinner exoskeletons in acidified conditions, causing them to sink more slowly and further alter carbon dioxide cycling in the water column (Gronlund, 2018). OA induced a community-level shift toward smaller cells in phytoplankton communities in Narragansett Bay, Rhode Island. Although currently being studied, these types of indirect effects of OA remain poorly known, and there are more questions than answers. Is the surface area of exposure of marine organisms to acidified water important and thus small planktonic organisms are more at risk than larger ones, impacting food webs? Does OA affect the ecological carbon pump by promoting growth in smaller forms of phytoplankton? The known impacts are concerning enough, but more OA research in this vein is needed to properly predict ecosystem interactions and reactions to changing pH.

The Socioeconomic Impacts of Threatened Marine Resources

New York State has 2,977 km (1850 mi) of tidal coastline (NOAA, 1975). The Natural Resources Defense Council (NRDC) states that New York ranks sixth nationally in economic dependence “for shellfish harvests but that harvest is in jeopardy due to OA” (NRDC, 2015). In 2016, New York had commercial fisheries with a value added[6] of about $1.6 billion, including imports, and a value added of about $85 million without imports. The value added from recreational fisheries was approximately $770 million (National Marine Fisheries Service, 2018). The threats to marine resources posed by OA can translate into socioeconomic costs not only through the loss of jobs and income, but also through the loss of cultural traditions, iconic species, jobs, and ecosystem services (shoreline protection, nutrient cycling, tourism, etc.) (Cooley et al., 2009). All face increasing risk.

Locally, shellfish such as ribbed mussels (*Geukensia demissa*) and oysters provide reinforcement to marshes that offer shoreline protection. The State is experimenting with living breakwaters off the southern portion of Staten Island initiated in response to Superstorm Sandy (October 2012). The intent is to reduce storm risk through ecological enhancement (New York State Governor’s Office of Storm Recovery). It is hoped that the oysters will improve harbor water quality through filtering and gradual shell dissolution, hence raising the calcium carbonate concentrations. When fully permitted, this living breakwater will include a veneer of oysters. Certainly, the functionality of the oysters in the breakwater system is dependent on whether oysters can survive in the environmental and physical conditions at the site in New York Harbor. New York State also has invested in developing sanctuaries for the hard-shell clam (*Mercenaria mercenaria*) in embayments around Long Island to test their ability to improve water quality by using the natural filtration capacity of these organisms. The potential benefits of these projects could be reduced if such species as the blue mussel (*Mytilus edulis*) and presumably other filter feeders, like clams, experience slower growth and survival due to OA (Doney et al., 2020).

The loss of the LIS lobster population in 1999 mentioned earlier, while not a consequence of OA, is an example of what can happen to a marine resource, industry, and coastal communities within New York State with an altered environment. Much of the lobster population, worth $36 million ex-vessel value[7] per year and affecting some 1,000 lobster fishermen, was nearly extinguished (Lopez et al., 2014). The consequences of lost services due to OA and adaptation to these changes will require mitigation measures in New York’s coastal ocean (Cooley et al., 2009).

6 Value-added is defined as the net value of an industry, i.e., the industry’s sales minus the cost of the goods and services it purchases from other industries to produce its outputs (National Marine Fisheries Service, 2018).

7 Ex-vessel value is the value of the fish at the point at which it has been unloaded from the vessel.

Pillar I. Mitigate

Implement measures to reduce the extent, magnitude, and impact of OA.

The mitigation measures recommended by the OATF address OA from multiple angles. Some of the measures are aimed at utilizing or ameliorating sources of nutrients or carbon dioxide, which are causing coastal acidification, while others are aimed at decreasing acidity more directly. Removing or neutralizing sources of acidic water helps in the short term to reduce coastal OA. Over the long term, mitigation measures that ecologically use, recycle, or store nitrogen and carbon are needed to counteract the fundamental causes of OA rather than just treat the resulting symptoms. An array of mitigation measures should be used in concert to effectively address various aspects of OA. The mitigation recommendations presented here are sorted into three categories and labeled parenthetically following the title of each recommendation. The categories are:

- Substantiated – Those that have been shown to be beneficial at geographic or ecosystem levels;
- Potential – Those that have promise but need more research on their impact in particular settings. Many proposed mitigation measures are experiments largely unquantified and are therefore not proven to be effective practices. Before solutions can be scaled up statewide or even embayment-wide, mitigation measures must be considered for research, and be monitored over the long term to ascertain viability and to determine if they have negative synergistic effects (Gobler et al., 2014);
- Conceptual – Those that may be promising but need to be further studied and developed before being put into practice. Many proposed mitigation measures are experiments largely unquantified and are therefore not proven to be effective practices. Before solutions can be scaled up statewide or even embayment-wide, mitigation measures must be considered for research, and be monitored over the long term to ascertain viability and to determine if they have negative synergistic effects—spreading shellfish disease, for example.

I-1. Review and implement nitrogen water quality standards in New York's coastal areas. (Substantiated)

Excess nitrogen in the water column may be the single greatest factor contributing to coastal acidification. Thus, it is imperative that New York State, in collaboration with its partners, accelerate the nitrogen management efforts. In the LIS and in many Long Island embayments, hypoxic and eutrophic[8] waters were found to be acidified during late summer and/or early fall (Wallace et al., 2014). Close spatial and temporal correspondence between low DO and increasing acidity, and areas of high nutrient loading, indicating that these two were driven by microbial respiration (Wallace et al., 2014). Nitrogen is a problem contributing to coastal OA globally and there is irrefutable evidence that it is also occurring in New York's coastal waters. Continuing efforts to implement more stringent nitrogen controls could help reduce coastal eutrophication, increasing the ability of the coastal waters to buffer[9] coastal OA.

In the LIS, hypoxia appears to have been reduced following rigorous adherence to a plan for reducing nitrogen inputs to the LIS by 58.8% in New York and Connecticut from contributing sewage treatment plants (STPs; Vlahos, 2020; Tedesco et al., 2014). This successful control strategy may have the added benefit of lessening the impacts of OA.

Upon proper monitoring and research, New York State and its partners should aspire to the establishment of justifiable water-quality standards appropriate to protect marine resources from the impacts of OA. But there are impediments to this approach. The current narrative standard for nitrogen in New York State is "none in amounts that result in the growths of algae, weeds, and slimes that will impair the waters for their best usages" (NYSDEC, Division of Water), which does not explicitly address the issue of OA. Parts 702/706 of 6 NYCRR lay out the requirements for deriving a new numeric water quality standard for the protection of aquatic life. The requirements include scientifically acceptable acute/chronic laboratory toxicity studies across eight different biological families. Nitrogen-induced OA toxicity data of this type and scope is not currently available. When the data becomes available, NYSDEC should consider the practicality of creating a new nitrogen water quality standard for OA. Additionally,

8 Hypoxic waters have low levels of dissolved oxygen, which disrupts ecosystems. Eutrophic water contains an overabundance of nutrients.
9 Buffering is the ability of a system to withstand or resist external changes. Specifically, it is the capacity of the system to uptake some of the free hydrogen ions, thus preventing pH shifts.

a single nitrogen standard may not be suitable considering the diverse nature of New York's coastal waterbodies and the different uses to which they are put.

An Alternative Restoration Plan has been approved for the south shore of Suffolk County, based on the Suffolk County Subwatershed Wastewater Plan (an approved Nine Element Plan). An Alternative Restoration Plan is planned to be written for Nassau County. Alternative Restoration Plans are accepted by the EPA for waterbodies where stakeholders are actively working to pursue restoration to achieve water quality standards, and are considered to be akin to a TMDL. TMDLs and Alternative Restoration Plans define the maximum amount of a pollutant (e.g., nitrogen, phosphorus, pathogens) a waterbody can receive and still meet water quality standards or avoid an impairment. Impairments such as low DO or OA might be used to justify development of TMDLs. To date, there has not been quantifiable impairment specified for OA, and therefore, this management approach is not appropriate to address OA.

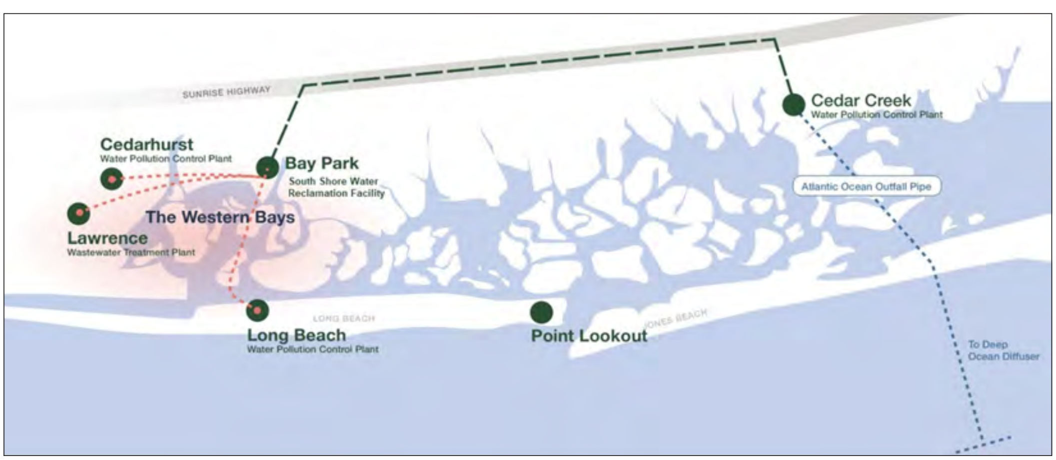
I-2. Minimize discharges that contribute to coastal OA. (Substantiated)

The most effective way to reduce the consequences of coastal OA is to limit the contributing sources that create it. In New York, eutrophication, largely driven by nitrogen inputs and by the redistribution and concentration of acidic freshwater discharges, has been implicated as a driver of coastal OA. In the East River, for example, acidified freshwater discharges are concentrated as point sources. These discharges are, for the most part, a result of excessive historical and modern terrestrial development (Swanson and Gobler, 2011), as demonstrated by high nitrogen concentrations in coastal embayments from high population density.

In addition to TMDLs, land use planning is used to reduce the impacts of OA (Kelly and Caldwell, 2013). Implementing smart growth, increasing riparian buffers, decreasing impermeable surfaces, and improving stormwater management should be considered (Kelly and Caldwell, 2013). Land-use zoning may be the best tool available to properly achieve a balance between land development and the protection of New York's marine waters and their economically important marine resources. Zoning boards must embrace a holistic view of proposed actions about cumulative wastewater management (including stormwater discharges) across each watershed instead of considering each in isolation. New York State and its partners can assist zoning boards and encourage them to plan for OA mitigation using existing resources like those provided by NYSDOS (see Pillar V).

Long Island is investing heavily in technologies and infrastructure to reduce nitrogen loads into coastal waterbodies. In Nassau County, the rerouting of the Bay Park Sewage Treatment Plant (STP) discharge from Reynolds Channel to the ocean outfall of the Cedar Creek Water Pollution Control Plant will reduce nitrogen and improve water quality overall in the Western Bays (Figure 4). Suffolk County is embarking on having individual homeowners convert conventional cesspools and septic systems to nitrogen-removing, innovative alternative systems. These systems are varied, some of them relying on organic material as substrata for microbial growth and nutrient uptake. While they are still being evaluated for their downstream carbon input, these systems are far more advanced than the conventional cesspools that many Long Island homes still utilize. Continued financial incentives at the federal, state, and local levels are required to expand the number of homeowners upgrading their septic systems. Given that on Long Island up to 70% of nitrogen loads are from conventional cesspools and septic systems, it is imperative to have programs like these to help address water quality and OA.

Figure 4. The Bay Park Conveyance Project: The project is rerouting the South Shore Water Reclamation Facility effluent from its current outfall in the Western Bays to connect to the existing Cedar Creek Ocean Outfall located three miles offshore in the Atlantic Ocean. The figure depicts the new conveyance pipeline under construction. Credit: Western Bays Constructors



I-3. Promote seaweed cultivation in conjunction with shellfish aquaculture to bioextract nitrogen and carbon dioxide from the surface waters. (Substantiated)

Bio-extraction removes nitrogen and carbon dioxide from the water by growing and harvesting seaweed and shellfish. Without the harvesting of the seagrasses and shellfish, the nitrogen and carbon dioxide would stay within the system and cycle naturally, but by harvesting these species, nitrogen and carbon dioxide are removed from the waterbody entirely (Figure 5a). A significant number of macro-algae (brown, red, and a few green algae) are more competitive in waters with increased levels of carbon dioxide (Clements and Chopin, 2017; Palacios and Zimmerman, 2007; Martin and Gattuso, 2009; Young et al., 2018). Aquaculture involving both macroalgae and shellfish has been demonstrated in other places, including the LIS.

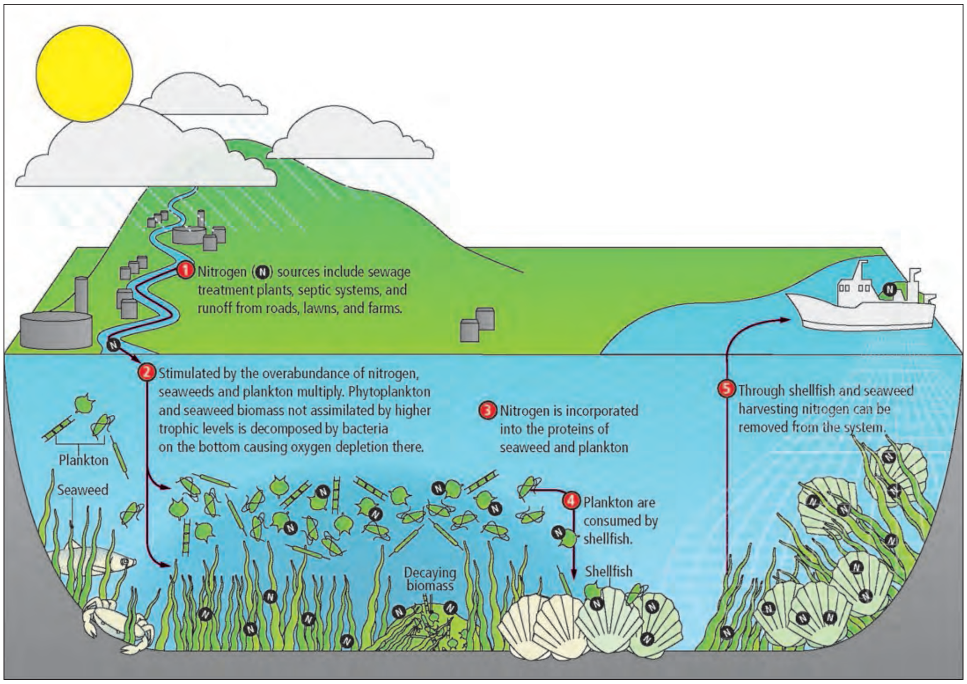


Figure 5a. Bio-extraction via harvesting of shellfish and seaweed. Credit: https://longislandsoundstudy.net/our-vision-and-plan/clean-waters-and-healthy-watersheds/nutrient-bioextraction-overview/

Figure 5b. Fishers Island oyster hatchery. Credit: Julie Qiu

Shellfish hatcheries here and on the West Coast (Figure 5b) are already feeling the effects of OA. Loss of larvae has led to drastically reduced production, attributed to local acidified waters (Clements and Chopin, 2017). Most hatcheries on Long Island buffer the seawater they take in.

As part of LINAP, the Bioextraction Coordinator is working with shellfish growers who are interested in diversifying into seaweed aquaculture to conduct a nutrient bioextraction pilot project using sugar kelp. Additionally, the Bioextraction Coordinator is a co-lead on the New York State Marine Aquaculture Advisory Committee, which provides advice and recommendations on regulatory, economic, and other issues related to shellfish and seaweed aquaculture and nutrient bioextraction.

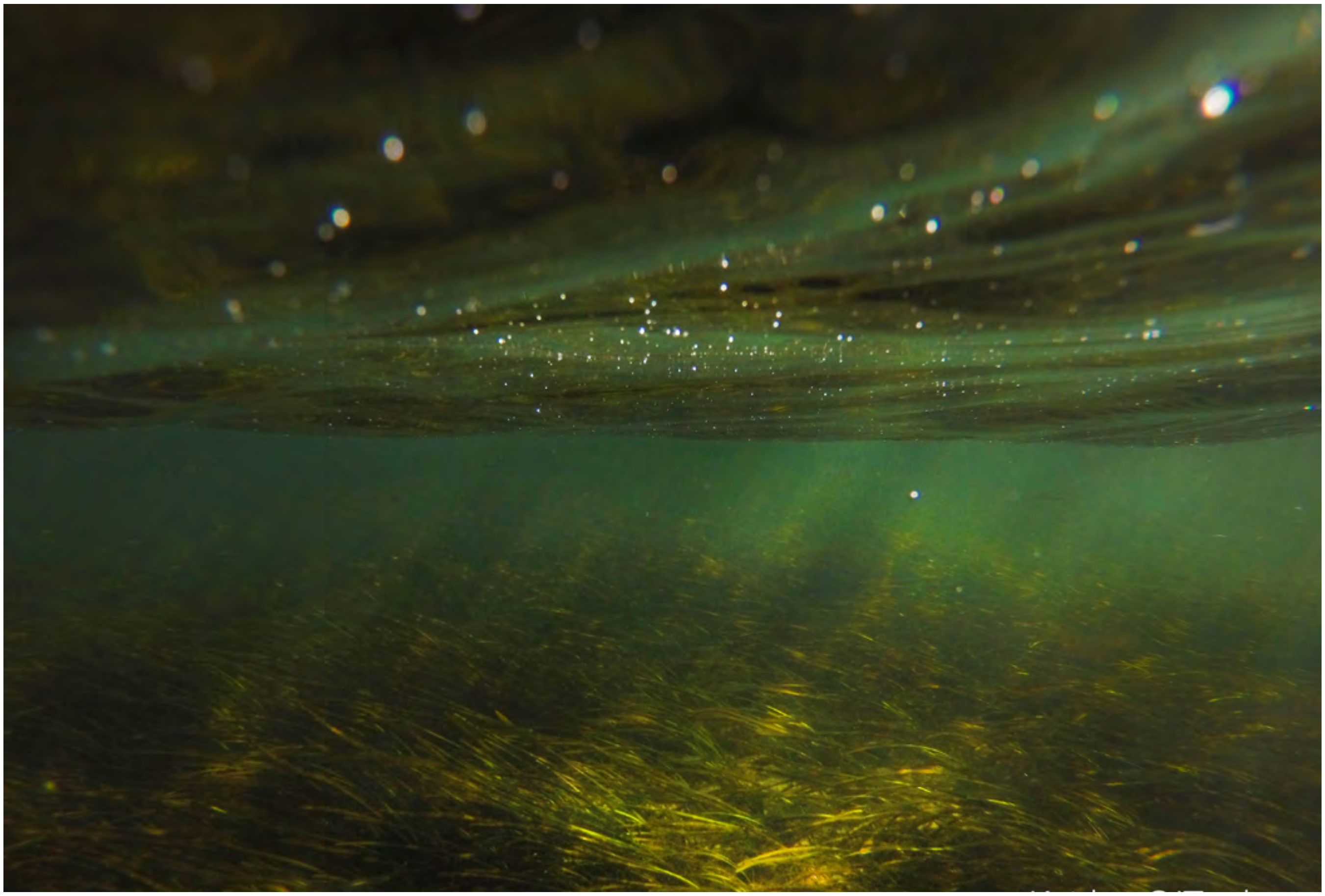


Figure 6. Long Island *Zostera marina* seagrass bed. Credit: Kaitlyn O'Toole

I-4. Enhance blue carbon sequestration using seagrasses, kelp beds, and marshes. (Substantiated)

In coastal ecosystem environments, carbon is sequestered by seagrasses, mangroves, and salt marshes. They take up the carbon as they grow, which ends up being buried and removed from the food web (NOAA, n.d.; Figure 6). Kelp beds, seagrasses, and salt marshes also contribute to blue carbon sequestration when the detritus makes its way into the sediment rather than going back into the food web (Atwood et al., 2015; Krause-Jensen and Duarte, 2016).

Wetlands, meadows, algal beds, and macroalgal forests sequester carbon differently. The diversity of carbon storage methods and the use of these natural systems must be protected. One of the benefits of salt marshes, eelgrass (*Zostera marina*), and mangroves is that they trap carbon via their roots, making them many times more effective than kelp (McLeod et al., 2011). Duarte (2017). However, carbon associated with macroalgae is often transported to other locations, such as the deep ocean, for long-term removal (Ortega et al., 2019; Krause-Jensen and Duarte, 2016).

In the Pacific Northwest, large canopy (tens of hectares) kelp beds (*Macrocystis* and *Nereocystis*) have been shown to change the seawater carbonate chemistry inside and outside the canopy. During the growing season, primarily in daylight, they decrease nitrates and the partial pressure of carbon dioxide, while reducing acidity and increasing calcification.

Seagrasses are also important net producers of DO during photosynthesis. This helps reduce areas of marine hypoxia as a condition of OA. For example, the biotic production of calcium carbonate by the seagrass *Thalassia testudinum* reduces acidity in the extensive grass beds of the upper Chesapeake Bay (Su et al., 2020).

Macroalgae, including *Laminaria* or sugar kelp, which is a native seaweed, take up carbon; but perhaps a greater benefit is that they take up nitrogen, reducing the likelihood of hypoxia. As already demonstrated in the LIS, macroalgae can then be harvested, totally removing the nitrogen from the marine environment (Jang et al., 2014). The Nutrient Bioextraction Initiative is examining this through a series of pilot studies on the South and North Shores of Long Island (both nitrogen and carbon content of the sugar kelp were analyzed). Harvesting of macroalgae could also be expanded to *Ulva* (sea lettuce). *Ulva* proliferates in the New York State Marine and Coastal District because of the excess nitrogen introduced to local waterways. Harvesting of *Ulva* in the Forge River and Hempstead Bay, West Bay, and East Bay (Figure 7) could improve water quality (Tsagkamilis et al., 2010), thereby removing nitrogen and increasing local pH, and should be considered in cases where benefits may outweigh possible adverse impacts.

Harvested macroalgae could then be used as a fertilizer or for other beneficial products. Studies are being conducted by Suffolk County Cornell Cooperative Extension, academic institutions, and New York State. Both seagrass and kelp have been observed to create what some call a halo effect, where water quality, specifically the partial pressure of carbon dioxide, near the seagrass and kelp is improved compared to that of the surrounding water. Once the beds or forests are removed, however, water quality returns to a poorer condition. The macroalgae must be maintained to provide continuing benefits.

Wetlands are extremely beneficial as they more permanently sequester carbon compared to seagrass or kelp. New York State already has strong wetlands protection regulations. However, over the last 40 years, wetlands have been lost at about 85 acres per year for a variety of reasons (Cameron Engineering and Associates, 2015). Figure 8a shows the erosion of salt marsh peat in Stony Brook Harbor, resulting in more than a meter of recession of the marsh edge from 2010–2020 due to sea level rise. As sea level rises, many wetlands have little or no room to transition landward (Figure 8b). New York needs to create opportunities for marsh transition. This can be accomplished by encouraging homeowners who own waterfront properties to make the property more resilient, and the State can provide resources and tools to homeowners. New York should expand wetlands regulations to gauge the appropriateness of nature-based features for landowners proposing shoreline modifications and consider sea-level rise, storm surge and flooding for major projects under Article 25, so as to allow wetland migration where appropriate. The State should also consider prohibiting the hardening of shorelines and consider Transfer-of-Development-Rights techniques to allow for wetland migration. New York State and its partners should continue purchasing lands where wetlands migration is occurring.

Figure 8a. Top: Eroding peat
Figure 8b. Bottom: Flax Pond salt marsh

Figure 7. Select New York small coastal embayments. Image created in Google Earth

To add to the complexity of protecting salt marshes and eelgrass beds, predators that consume the herbivores of marsh grass and eelgrass also deserve protection (Atwood et al., 2015). For example, excessive harvesting of blue crabs from the U.S. East Coast has contributed to a loss of marsh plant production (Silliman and Bertness, 2022). Thus, protecting and enhancing blue carbon sequestration is much more complicated than just setting aside acreage—it requires ecosystem-based management.

Seagrasses

Seagrasses are rooted plants that live in coastal systems. New York has two species of seagrass: eelgrass (*Zostera marina*) and Widgeon grass (*Ruppia maritima*). Water conditions are known to be favorable for eelgrass in some places in the Long Island Sound where these plants have been successfully restored or have naturally flourished. However, unlike macroalgae, seagrasses are generally carbon limited (Buapet et al., 2013). That is because they cannot as readily use bicarbonate in the water as macroalgae can. When seagrasses have been exposed to higher dissolved organic carbon, which happens during OA, these plants respond by significantly increasing their photosynthesis and productivity. In addition, seagrasses have shown higher reproductive output, increased belowground biomass, and increased carbohydrate investment in experimentally elevated carbon dioxide levels. As a result, seagrass meadows have been recognized as important carbon sinks in coastal environments.

The ability of seagrasses to simultaneously draw-down carbon dioxide and oxygenate the water column may also be increasingly important; recent work suggests that with increasing seawater carbon dioxide, the ratio of oxygen to carbon dioxide will decrease, and practical dead zones (areas where aerobic respiration is not observed) may increase. The net carbon uptake within seagrass habitats will result in a localized draw-down of dissolved inorganic carbon; an increase in oxygen, pH, and aragonite saturation state; as well as a reduction in total partial pressure of carbon dioxide, thereby effectively buffering against acidification. This will have significant impacts for the organisms that live within the seagrasses, particularly shellfish and juvenile finfish. What is unknown is how significant an effect the seagrasses will have on modifying the water that flows through them. Will seagrasses only modify the water immediately associated with their leaves or will low partial pressure of carbon dioxide carry to surrounding areas as water flows out of seagrass meadows to other adjacent areas?

There is sufficient evidence that seagrasses can modify local seawater within their canopies to generate refugia from acidified waters (Manzello et al., 2012; Bergstrom et al., 2019). Many management strategies call for increasing their abundance and coverage to mitigate the effects of OA. For New York, that strategy is hampered by decreasing water quality and clarity. Seagrasses' extent will only increase with improved water quality. The greatest potential for increasing seagrass acreage and abundance is in the South Shore estuaries. However, potential sites for increasing seagrasses also exist in the Peconic Bays. Currently, the water quality within Jamaica Bay prevents restoration efforts. Enhancing New York's seagrass coverage and abundance is intimately linked with LINAP, which strives to improve the water quality by reducing nitrogen inputs to waterbodies, increasing water clarity, and improving DO levels.

I-5. Support and broaden mollusk-shell recycling programs. (Substantiated)

Several local governmental and nongovernmental organizations on Long Island and in New York City have implemented shell recycling programs whereby restaurants save shells for use in shoreline stabilization projects or for setting oyster larvae. Shell placement is regulated by NYSDEC under Article 15, 6NYCRR, Part 608 – Use and Protection of Waters. A permit is also required from the U.S. Army Corps of Engineers under Section 404, Federal Water Pollution Control Act, and its Amendments. This is a time-consuming process, but worthwhile if used shells can be returned to the water to buffer sediments to increase shellfish survivability (Green et al., 2009). By returning the shells to coastal waters, the concentrations of calcium carbonate are increased through dissolution. This program should be encouraged and possibly expanded to become mandatory if it can be ascertained that it can increase calcium carbonate at a waterbody scale. Further, to increase the dissolution rate and thereby increase calcium carbonate in solution, research should be undertaken to explore the value of crushing shells and optimally distributing them to OA hot spots such as northern Jamaica Bay and portions of Hempstead Bay (Wallace et al., 2014). So far, crushing shells, while theoretically advantageous, has not been studied enough to reasonably predict whether it can be scaled up beyond the laboratory to increase calcium carbonate in a waterbody, or even produce a halo effect around a placement area.

I-6. Support and broaden the Long Island Shellfish Restoration Project. (Potential)

The goal of the Long Island Shellfish Restoration Project is to "improve Long Island's water quality and bolster the economies and resilience of coastal communities by restoring native shellfish populations to coastal waters" (Long Island Shellfish Restoration Project, n.d.). This program is directly applicable to mitigating coastal OA by removing nitrogen via nutrient sequestration. Trial sanctuary sites in Bellport Bay, Huntington Harbor, Shinnecock Bay, South Oyster Bay, and Hempstead Bay should continue to be evaluated for restoration success and expanded to extend the project's reach and impact as appropriate. Bay scallop hatchery programs have the additional benefit of restoring a species that has suffered severe adult die-offs since 2019[10], once the source of die-off is understood and reseeding is likely to be successful (Peconic Estuary Partnership, 2020).

10 In 2019, there was no commercial harvest of Peconic Bay scallops due to this die-off of adults, but the die-off was probably not related to OA.

To be effective, large numbers of hatchery-reared shellfish will be required. Ownership of the shellfish, once transplanted, will have to be resolved, as will potential attractive nuisance harvesting issues. Restoring shellfish to local waterways will have little impact, however, if water quality is severely degraded. This option is best considered in select locations where it is likely to succeed.

I-7. Maintain barrier island inlet openings to improve estuarine circulation, thus reducing acidic conditions. (Potential)

The wilderness breach that was opened in the eastern reaches of Fire Island National Seashore during Superstorm Sandy introduced oceanic waters into the relatively slowly circulating waters at the east end of the Great South Bay (Hinrichs et al., 2018; Gobler et al., 2019). Although there are some adverse impacts to be considered, ecological benefits have been documented for the area, including a reduction in the likelihood of hypoxia and harmful algal blooms in that end of the bay (Hinrichs et al., 2018). Shellfish growth may be enhanced by the breach (Gobler et al., 2019). Reducing the "residence time"[11] of enclosed waterbodies is a means to lessening pollution impacts, including eutrophication, and coastal OA because waterbodies having long residence times tend to store nutrients (Cloern, 2001). The amount of nitrogen exported from a waterbody depends on its residence time (Deltmann, 2001). A flexible policy on the closure of new breaches should be considered in conjunction with the mitigation of coastal OA.

Keeping active circulation through authorized navigational inlets to the South Shore estuaries and some of the hypoxia-prone North Shore harbors is a means to reduce residence times, nitrogen accumulation, occurrences of low DO, and eutrophic conditions with concomitant coastal OA. Waterbodies in the Marine and Coastal District with short residence times (Table 3) are not as prone to hypoxia. For example, the lack of inlet maintenance in Flax Pond on Long Island's North Shore impaired its water quality (Swanson et al., 2021). Flushing time would be halved if the inlet was dredged and maintained to mean low water in the LIS as originally designed. The U.S. Army Corps of Engineers generally only dredges for navigational purposes, but to improve water quality, they approved the maintenance of dredged inlets for environmental purposes as well. The LINAP is studying hydrodynamic modifications, including environmental dredging, to review various water exchange scenarios and their feasibility and success. This work has indicated a low benefit, if any, in all scenarios, with a high cost of implementation. More site-specific research would be necessary to substantiate maintaining barrier inlet openings as a long-term option.

Table 3. Average flushing times for selected Long Island embayments

Embayment	Average Flushing Time (days)
North Shore:	
Little Neck Bay	1
Manhasset Bay (head)	2.8
Hempstead Bay (head)	7.4
Oyster Bay:	
Oyster Bay Cove	7.6
Eastern Smithtown Bay	3
Port Jefferson Harbor:	
North and tributaries	4.3
South and tributaries	2.6
Mt. Sinai Harbor	4.5
South Shore:	
Hempstead Harbor	9.3
South Oyster Bay	8.0
Patchogue Bay	4.0
Bellport Bay	4.0
Fort Pond Bay	2.8

Data and calculations courtesy of Robert E. Wilson and LINAP. Those embayments in bold experience chronic summertime bottom water hypoxia. (R.L. Swanson, Stony Brook University, 2021, personal communication)

I-8. Introduce highly alkaline material into the marine environment. (Conceptual)

If a source of acidic water cannot be removed from a marine ecosystem, then neutralizing it might be the best alternative.

Scrubber residuals are alkaline materials that are currently being disposed of at a significant cost but instead could be used in a way like shell-recycling programs, to help mitigate local acidification. This material, predominately quicklime, is the by-product of acid gas removal from coal-fired power plants and waste-to-energy (WTE) facilities. While the New York City-Long Island region does not have any coal-fired power plants, numerous WTE facilities are in close proximity to the coastline. Long Island has four such facilities, Westchester and Dutchess counties have several operations, located near the Hudson River, and there is a WTE facility in Essex, New Jersey.

11 The residence time expresses the how fast a pollutant moves through the waterbody. Residence time (flushing time) = time required for a dissolved substance within the embayment to drop to about 37% of its initial value.

Combined, there is a large supply of quicklime. This waste, if meeting marine disposal criteria, could be used for beneficial purposes (e.g., reefs) in marine systems, and might help mitigate the effects of OA instead of being disposed of as waste in a terrestrial setting. Other materials, such as limestone and silicates (e.g., basalts) should also be considered, in the event that quicklime cannot meet marine disposal criteria.

I-9. Expand use of ocean outfalls for discharge of sewage effluent. (Conceptual)

Because nitrogen is a driver of hypoxia and the lowering of pH of coastal waters, New York State and its partners might optimize their use of ocean outfalls, with tertiary treatment, to minimize coastal OA by increasing dilution. Water and sediment quality in Boston Harbor have

Buffering Solutions Reduce Acidity

Buffering techniques have been used for lakes, feedwater, and water discharges with considerable success and may have applicability in wastewater effluents, such as sewage (pH ≈ 6.8–7.3). Acid deposition caused many Adirondack lakes and ponds to become fishless. To address this problem and reestablish native brook trout populations in some of these decimated waters, NYSDEC's Bureau of Fisheries started a liming program. In 1959, NYSDEC began to apply agricultural lime to certain ponds to raise their pH. This program has been found to enhance fish survival (Shea, 2008). While typically used to enhance farm soil, the agricultural lime temporarily improves the water's ability to buffer acid deposition, raising the pH to a level that fish can tolerate. Today's liming program includes 37 waters across the Adirondacks. Each year, researchers take water samples from the ponds to monitor their pH and acid-neutralizing capacity (ANC). If a pond's water has a pH below 6 and an ANC below 20, it is scheduled for a liming treatment. Treatments, which last between 5 and 15 years, are often done in the winter by spreading lime across the pond's frozen surface. These treatments are only a stop-gap measure while working to limit acid precipitation. However, without liming, these waters would remain fishless. Liming also benefits a wide range of native fauna and flora, including many sensitive species such as loons and otters. The areas that were sensitive to acidity are resurging, suggesting that the whole region may undergo revitalization.

Fish and shellfish hatcheries have been buffering low-pH water to improve the survival of larvae in the Pacific Northwest (Brown, 2017) and in the Northeast (Sibrell et al., 2006). In the Pacific Northwest, oyster hatcheries have added sodium carbonate to their influent waters in order to raise pH from as low as 7.5 up into the range of 8.1–8.2. This buffered water, which is then discharged back into the environment, helps the young oysters survive the early stages of life. On the East Coast, the Craig Brook National Fish Hatchery in Maine has used a limestone fluidized-bed treatment for acidified waters (Sibrell et al., 2006). In New York, Mystic Oysters, an aquaculture enterprise in the Town of Southold, has used sodium bicarbonate to bolster pH of the intake-water from 6.8-7.2 up to about pH 8 to aid young oyster larvae (Karen Rivera, personal communication).

Sewage treatment plants (STPs) already adjust pH to enhance phosphorus precipitation, though wastewater effluent is generally still a source of acidifying water for the New York coastal region, so there is a precedent for buffering wastewater. Soda ash and liquid caustic soda (sodium hydroxide) have both been used to raise pH (Cheremisinoff, 1994). Sodium hydroxide (Cheremisinoff, 1994) and magnesium hydroxide are also used in STPs to adjust alkalinity. Suffolk County Sewer District 3 (Southwest Sewer District) has fed a magnesium hydroxide slurry to seasonally reduce nitrogen and the concurrent consumption of alkalinity in the aeration system (Ben Wright, personal communication). As the plant expands, the engineers are exploring the use of magnesium hydroxide and sodium hydroxide to maintain pH and accommodate the nitrification process.

Thus, there is precedent for using caustic drips to adjust pH for various reasons in waters that are eventually discharged to marine and freshwater environments. New York has a vast array of marine discharges where this approach could be beneficial to increase the pH in localized waters. STPs, stormwater discharges, and power plants might be eligible for such treatment.

For example, roughly 1 billion gallons of secondary treated sewage are discharged daily to the East River from five STPs. This effluent represents 7% of the East River total flow (Blumberg and Pritchard, 1997). Theoretically, raising the pH of these STP discharges from around 7.3 to 8 could have the potential to be an effective local OA buffer. In the East River, pH fluctuates annually in the range of 7.1–8.1. This type of buffering of STP discharges is novel and should be investigated further to determine its real-world effects and implications. Potential sites for case studies could include smaller STPs that discharge into enclosed embayments that are currently impacted by low pH.

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improved dramatically since the Deer Island STP outfall was relocated to Massachusetts Bay around 2006, with minor impacts in the bay itself (Werme et al., 2019). There are currently two sewage outfalls, discharging directly to ocean waters on Long Island's South Shore about 2.5 nautical miles offshore. These are Cedar Creek in Nassau County and the Southwest Sewer District in Suffolk County. Each facility will be releasing greater volumes soon. The Bay Park STP, along with several smaller facilities, will be combined and discharged through Cedar Creek for the purposes of abating eutrophication in the Western Bays (Swanson et al., 2017; Figure 4). Investigations should be carried out to determine the carrying capacity and the environmental consequences of expanding the use of ocean outfalls on the South Shore of Long Island, including where such discharges can be optimally located, volumes that can be safely discharged, and how many such discharges the South Shore can accommodate without negative synergistic effects. NYSDEC has funded studies of this nature at the two existing outfalls on Long Island's South Shore.

I-10. Fill in dredged hypoxic holes. (Conceptual)

Hypoxic dredged holes in the seafloor have the potential to contribute to OA in coastal waters. Filling these in to recontour the bay bottoms where hypoxic conditions exist, circulation is sluggish, and water residence times are long would eliminate hypoxia and reduce the likelihood of it contributing to OA. Ideally, clean dredge material could be used as fill for this purpose. However, some fill might come from recyclable ground glass covered with clean sand. Recycled glass currently has a small market and is in excess supply locally. This approach would create a beneficial use for an existing waste material.

Pillar II. Educate

Promote awareness concerning OA state of knowledge, its impacts, and opportunities for reduction.

A crucial part of addressing a large-scale problem such as OA is to increase public awareness, understanding, and concern for the problem. All efforts should be based on the current understanding of social sciences and developing research on effective strategies of behavioral change campaigns. Whereas some issues, like marine debris, have been readily visible to the public, OA is an elusive concept, largely because it isn't visible. It must be promoted to establish public awareness. Perhaps shells with holes in them are the best symbol of the problem, but they are not the only, or even the most pressing, concern about the biological impacts of OA. Additionally, the regional waters have not yet gotten so acidified as to cause such an obvious impact. such as dramatic fish and shellfish larvae mortality. Consequently, to generate support for mitigation, research, monitoring, and legislation, it is important to effectively alert and inform the public and industrial community. Additionally, there are extensive, ongoing outreach and extension efforts, and OA outreach and education should coordinate with existing efforts.

II-1. Develop a statewide marketing and communications strategy around messaging on OA.

II-1a. Develop an OA module for the State's secondary science level programs aligned to the New York State Next Generation Science Standards, which became testable in 2020.

An OA module is an ideal topic to create three distinct and equally important dimensions to learning science—cross-cutting concepts, science and engineering practices, and core concepts. It could be incorporated into the existing curricula for Regents Earth Science, Biology, and Chemistry as well as Advanced Placement Biology, Chemistry, and Environmental Science. An OA module could be integrated into all the existing statewide curricula, general education courses for marine science, environmental science, and ecology. This could provide a model for national application.

II-1b. Use public service announcements on radio, TV, and other platforms to generate interest and concern about climate change and OA.

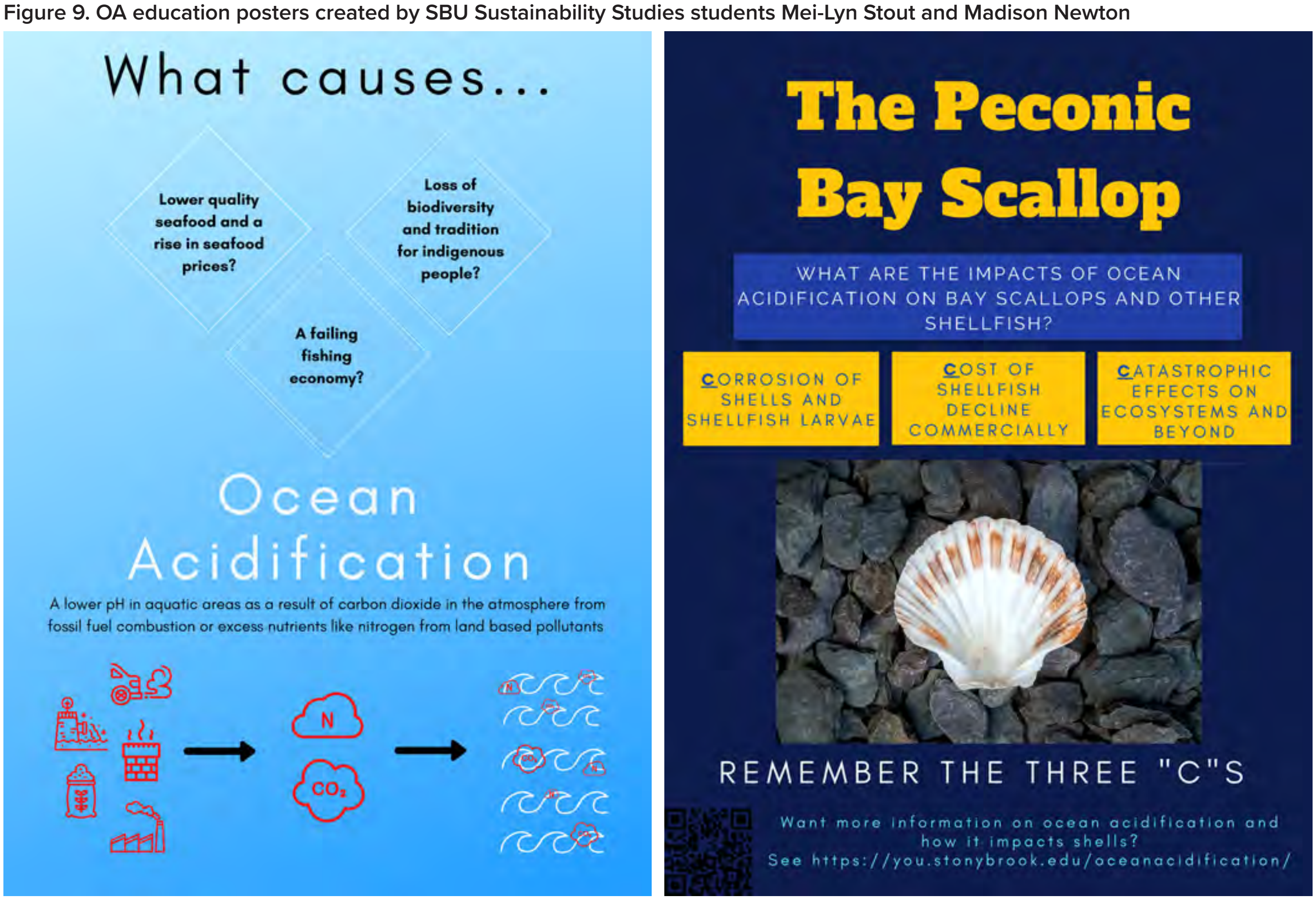
The visual arts are an effective means for reaching and inspiring the public to take an interest in environmental issues. Poster art can be appealing, and its creation can be a learning experience (e.g., Figure 9). Sponsoring school posters and art contests will inspire both interest in the science behind the problem as well its amelioration. In addition to classroom settings, the marine community should engage in outreach opportunities to spread the word concerning OA and its impact. Seafood festivals, environmental celebrations, and Maker Faires represent opportunities for spreading the word. Exciting OA demonstration materials could be developed for organizations like New York Sea Grant, Cornell Cooperative Extension, School of Marine and Atmospheric Sciences at Stony Brook University (SBU), Science and Resiliency Institute at Jamaica Bay, and various environmental organizations to use in a variety of public venues. The New York Marine Sciences Consortium might be engaged to broaden this initiative.

An effective means of communicating science is direct contact with an audience using visual displays and demonstrations. Marketing firms can assist the State and its partners with effective messaging as they have experience in developing public awareness through news vignettes, insertion of content into TV plotlines, public service announcements (PSAs), etc. PSAs can call attention to the OA situation and educate about the associated processes creating the OA problem and the consequences of ignoring it.

II-1c. Use social media creatively to generate public interest in OA issues and remediation measures.

Investing in outreach tools on Facebook, Twitter, Instagram, and other platforms to create campaigns can have broad impacts, increasing awareness, educating the public, and serving as a call to action. Infographics from the PSAs should be used across social media platforms like memes to spread awareness to a larger audience. A contest could be started with the effect of generating short video clips describing OA to a broad audience, like the Flame Challenge initiated by actor and science promoter Alan Alda.

Figure 9. OA education posters created by SBU Sustainability Studies students Mei-Lyn Stout and Madison Newton



II-2. Require all SUNY institutions of higher learning (64 campuses) to have an introductory course on the environment that includes a segment on climate change along with its connection to OA and its implications.

The Chancellor of SUNY could be encouraged to initiate an environmental module across the 64 SUNY campuses for all incoming students concerning global climate change. This should include such topics as waste management and climate change, their connection to OA, and their impacts.

II-3. Provide financial support for OA graduate research.

The Mid-Atlantic Sea Grant Programs, in partnership with the NOAA OA Program, announced the OA Graduate Research Fellowships for the two-year period covering the 2018 and 2019 academic years. The fellowship was open to full-time graduate students at any academic institution in Delaware, Maryland, New Jersey, New York, and Virginia who were engaged in coastal and marine research relevant to regional ocean, coastal, and estuarine acidification. OA Graduate Research Fellows address issues relevant to coastal ecosystems and adjacent communities related to coastal and OA. Projects encompass natural and/or social science research topics. New York State could institute a similar program cooperatively managed by NYSDEC, New York Sea Grant, and other appropriate partners, and continue providing support for graduate students researching OA in the New York Bight through existing mechanisms.

Pillar III. Investigate

Conduct relevant research and monitoring.

Improving the scientific understanding of coastal OA processes and consequences is essential for ultimately managing it. Therefore, research and monitoring are key. For this pillar, recommended research and monitoring tasks were ranked as high-, medium-, or low-priority levels. The categorization is listed in parenthesis following the recommendation title. Nevertheless, all the recommendations within the pillar are worth pursuing regardless of their priority at this time.

III-1. Quantify mitigation measures in their effectiveness to reduce OA and its consequences. (High priority)

Most OA marine mitigation measures are aspirational; that is, they are based on laboratory studies or constrained field experiments. These experiments must be scaled up to ecosystem and waterbody dimensions. While results appear promising, their impact on ecosystems needs to be quantifiable on a large scale along with potential synergistic or antagonistic effects on marine systems to justify investment in their implementation. Modeling can play a role, but large-scale field research over time is required. For example, a recent study has found success in buffering muddy sediments with aged shell hash to significantly increase pH and aragonite saturation and improve survival and growth of early life stage hard clams (Curtin et al., 2022). In Humboldt, California, eelgrass beds located near oyster hatchery seawater intakes could reduce acidity of the influent so that buffering chemicals might not be required (Werblow, 2020), but did not remove carbon sufficiently to meet the requirements of the oyster hatchery. So, the question remains: at what scale can eelgrass beds be considered a coastal OA mitigation measure? Along these lines, the Shinnecock Bay Restoration Program is exploring the benefits of restored oyster reefs, clam spawner sanctuaries, and eelgrass reseeding. Partner programing and initiatives are an ideal opportunity to test for changes, if any, in aragonite saturation states as a result of these and other types of interventions.

III-2. Invest in monitoring New York's nearshore and estuarine waters. (High priority)

Monitoring coastal OA is imperative to clearly establish the natural variability in the parameters of interest (aragonite saturation, dissolved inorganic carbon, pH, partial pressure of carbon dioxide, total alkalinity) and identify changes that may be detrimental to ecosystem goods and services. The state of knowledge concerning OA and its complex drivers is changing rapidly (Doney et al., 2020). Monitoring and management strategies will need to be flexible and adaptive to meet evolving understanding. Entities that conduct monitoring should be encouraged to add their data to the federal Water Quality Data Exchange (WQX) to make it accessible to all interested parties.

Watching sentinel organisms most impacted by OA is a proven strategy. Shellfish are some of the best sentinel organisms for OA because they have a known sensitivity to low aragonite states, are ecosystem engineers, are prey to fishes, and are iconic species in New York State (*New York Ocean Action Plan* 2017). However, because of climate change, marine organisms are responding to many stresses, not solely OA, as well as moving across traditional marine boundaries (Doney et al., 2020).

New York Ocean Action Plan (2017) Recommendations

- Monitor OA and investigate the impacts of OA on shellfish and crustaceans.
- Using currently available data, develop methods to assess impacts and predict future responses of commercially important shellfish (e.g., surf clams, ocean quahogs) and crustacean (e.g., blue crabs, lobster, horseshoe crabs) species to increased OA (decreased pH), decreased carbonate concentration, various carbonate saturation states, and an increase in gaseous carbon dioxide in seawater.
- Monitor inshore species, such as oysters, hard clams, and bay scallops, that may be predictive indicators of impacts associated with climate change.
- Collaborate on an OA monitoring network through the Mid-Atlantic Regional Planning Body and develop mitigation strategies for New York.

Each waterbody in New York State is characterized by different assemblages of shellfish species, with different social and economic values as well as different sensitivities to OA. Any standards should be based on established and justified scientific methods. The State-established methodology to develop standards is designed to protect even the most sensitive species. The early life stages of marine bivalves and fishes are known to be the most vulnerable to OA. So, water quality criteria might be based on early life stages of shellfish in conjunction with aragonite saturation states, while research is continued to determine how the impacts on early life stages affect overall population productivity.

Establishing baselines now and observing changes caused by various stressors, such as excessive runoff and nutrient loading, will provide the justification needed to invest in mitigation efforts. Ideally, aragonite saturation should be monitored to ascertain the impact of OA on shellfish species, as aragonite is the form of calcium carbonate that is biologically available to them. Unfortunately, aragonite cannot currently be measured directly in seawater, but aragonite saturation can be calculated by measuring any two of the four related carbonate chemistry parameters concurrently (partial pressure of carbon dioxide, total alkalinity, dissolved inorganic carbon, and pH), although to fully understand OA impacts, all four should be measured. NYSDEC began funding an OA monitoring program in the New York Bight in 2018. Measurements of the partial pressure of carbon dioxide along with pH are being collected by researchers at SBU via a flow-through shipboard monitoring system and this will continue for a 10-year period (Figure 10). A similar investigation should be undertaken in New York's coastal waters.

While minimum monitoring occurs within New York's coastal waters, additional monitoring and funding are needed in the future. There is already an administrative structure that could oversee this monitoring provided by the five New York estuary programs: the LIS Study, Peconic-National Estuary Program, New York South Shore Estuary Reserve, New York-New Jersey Harbor Estuary Program, and the Hudson River Estuary Program, as well as the Hudson River National Estuarine Research Reserve and its partners. Providing funding to these estuary programs would aid in the management and coordination of such monitoring program activities.

Figure 10. Top: *R/V SEAWOLF* OA equipment. Credit: Thomas Wilson; Bottom: CTD cast from the *R/V SEAWOLF*. Credit: Karin Schweitzer

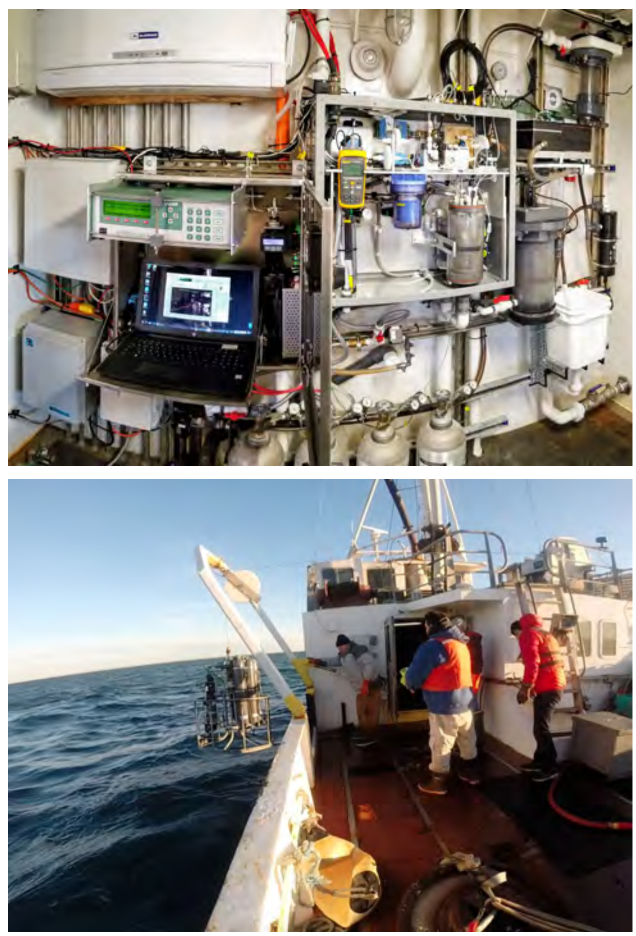


Figure 11. New York's large coastal waterbodies. Image created in Google Earth

Additionally, New York City operates the longest running marine water quality monitoring program in the country and would have the appropriate infrastructure to manage OA monitoring efforts, if provided with the requisite funding. Specifically, the State should collaborate with its partners to invest in a dual-sensor monitoring program that measures the carbonate chemistry parameters so that aragonite saturation can be calculated and the potential for shell growth and health can be determined. This investment should not be limited to equipment, but should also include funds for maintenance, calibration, data management, quality assurance, and reporting. The most tractable parameters to measure in terms of cost and available sensor technology are pH and the partial pressure of carbon dioxide, but in instances where vessel-based water quality monitoring programs are ongoing, water samples could be added to the regular collection program to be analyzed in a laboratory for pH, dissolved inorganic carbon, and total alkalinity. Such investigations can also lead to further understanding of the aragonite saturation process.

Programs for OA monitoring should be located throughout the Marine and Coastal District and into the New York Bight (Figure 11). The estuary programs acquire publicly available data that have an approved Quality Assurance Program plan and can act as a data repository for OA monitoring.

Supplemental funding for OA equipment and analyses for these existing programs will allow for complete monitoring coverage with associated, standardized Quality Assurance/Quality Control (QAQC) protocols throughout State waters. Community science monitoring can also play a role collecting shallow-water samples for measurements of, for example, total alkalinity and dissolved inorganic carbon (DIC), and for further assessment by certified laboratories, like those at SBU or the environmental laboratory run by the Town of Hempstead.

The Iconic Bay Scallop as a Monitoring Standard for the Peconic Bays

White et al. (2013) investigated the effect of OA on the larval stages of shell growth of the bay scallop, which is found in bays and estuaries of the northwest Atlantic Ocean. They determined that high concentrations of carbon dioxide during the first week following spawning compared to ambient conditions led to reduced survival and diminished shell length for those that did survive.

Baumann et al. (2015) remind us that pH is highly variable over the year with seasonal changes and diurnal fluctuations. The latter may surpass the seasonal fluctuations. For example, in Flax Pond on Long Island's North Shore, they found that the average seasonal signal of pH varied 0.6 units and daily could exceed 0.7 units. In the same study, the observed daily changes in partial pressure of carbon dioxide were on the order of 3,500 µatm at some times of year.

In the White et al. (2013) experiments, ambient conditions were pH and a partial pressure of carbon dioxide of 7.9 and 509 µatm (aragonite saturation = 2.26), respectively. The high carbon dioxide conditions (pH = 7.4; partial pressure of carbon dioxide = 1,987 µatm; aragonite saturation = 0.74) resulted in a shell length of 88% than that of ambient conditions after a week. Importantly, the shell formation didn't recover once the organisms were exposed to ambient conditions after seven days.

Thus, if the goal is to maintain coastal OA at a level to support the bay scallop in the Peconic Bay, a standard aragonite saturation state during spawning season (May–September) might be appropriate.

III-3. Develop a geospatial tool to prioritize locations for OA mitigation efforts. (High priority)

Different types of mitigation measures are not likely to have the same effect in all locations. For example, some mitigation measures may be ill-suited to areas with high flow volume, like in the western Long Island Sound, or fast water speeds, such as the East River, but could be beneficial in shallower, more enclosed embayments, such as those found on Long Island's South Shore. Furthermore, some areas are likely to benefit more than others from mitigation efforts. These are the places where New York State and its partners could expect a greater return on their investment. A geospatial tool should be developed to help funding agencies prioritize areas for OA mitigation efforts based on the probability of improving the water quality/acidity in that area.

III-4. Quantify linkages between nutrient enrichment, hypoxic waters, and OA. (High priority)

The extent to which nitrogen impacts the carbonate chemistry of marine and estuarine waters is modified by many physical, chemical, and biological factors. Many earlier studies of water quality discuss acidity or hypoxia in isolation. For example, although discussing low DO, the LIS Study's *Prospects for the Urban Sea* (Latimer et al., 2014) does not cover OA. While there are many mechanisms and methods to regulate water quality standards for nitrogen, some other factors such as large-scale circulation and wind are beyond human control. Nevertheless, it is critical to understand and quantify the extent to which each of these factors, particularly nitrogen pollution, affect DO.

Research needs to be advanced to understand the causes of hyperlocal coastal OA in order to impose regulatory restrictions and remediation measures (Rheuban et al., 2019). For example, to what extent is OA in the East River and Jamaica Bay caused directly by acidic effluent as opposed to by drivers of hypoxic conditions or other contributing factors like long residence times (Table 3)? An understanding of local drivers of coastal OA is needed for all our estuary programs in New York State.

III-5. Scale from individual physiological effects to populations and ecosystems. (High priority)

It is necessary to learn more about how OA-impacted species affect ecosystems. The individual effects of temperature and OA have been established for some species, but natural resources are managed at the level of populations and ecosystems rather than that of individual organisms. For example, fish and shellfish are managed at the stock or population level, but to provide good scientific advice on harvest limits, the degree to which changes in growth, survival, and reproduction impact harvestable populations must be quantified. Harvest limits might have to change to sustain populations resilient to multiple environmental stressors. In New York State waters, a doubling of the daytime partial pressure of carbon dioxide could increase the risk of population decline within five years from 25% to more than 79% for hard clams and from 56% to 99% for bay scallops (Grear et al., 2020). Eutrophication and OA could cause such doubling of the partial pressure of carbon dioxide through the seasonal period of early life stage development in the near future. Massive declines in shellfish production could lead to declines in the higher trophic level organisms that rely on them for food, as has been illustrated in ecosystem models (Fay et al., 2017; Olsen et al., 2018).

It is of considerable importance to investigate the synergistic and antagonistic effects of redistributions, changing abundances, or total disappearance of calcareous phytoplankton caused by OA on the associated food webs even though research will be difficult because of other environmental shifts, including ocean warming (Guinotte and Fabry, 2008).

III-6. Study genetic variation of marine organisms to identify genetic disparities associated with resilience in the face of OA. (High priority)

Despite the challenges marine organisms face to build their shells, many species flourish in estuarine environments that experience large fluctuations in OA and calcium carbonate concentrations (Parker et al., 2011; Sanders et al., 2013). These spatially and temporally variable environments represent a major source of genetic diversity to which individual organisms may adapt. This genetic richness has been shown to produce resilience in marine species in the face of environmental alterations. For example, different populations of the Sydney rock oyster (*Saccostrea glomerata*) perform differently in response to OA (Parker et al., 2011). Other studies highlighted that good performance in some individuals is genetically encoded. For instance, genetic determinants of adaptation in populations of the purple sea urchin (*Strongylocentrotus purpuratus*) along the west coast of the U.S. suggest adaptations to acidification conditions (Pespeni et al., 2013a; Pespeni et al., 2013b). Similar findings of genetic determinants for resilience toward climate change, including OA, were also described in phytoplankton (Collins et al., 2014; Lohbeck et al., 2012). These results highlight that natural genetic variation represents a valuable source of resilience to OA. Genetic variations associated with resilience toward other stressors (e.g., temperature stress, heat tolerance, disease) have been widely used to improve the production of resistant stocks. In this context, it is a primary research priority to develop strategies and approaches to identify and promote stocks that are resistant to OA for aquaculture and restoration needs and to determine whether such actions would alter responses to other stressors.

III-7. Study the chemistry of mitigation measures such as artificial ocean alkalinization of coastal waters. (High priority)

Artificial ocean alkalinization is the process by which alkaline components are added to the marine environment to decrease acidity (Burns and Corbett, 2020). While this may decrease OA, the benefits may not persist (Cripps et al., 2013; Burns and Corbett, 2020). Some studies in marine systems have shown that the buffering effect of calcium carbonate enrichment only lasts while the enrichment project is ongoing (Feng et al., 2016). In addition, large-scale deployment may not be practical. Those uncertainties concerning the long-term benefits of calcium-carbonate buffering should be investigated further.

III-8. Understand ecological functioning in salt marshes and its relationship to OA. (High priority)

As discussed earlier, salt marshes will be important in offsetting the effects of OA through blue-carbon sequestration. Thus, it is essential to protect their status and ecological health as well as to provide space for their landward progression as rising sea levels force their migration, while research continues to better understand their complex ecology. For example, fiddler crabs are important as prey but also help with decomposition processes and provide drainage and aeration for marsh soils (Bertness, 1985; Howes et al., 1981). Their shells are partially made from calcium carbonate and they already live in an acidic environment. The effect of OA on these types of organisms and their subsequent effect on the health of the marsh should be studied.

III-9. Support investigations of ribbed mussel restoration. (High priority)

NYC DEP and NYSDEC are investigating the restoration of ribbed mussel (*Geukensia demissa*) populations as a means of improving water quality to meet State standards and reducing coastal OA. The project outcomes will provide resource managers and regulators with a comprehensive understanding of the value and efficacy of ribbed mussels as a water quality improvement strategy. Ribbed mussels help to stabilize wetlands, provide nutrients to marsh grasses, and, when in abundance, consume significant amounts of small particles such as algae that can form harmful algal blooms. Also, ribbed mussels are not a species used for human consumption due to their taste; therefore, restoring ribbed mussels, opposed to clams and oysters, avoids issues associated with illegal harvesting.

III-10. Determine residence times for embayments in the Marine and Coastal District. (High priority)

Residence times, a controlling factor for ecosystem functioning, are extremely varied throughout the Marine and Coastal District. Residence times have been calculated for all of Nassau County's and Suffolk County's waterbodies (Table 1). For managing coastal OA, estimates of discharge loading for different embayments should be normalized to residence times to understand the carrying capacity of these waterbodies for a variety of pollutants. Further, the effectiveness of some mitigation measures, such as placing shells to raise calcium carbonate, will depend on residence times.

A review of residence time calculations throughout the Marine and Coastal District should be undertaken to ascertain the methodology used, boundary conditions, driving forces, wetting, and drying capabilities, bathymetric detail, and spatial resolution. Where residence time calculations are not available or do not meet modern standards, such determinations should be made. Probably the best measure of residence time would be the time required for an embayment averaged concentration of a substance to decrease to 1/e, or about 37%, of the initial value (Table 3). However, whatever technique is used for calculation, it must be consistent across embayments to be meaningful.

III-11. Understand the altering of freshwater flows on coastal OA. (High priority)

The pH of precipitation remains low, and riverine and other freshwater inputs are more acidic than the coastal waters they enter. Natural runoff patterns have been concentrated by sewers, combined sewers, roads, etc., which may affect OA. In addition, annual precipitation in the Marine and Coastal District is projected to increase 5–10% by 2080 due to climate change (Horton et al., 2014), often occurring as heavy downpours caused by wet microbursts (New York Climate Change Science Clearinghouse, n.d.). Also due to a warming climate, the distribution of runoff throughout the year has been altered. The timing of the spring freshet impacting the LIS associated with snow melt occurs about six weeks earlier in the year relative to 50 years ago (Tedesco et al., 2014). Thus, seasonal stratification commences earlier in some waterbodies, increasing the likelihood of hypoxia throughout summers. Research should be initiated to explore the consequences of altering freshwater flows on coastal OA and benefits that may accrue from more broadly distributing such flows to resemble those typically seen in stable coastal ecosystems.

III-12. Study the socioeconomic impacts of OA as well as economic incentives for a mitigation strategy. (High priority)

In 2016, the marine sector contributed $304 billion or 1.6% of GDP to the U.S. economy (NOAA, 2019a) and the share of the New York State GDP from fishing, ship building, transportation, marine construction, offshore minerals, and tourism was $27.7 billion (NOAA, 2019b). Society will be impacted by a more acidified ocean (Wilson et al., 2020). The National Academy of Sciences (2010) warned that the complexities of OA may take some years to appreciate and realize but its consequences will be with us for a long time. In fact, we are already seeing its impact.

A problem with considering the importance of the marine sector to the economy is that it is limited to quantities such as jobs added and the value of physical goods and services, without considering ecosystem services. The National Academy of Sciences (2010) described ecosystem services as "non-use values," or those that are not seen in terms of present or future uses. Non-use values provided by the coastal ocean include ecosystem functions and regulation (nutrient cycling, climate control), protection (storm mitigation, flood control, natural beach nourishment), aesthetics (inspiration, tranquility), and cultural value (community identity, education, spiritual importance). In the case of OA, a non-use value of an oyster reef is that it protects the shore from erosion if it is not dissolved by OA.

Non-use values need to be assessed and considered along with jobs and goods in decisions to utilize and protect often-underappreciated resources of New York State's coastal waters. Coastal, marine, and socioeconomic research will help broaden appreciation of the importance of the marine environment and ultimately lead to greater support for employing mitigation measures.

III-13. Conduct a periodic OA status report from monitoring programs. (High priority)

Once OA monitoring has been established through the estuary programs and other identified programs (see III-2), New York State, with its partners, like the NYS Marine Sciences Consortium, should be committed to periodically (perhaps biennially) synthesize the OA status for the State's coastal waters and the New York Bight (see Legislative Pillar V-11).

III-14. Establish a New York State sentinel OA site, supported by the newly renovated, state-of-the-art Flax Pond facility as a New York OA research facility. (High priority)

Sentinel OA sites are needed all around the U.S. coastline. Sentinel sites should be representative of the coastal area and not likely to have significant anthropogenic change over the next several years.

The Flax Pond Marine Lab is jointly owned by NYSDEC and SBU. It provides a modern research facility for investigators to conduct relevant OA research in both a laboratory and a natural open water setting. The lab includes a multi-stressor system for controlling seawater temperature, salinity, pH, and DO in flow-through mesocosms. It is one of the most advanced OA laboratories in the northeast U.S., allowing novel experiments such as the study of the interaction of the physiology of marine organism with changes in both the physical and biological condition in the coastal ocean.

While Flax Pond might be New York's contribution to a regional sentinel site, to monitor status and trends in New York's diverse Marine and Coastal District, other opportunities exist to employ and enhance sensors for incorporation into a New York system. The existing instrumented suite in the New York's Marine and Coastal District could be incorporated or augmented to provide measurements relevant to coastal OA. USGS, for example, already has established about 20 instrumented sensor sites (https://waterdata.usgs.gov/ny/nwis/current/?type=tidal&group_key=basin_cd); Stony Brook University has another 17 sites (https://www.lishore.org/); and others are maintained by the Hudson River Environmental Conditions Observing System, (https://www.hrecos.org/). Additional coastal facilities could be engaged in measuring and monitoring sentinel species at, for example, the Science and Resilience Institute at Jamaica Bay (https://www.srijb.org/) and the Cary Institute of Ecosystem Studies (https://www.caryinstitute.org/).

III-15. Study the physiological and synergistic effects of OA on bivalves and other marine organisms, including at early life stages. (Medium priority)

In New York's coastal waters, OA and hypoxia often coincide, and recent studies have begun to examine how waters that are both acidified and hypoxic affect organisms. At a minimum, the combined effects of DO and OA are equal to what would be expected by adding the individual effects of each stressor together, but for some organisms, the combined effect of DO and OA is worse than if the isolated effects of each stressor were added together (Gobler et al., 2014).

New York's estuarine waters experience some of the greatest temperature fluctuations in the world (Swanson and Bowman, 2016) and wide diurnal fluctuations (Figure 12). Impacts of the combined effects of OA and DO have varied among species and initial conclusions suggest that there could be benefits to multi-trophic aquaculture. Wide fluctuations on the diurnal, co-varying partial pressure of carbon dioxide and DO concentrations provided relief from static conditions of low DO exposure, for example, in the important forage fish, Atlantic silversides (*Menidia menidia*) (Cross et al., 2019). The ability of marine organisms to acclimate can help maintain fitness in OA conditions (Sunday et al., 2014). Acclimation, however, has a cost resulting in the reallocation of energy among different physiological functions. The growth/fitness reduction observed in many marine organisms subjected to acidification is the result of a metabolic trade-off to maintain homeostatic processes (Lannig et al., 2010; Lardies et al., 2014; Thomsen and Melzner, 2010). The reallocation of energy for maintaining ionic balances is therefore expected to be at the expense of other important physiological processes, like immunity and resistance to infections, reproduction, etc. Several studies also reported increased resilience to acidified environments when food supply is abundant to balance the increased metabolic costs associated with homeostasis maintenance (Hettinger et al., 2013; Sanders et al., 2013; Thomsen et al., 2013). Thus, investigations of the complex linkages among nutrient inputs generating OA and aragonite saturation and the effect of OA on energy turnover and trophic interactions are a high priority.

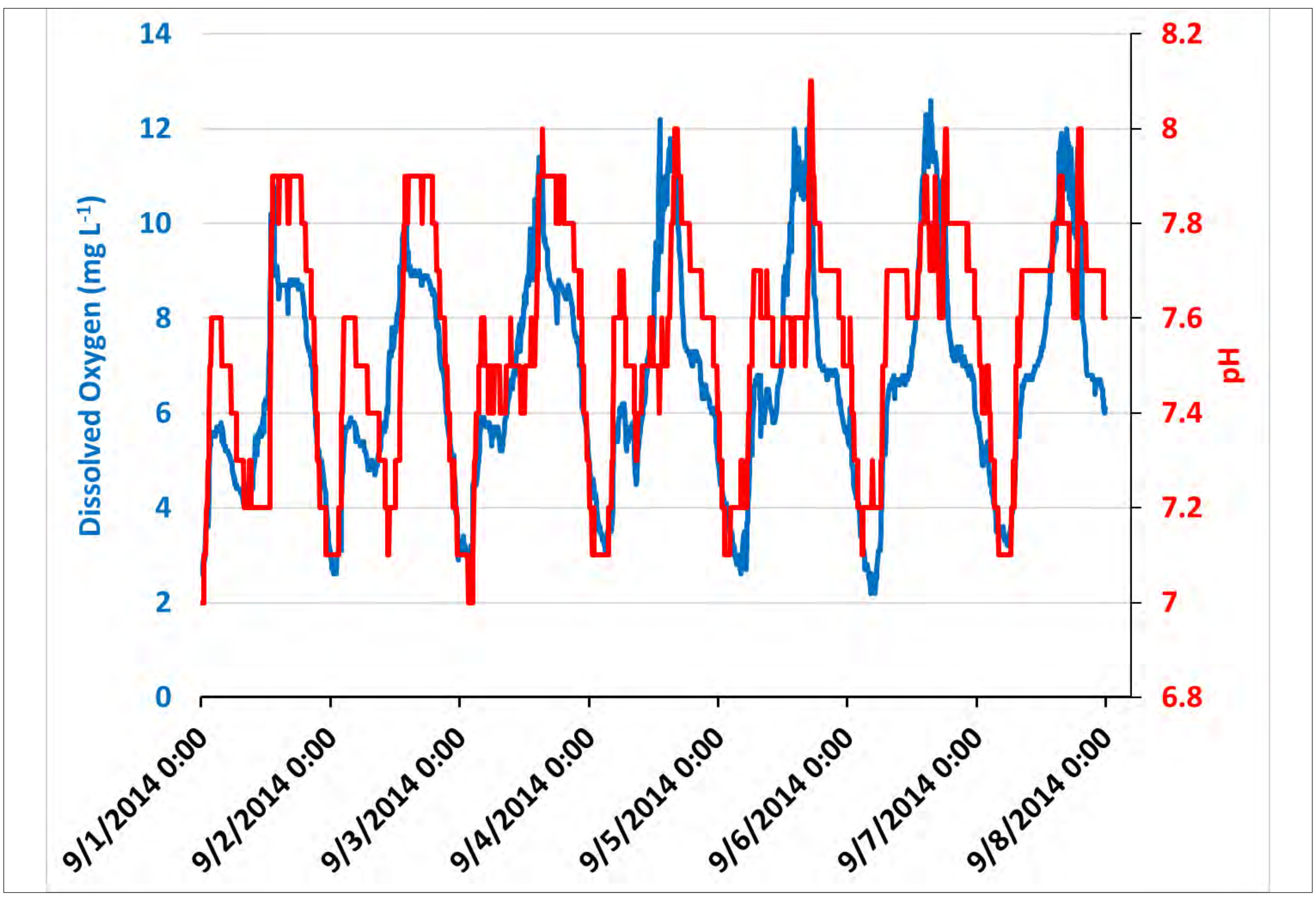


Figure 12. Concurrent low DO and pH trends at night near the bottom of Flax Pond, September 2014. Carbon dioxide is in a mixed water column, but decomposes mostly in the bottom waters, causing low DO. Credit: R.L. Swanson, K.W. Giglio, and L. Chi, 2021

III-16. Understand the physical stability of the marine environment to enhance blue carbon sequestration. (Medium priority)

New York State lost some 13% of its tidal wetlands between 1974 and 2008 (Cameron Engineering and Associates, 2015). Hardening of shorelines has prevented marsh migration and disrupted sediment supply for marsh maintenance. Waterlogging, erosion of marsh edges, and widening of channels (Cameron Engineering and Associates, 2015) are all indicators of marsh loss. Excessive nitrogen loading can result in marsh loss by reducing the rhizome biomass that contributes to marsh stability (Deegan et al., 2012). Shellfish, like oyster and ribbed mussels, provide protective barriers and stimulate vegetation to enhance marshes (Sterling, 1967). As discussed earlier, these organisms are vulnerable to OA (https://ocean.si.edu/oceanlife/invertebrates/ocean-acidification, downloaded August 23, 2019). Since blue carbon sequestration is important to reducing OA, it is important to understand how marshes are physically stabilized and destabilized, and how to keep them healthy and in a condition whereby they can expand and migrate upward as the climate changes. Investigation of living organisms (ecosystem engineers) contributing to physical stability of marine environments is needed.

If sedimentation on wetlands cannot keep up with rising sea levels, spray sedimentation techniques may serve as an amelioration measure. The U.S. Army Corps of Engineers, the National Park Service, and NYC have successfully partnered to stabilize and restore some marshland in the interior of Jamaica Bay (Davis et al., 2017). Given the importance of marshes in mitigating the effects of OA, an investigation into marsh stabilization techniques, including constructed wetlands, in the face of climate change and sea level rise, is required.

III-17. Understand the dynamics of the Cold Pool on coastal OA. (Medium priority)

The origin and dynamics of the Mid-Atlantic Cold Pool and its influence on OA in the New York Bight should be thoroughly understood. The Mid-Atlantic Cold Pool is associated with both low DO and OA. The transport of offshore, carbon dioxide-rich water toward the coast interacts with the Cold Pool; this upwelling contributes to the creation of OA (Kelly and Caldwell, 2013). Upwelling across New York's broad continental shelf occurs episodically, typically in the summer months (Glenn et al., 2004). While the formation of the Mid-Atlantic Cold Pool is well understood, its size and extent toward the coast are variable from year to year. Understanding the Cold Pool is a research priority for many groups, such as NYSERDA, who is currently conducting a survey to better understand offshore wind areas. All efforts should be coordinated with appropriate partners.

The Cold Pool

The New York Bight is prone to coastal upwelling or onwelling across the continental shelf during summer when southwesterly winds are persistent (Swanson and Sindermann, 1979; Glenn et al., 2004). Upwelling is a process where surface waters are transported offshore and replaced by cold bottom waters. A bottom-waterbody known as the Cold Pool is located on the mid-continental shelf in the Bight, persisting during seasonal thermal stratification (Lentz, 2017). It is remnant winter water and is important for OA because carbon dioxide gas solubility is greater for cold water than warm, thus potentially lowering pH. Additionally, as this water mass is subject to reduced mixing and ventilation with oxygenated, higher ratio of pH/aragonite saturation surface water during summer, biological respiration is also a likely contributor to lower ratio of pH/aragonite saturation (Wright-Fairbanks et al. 2020). Geographically it is large, from 20 m–60 m (66 ft–197 ft) thick (Lentz, 2017) and it has a volume of 3,100 km^3 (488 nautical $miles^3$) or some 30% of the volume of water of the Mid-Atlantic Bight shelf water (Cook, 1983). That portion of the Cold Pool in the New York Bight experiences the coldest temperatures throughout the Mid-Atlantic Bight. Thus, the influence of the Cold Pool on New York ecosystems is of particular concern since its waters can be transported shoreward by upwelling. Goldsmith et al. (2019) discussed the transport of this remnant water that can bring acidic waters into New York's Territorial Sea (three nautical mile limit).

III-18. Include pH and other measures of OA in the next iteration of the System-Wide Eutrophication Model. (Medium priority)

The System-Wide Eutrophication Model covers much of New York Harbor and the LIS. NYSDEC should suggest to New York City, who is leading the project, to include appropriate OA/biogeochemical parameters (pH, the partial pressure of carbon dioxide, alkalinity, dissolved inorganic carbon) as part of the model output as feasible to expand the overall utility in managing water quality. Observational data could then be used to parameterize the model and improve model output.

III-19. Understand the benefits of *Phragmites australis* (spp. americanus) for nitrogen uptake and OA mitigation. (Low priority)

Phragmites australis may be more effective in removing nitrogen and carbonaceous materials from the environment than classic New England-type salt marsh grasses (Toyama et al., 2016; Alldred, 2019; Alldred et al., 2016) and therefore may play an important role in mitigating OA (Toyama et al., 2016; Alldred, 2019; Alldred et al., 2016). There is some evidence that *Spartina* marshes are not as effective nitrogen sinks as once thought (Alldred et al., 2017; Johnson et al., 2016). *Phragmites*'s ability to sequester nutrients in the context of reducing coastal OA could possibly outweigh its threat to the native *Spartina*.

III-20. Study the effect of OA on the nutritional value of shellfish. (Low priority)

In a recent study, a 12-week exposure to six OA and warming scenarios resulted in lower nutritional content (i.e., lower levels of protein, lipid, and carbohydrate) and reduced caloric content from *Magallana gigias* and *Ostrea edulis* (two commercially valuable oyster species) than in existing marine environmental conditions (Lemmasson et al., 2018). Also, compared to existing ambient conditions, increased accumulation of copper in *M. gigas* was observed and could pose a health concern for consumption. Research on OA-altered nutritional benefits and health concerns of shellfishes for ecosystems and people should be undertaken.

Pillar IV. Engage

Inspire and stimulate businesses, industry, and governments to understand, reduce, and eliminate factors contributing to OA.

Businesses and industry should be nurtured to become actively involved in OA reduction. They need pathways to create profitable products that also reduce OA's detrimental aspects. New York State must collaborate with its partners to create and maintain these pathways and encourage business and industry involvement in OA-reduction efforts.

IV-1. Require that new development be carbon neutral.

To the extent consistent with the State Environmental Quality Review Act (SEQR), new development should demonstrate efforts to be carbon neutral and be required to respond to proposed revisions of Environmental Assessment Forms (See Pillar V). Projects should identify their carbon footprint and provide a mitigation plan.

A modified carbon cap-and-trade system should be considered as part of the SEQR analysis as an alternative, if appropriate, including investigating the value of it or a carbon tax that creates incentives for projects like wetland restoration in ways that are environmentally and socially just. It is important that new businesses are not hindered, but that those businesses that are, for example, older than five years should have dedicated plans to achieve carbon-zero or be required to participate in cap-and-trade systems.

IV-2. Work with the agricultural industry to foster carbon sequestration.

Carbon capture can be improved by replacing fields lying fallow in winter with appropriate cover crops. The New York agricultural community may be able to increase carbon sequestration by the planting of more winter cover crops. The University of California at Davis completed a 19-year experiment showing winter cover crops supplemented with compost enhanced soil carbon sequestration (Tautges et al., 2019). This treatment of the cover crop with compost improved soil organic carbon by 12.6%. If such a program could be implemented in New York, the value would not only be to sequester carbon, but to provide a beneficial use for compost.

Regionally, grains, legumes, winter peas, rye, and hairy vetch are viable candidates for winter cover crops. The Town of East Hampton recently modified its zoning code to require winter cover crops to protect soil from wind erosion. Thus, there is already precedent for communities to require cover crops to improve environmental conditions. The county-run agricultural extension programs and farm bureaus should work with the farming community to explore increasing planting of winter cover crops to improve carbon storage. The practice might be encouraged with tax incentives for farmers.

Another method that might be considered to foster carbon sequestration is enhanced rock weathering (Beerling et al., 2020). This consists of adding crushed calcium-rich and magnesium-rich silicate rock or limestone to accelerate carbon-dioxide sequestration with potential co-benefits for crop production and soil pH. A small pilot project had been done on Long Island to help growers amend their soil pH with lime applications (Corey Humphrey, District Manager, Suffolk County Soil and Water Conservation District, 2020 personal communication). Costs and logistics were identified as obstacles.

IV-3. Work with the construction industry to substitute alternative materials such as carbon-sequestering cement.

The cement industry contributes between four and seven percent of the world's carbon-dioxide emissions (Andrew, 2018; Reed, 2018). Research is ongoing to find a means to reduce this output, including the use of powdered recycled glass, which has pozzolanic engineering properties as a substitute for Portland cement. Using powdered glass as a substitute for Portland cement has been shown to reduce carbon emissions compared with landfilling glass and glass to glass recycling (Tucker et al., 2018). Six tons of powdered glass substituted for Portland cement results in a one-ton reduction in carbon dioxide emissions (Islam et al., 2017). The Waste Reduction and Management Institute at SBU, along with Urban Mining and the World Center for Concrete Technology (Alpena, Michigan), have initiated a research program to assess using pulverized glass as a substitute for Portland cement in concrete products (Figure 13). Expanding the engineering aspects of this research could lead to the New York construction industry having a mitigative impact on carbon dioxide emissions and OA. It would also provide a U.S. market for recycled glass. Tax breaks requiring this type of product's use on State contracts and State grants for conversion of cement plants might be considered as ways to incentivize this practice.

Figure 13. Cement made with pulverized glass at the World Center for Concrete Technology. Credit: Frank Roethel

Portland Cement

The production of Portland cement generates carbon dioxide through the use of fossil fuels in manufacturing and calcination (calcium carbonate, when heated, breaks down to calcium oxide and carbon dioxide) (National Ready Mix Concrete Association, 2012). In the heating process, temperatures reach 1,482°C (2,700 °F) (Portland Cement Association, 2019a).

Coal fly ash, which is used as a supplementary cementitious material, is in decline with the demise of the coal industry. Thus, Portland cement use will probably increase (Wicks, 2019). However, micro-sized waste glass has pozzolanic reactions with cement hydrates that form calcium silicate hydrate and thus can be used to replace Portland cement, meeting ASTM standards (Islam et al., 2017). According to Islam et al. (2017), for every six tons of glass powdered concrete used in lieu of typical concrete, there will be a carbon-dioxide reduction of one ton. Very little energy is required to pulverize glass.

IV-4. Encourage and enforce robust community recycling programs.

Warming the ocean surface leads to increased stratification of the water column that can result in increasing hypoxia, which then contributes to coastal OA. Utilizing recycled materials provides environmental benefits that include improving New York State's coastal waters by reducing carbon dioxide and methane production. For each ton of material typically recycled (aluminum, steel, glass, high-density polyethylene), 756 pounds of carbon-dioxide equivalents are avoided. Even though there are few markets for recycled materials, communities should not curtail recycling. New York State should be looking for new opportunities to encourage and support recycling with new technologies, new venues, new products, and new markets.

Pillar V. Legislate

Develop a legislative action plan.

Because the understanding of OA is evolving, legislation to manage OA must be flexible, perhaps requiring a periodic review of the state of knowledge.

To develop effective legislation to implement the recommendations in this *OA Report*, a mechanism is needed to implement and fund them. NYSDEC, with the support of various partners conducting OA activities, should be committed to carry out the report's recommendations and summarize biennially on progress toward meeting the goals herein. NYSDEC will need substantial funding to support a program and to hire personnel with the best qualifications and experience to manage the effort. This will also require substantial interagency coordination to assure consistency and monitor outcomes.

V-1. Participate in and contribute to national and global OA legislative actions.

The Federal OA Research and Monitoring (FOARAM) Act was passed in 2009, but other bills passed in the U.S. House of Representatives have not made it through the U.S. Senate, with the exception of the Coordinated Ocean Observations and Research Act of 2020. By continually engaging our State and federal legislators and executives, New York State can convey the importance of the OA message. Additional federal legislation must be enacted that provides resources for OA research, monitoring, and mitigation, and New York State needs to be prepared to compete when opportunities and funding arise.

Recent, Relevant Federal OA Legislation

In June 2019, the U.S. House of Representatives passed OA legislation for the first time in 10 years with four bills (H.R. 988, "NEAR Act of 2019"; H.R. 1237, "COAST Research Act of 2019"; H.R. 1716, "Coastal Communities Ocean Acidification Act of 2019"; H.R. 1921, "Ocean Acidification Innovation Act of 2019"). While none of these initial bills were approved by the U.S. Senate, the House has not abandoned these bills, and new, revised iterations have been reintroduced since 2019. Three bills have been introduced and passed by the House and one has been made law (S. 914). The latest OA bills to have passed through the chamber include:

- H.R. 2533, the NEAR Act of 2021
- H.R. 1447, the COAST Research Act of 2019
- H.R. 8632, the Ocean-Based Climate Solutions Act of 2020
- S. 914, the Coordinated Ocean Observations and Research Act of 2020

H.R. 2533, the NEAR Act of 2021
The NEAR Act of 2021 would direct the National Academies of Sciences, Engineering, and Medicine (NAS) to examine the existing science related to the impact of OA on U.S. estuaries and nearshore waters and to further examine the challenges to studying OA and its interactions with other stressors in estuarine environments. Further, the NAS would be tasked with providing recommendations for science in management and mitigation decisions.

H.R. 1447, the COAST Research Act of 2019
This bill reauthorizes the Ocean Acidification Program of NOAA and the OA grant program of the National Science Foundation through FY 2026. It additionally expands these programs and the OA activities of the National Aeronautics and Space Administration (NASA) to include coastal acidification in addition to OA.

H.R. 8632, the Ocean-Based Climate Solutions Act of 2020
This bill amends FOARAM to require an assessment of coastal community vulnerability with regard to OA and climate change, broaden the scope of work on OA to include coastal acidification in addition to ocean acidification, update recommended funding levels for OA research, and authorize the establishment of an Ocean Acidification Advisory Board which would include representatives from OA advisory groups across the country. It additionally established the Blue Carbon Program to further conservation objectives for fish and wildlife habitat conservation and restoration and coastal resilience.

S. 914, the Coordinated Ocean Observations and Research Act of 2020
This bill amends FOARAM to require a report on OA every six years (beginning two years after the date of the enactment of this bill) submitted to Congress, in addition to broadening the research outlined in FOARAM to include combined impacts of changing ocean chemistry and other environmental stressors.

OA is a national issue. The New York delegation is encouraged to move these and future OA legislation forward to help the nation as well as the state.

V-2. Revise, modernize, and enforce New York State's pH water quality standards.

Standards and effluent limitations need to be defined that are meaningful and enforceable for the coastal environment, considering climate change and its ramifications (Tomassetti and Gobler, 2020). Existing standards for New York State are insufficient for managing coastal OA. The current pH standards are derived from the Federal Water Pollution Control Act, but individual states have the authority to make the standards more stringent (Kelly and Caldwell, 2013). New effluent limitations should be adopted based on aragonite saturation required for specific sentinel organisms identified for each of New York State's major waterbodies (see Pillar III). The current pH limitation for marine waters is that "the normal [pH] range shall not be extended by more than one-tenth (0.1) of a pH unit" (NYSDEC, 2020) and has little meaning for assessing the complex carbonate chemistry influencing coastal OA. "Normal" is used because the range of fluctuation of pH varies from waterbody to waterbody and also within waterbodies (Kelly and Caldwell, 2013). "Normal" is undefined statistically on both temporal and spatial scales; it is neither practicable nor enforceable. Additionally, pH alone cannot act as a proxy for aragonite saturation state, which is most important for the success of marine calcifying organisms. However, by using pH along with another parameter to define aragonite saturation state, a numeric value for pH may be more attainable, or at least a value such as "shall not be less than" may be defined for specific waterbodies (Kelly and Caldwell, 2013).

Measurement methodology may have to be specified to be enforceable. If OA impairments are to be mitigated through statues and regulations, pH is reported and is acceptable as an indicator for the SPDES permits for all sewage and industrial effluents discharged into marine waters. However, the allowable range of pH for some discharges such as STPs is large, and violations may not have been actionable. While actionable OA standards are a goal, those establishing and enforcing them (and those complying with them) must be mindful that they must be adaptable because of the complex and changing chemistry of OA and the scientific understanding of it (Doney et al., 2020). A strong data set is needed to create new standards. Putting quality-assured, quality-controlled data into WQX will help build a robust data set.

V-3. Review the State Environmental Quality Review Act (SEQR) in order to use existing laws to reduce OA impacts.

Once sufficient monitoring has taken place to support modification/development of the standards, SEQR should be modified to consider the impact of a proposed project on acidity and on aragonite saturation as a contributor to coastal OA. State and federal governments have the authority to define significant adverse environmental impacts that are subject to assessment (Kelly and Caldwell, 2013). Coastal OA is largely generated by development, so eutrophication and its relationship to OA should require environmental review (Kelly and Caldwell, 2013). Just as an impact of a project must be considered on water quality, the Environmental Assessment Form (EAF), Part 1, should be redesigned to identify the potential actions that contribute to coastal OA. These activities should be subject to assessment and analysis in an Environmental Impact Statement.

V-4. Coordinate OA Task Force recommendations with the *Scoping Plan* recommendations of the Climate Action Council.

The goals of these two bodies are complementary. The Climate Leadership and Community Protection Act became law in 2019, established the Climate Action Council (CAC) (https://climate.ny.gov/Our-Climate-Act/Climate-Action-Council accessed May 2022) and issued a Scoping Plan with climate adaptation and resilience recommendations in "Appendix H: Adaptation & Resilience Recommendation Components." The CAC, OATF, and other appropriate entities should coordinate findings and recommendations.

V-5. Embrace Suffolk and Nassau counties' Subwatershed Wastewater Management Plans.

The Suffolk County Subwatershed Wastewater Management Plan (Suffolk County Department of Health Service, 2019) identifies cesspools and septic systems from around 360,000 homes as the primary source of nitrogen to the county's surface waters. The county's report focuses on reducing nitrogen to groundwater to improve water quality. Targets include improved DO concentrations, reduced chlorophyll-a concentrations and harmful algal blooms, and increased acreage of eelgrass beds.

Suffolk County has embarked on an aggressive plan of action through its Comprehensive Wastewater Management Plan for reducing nitrogen from septic systems with the goal of improving ground water resources as well as surface waters. LINAP expands this effort into Nassau County, seeking to identify sources of nitrogen to surface and ground water, establish nitrogen reduction goals, and develop an implementation plan to achieve reductions. Monitoring endpoints, as identified in Suffolk County's plan, is necessary to assess how much improvement will occur. If there is reduced hypoxia in local embayments from improved DO concentrations, a concomitant increase in pH may also take place in the same waters, to the extent that DO and pH are coupled through ecosystem metabolism. This should be monitored as part of the plan implementation.

Assuming the Subwatershed Plan is fully implemented, Suffolk County anticipates that there could be a reduction in nitrogen loading to coastal waters from 44% of the current total load (using the existing on-site systems) to 22% (with the new innovative/alternative systems). Legacy nitrogen, however, will continue to seep into the waterways. This program should be supported, and the coastal waterbodies monitored. But for this effort to be effective, homeowners need ongoing assistance in directly financing the new innovative alternative septic systems. New York State's Septic System Replacement Fund Program provides funding to counties to help homeowners upgrade septic systems through participating counties (https://efc.ny.gov/septic-replacement accessed June 2022).

In Nassau County, an initial report which characterized the nitrogen loading to the groundwater sheds using the same methods as Suffolk County was completed in 2020. In 2022, an update to the report was completed using new groundwatershed boundaries from USGS and adding an implementation plan to take action on reducing the nitrogen load. The results from the Nassau County plan show the north shore of the county needing to focus on septic system replacements. Nassau County now has a State- and county-funded septic upgrade program to replace cesspools and old septic system (https://www.nassaucountyny.gov/5191/Nassau-Septic). The south shore of the county needs to focus on fertilizer reduction. The Nassau County plan outlines which best management actions are appropriate for each subwatershed to meet its load reduction goals and offers a blueprint for stakeholders to take part in these efforts.

V-6. Create an initiative to reduce carbon dioxide emissions by improving building insulation.

Electricity and heat production accounted for 28% of the 2017 global greenhouse gas emissions (City of New York, 2017). Heating buildings ranks as the greatest source of carbon dioxide emissions worldwide. Given development throughout New York State and particularly in the Marine and Coastal District (Figure 1), the state is an important contributor locally. New York State should require improving and maintaining insulation of homes and buildings for the purpose of reducing carbon dioxide emissions. Such an effort should involve the programs of NYSERDA (https://www.nyserda.ny.gov/All-Programs/home-energy-efficiency-upgrades, accessed June 2022).

V-7. Create an expedited permitting process for aquaculture operations.

The permitting processes for implementing aquaculture operations are cumbersome and time consuming. Regulations need to explore expediting permitting processes for aquaculture to encourage coastal OA mitigation. While it is important to appropriately vet the environmental consequences of proposed actions, a permitting process should be in place that is both thorough and efficient.

V-8. Develop a legislative process to avert conflicts between possible OA mitigation measures and freedom of navigation.

A legislative process should be started to resolve potential conflicts between possible coastal OA mitigation measures such as aquaculture and the U.S. Freedom of Navigation Program. How much nearshore water and bay bottom is appropriate to set aside for OA mitigation at the expense of freely maneuvering in and otherwise using these waters? Cost-benefit analyses should be undertaken for coastal OA mitigation measures that might impinge on the freedom of navigation.

V-9. Coordinate New York State's OA initiatives with Connecticut and New Jersey.

New York State and its partners need to work with our tri-state neighbors, and beyond[12], to initiate OA mitigation, research, and monitoring programs. The five estuary programs (New York-New Jersey Harbor Estuary Program, LIS Study, Peconic Estuary Partnership, and the South Shore Estuary Program, Hudson River Estuary Program) can play an important role in this coordination. The New York-New Jersey Harbor Estuary Program and the LIS Study are already successful multistate programs. At a minimum, there should be a coordinated, if not a unified, monitoring program for OA amongst these estuary programs.

V-10. Participate in international OA activities.

New York State should become a leader in the International Alliance to Combat Ocean Acidification. New York is already becoming a national leader in addressing the impacts of OA and other marine issues. For example, see the *New York Ocean Action Plan* covering the period 2017–2027 (NYSDEC and NYSDOS, n.d.). The State should aggressively continue this precedent and expand the promotion of sound ideas and policies internationally. Resources should be made available to allow participation in the global arena.

V-11. Create an OA advisory committee out of the Governor's Office to help implement the OA plan.

The Governor is hereby encouraged to create an OA Advisory Committee once an OA report is submitted and reviewed. The mission of the committee should be to oversee, advise, and promote adherence to the report's recommendations, including lobbying for State resources and promoting the participation of businesses and industry. The committee should consist of non-conflicted experts who represent the relevant science, business and industry, environmental, and social issues associated with OA. Among other responsibilities, the Advisory Committee should work with NYSDEC to report periodically on the state of OA in the Marine and Coastal District and biennially on how the State is addressing and meeting the recommendations of the OATF's *Ocean Acidification* report.

V-12. Amend legislation so that all indigenous macroalgal species are approved for aquaculture in the Marine and Coastal District of New York State.

New York State recently permitted kelp (*Saccharina latissima*) cultivation in Gardiners and Peconic bays (Senate Bill S6532A), but not in other waterbodies in its Marine and Coastal District. In addition to sugar kelp, other potentially cultivable macroalgae include *Porphyra* spp., *Gracilaria tikvahiae* (graceful red weed), and *Chondrus crispus* (Irish moss). As discussed in Section I-4, the opportunity for seaweed aquaculture should be expanded to help extract nitrogen and carbon dioxide from the surface waters.

V-13. Reduce fertilizer use.

Fertilizer is the second leading source of nitrogen contamination of Long Island's waters. The LINAP Fertilizer Management Workgroup advised the LINAP project management team on recommendations that balance residents' desire for a healthy lawn with the need to significantly reduce nitrogen loads to Long Island's waterbodies. These recommendations are the most comprehensive in the nation. New York State is leading the way by calling for lower nitrogen application rates and for fertilizers with a large fraction of slowly available nitrogen to minimize nitrogen leaching to groundwater. When these recommendations are implemented, there will be up to a 40% reduction in fertilizer-sourced nitrogen entering the environment. The recommendations are available on NYSDEC's website (http://www.dec.ny.gov/docs/water_pdf/linapfertilizer.pdf).

12 Elements of the East Coast Coastal Acidification Networks include The Northeast Coastal Acidification Network (NECAN), the MidAtlantic Coastal Acidification Network (MACAN), the Southeast Ocean and Coastal Acidification Network (SOCAN), and the Gulf of Mexico Coastal Acidification Network (GCAN), as well as global OA networks. New York lies at the northernmost edge of the Mid-Atlantic Region, although participating in MACAN waters of the Long Island Sound are within the NECAN Network. https://midacan.org/

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