STATE OF MAINE
126th LEGISLATURE
SECOND REGULAR SESSION

COMMISSION TO STUDY THE EFFECTS OF COASTAL AND OCEAN ACIDIFICATION AND ITS EXISTING AND POTENTIAL EFFECTS ON SPECIES THAT ARE COMMERCIALLY HARVESTED AND GROWN ALONG THE MAINE COAST

January 2015

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Sen. Christopher K. Johnson, Chair
Sen. Brian D. Langley
Rep. Michael G. Devin, Chair
Rep. Wayne R. Parry
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Final Report of the

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Image courtesy of the artist, Patricia McNickle

Executive Summary

In 2014, the 126th Maine Legislature established the Commission to Study the Effects of Coastal and Ocean Acidification and Its Existing and Potential Effects on Species That Are Commercially Harvested and Grown Along the Maine Coast (the "commission") with the passage of Resolve 2013, chapter 110. The resolve provided for a 16-member commission, specified its duties and directed the commission to submit its report by December 5, 2014 to the joint standing committee of the Legislature having jurisdiction over marine resources matters. Resolve 2013, chapter 110 is included as Appendix A.

The commission's membership includes two state senators, three state representatives, two representatives of an environmental or community group, one person who fishes commercially, two aquaculturists, three scientists who have studied coastal or ocean acidification, the Commissioner of Marine Resources, the Commissioner of Environmental Protection and the Commissioner of Agriculture, Conservation and Forestry or those commissioners' designees. The membership of the commission is included as Appendix B.

The commission's duties included, but were not limited to, a review of the scientific literature to identify what is known about ocean acidification and steps that are needed to enhance scientific research and monitoring, develop mitigation and remediation strategies, and steps that could be taken to increase public awareness of coastal and ocean acidification. Resolve 2013, chapter, 110, directed the commission to submit any proposed legislation needed to implement its recommendations to the joint standing committee of the Legislature having jurisdiction over marine resources matters.

The commission met on August 1, September 4, September 18, October 10, October 21, November 10 and December 1, 2014. The August 1, 2014 meeting was held at the Darling Marine Center, University of Maine's Marine Laboratory in Walpole, Maine. The inaugural meeting of the commission included presentations by scientists and other experts on ocean acidification and the economic and policy implications for Maine. The remaining meetings were held in the Cross State Office Building in Augusta. Meeting summaries can be found at http://legislature.maine.gov/legis/opla/oceanacidificationmtgmatrls.htm.

To facilitate the commission's work, two subcommittees were established: the State of the Science, Research and Monitoring Priorities Subcommittee, charged with delving into the scientific literature and data pertaining to ocean acidification; and a subcommittee to review the Washington State Blue Ribbon Panel of Ocean Acidification report to determine the applicability of that panel's recommendations to the conditions in Maine. The State of the Science, Research and Monitoring Priorities Subcommittee report (State of the Science report) is a comprehensive review of the scientific literature related to ocean acidification; a summary of the report can be found in section III of this report, and the full report can be found in Appendix C.

On a global scale, ocean acidification is caused by the release of carbon dioxide (CO_2) to the atmosphere from burning fossil fuels, which until the Industrial Revolution had been buried in the earth's crust in the form of fossilized plant and animal remains for millions of years. Worldwide, approximately 25% of the CO_2 released from the combustion of fossil fuels dissolves in the world's oceans where it forms carbonic acid. This increased concentration of CO_2 in the earth's atmosphere can explain the 30% increase in the average acidity of ocean surface waters, most of which has occurred in the last 70 years. Globally, ocean acidification is accelerating as CO_2 emissions increase and the increased atmospheric input of CO_2 can explain the observed multidecadal change in acidity of the seawater. While the global scale process of ocean acidification is fairly straightforward and well understood, other sources of acidification also affect Maine's marine environment and in some cases can exacerbate the increases of acidity from atmospheric CO_2. Elucidating these processes and their importance relative to the flux of CO_2 from the atmosphere is difficult because of the complexity of Maine's ecosystems and considerable gaps in our knowledge about these other sources of acidification.

In addition to atmospheric CO_2, there are two other drivers of inshore acidification potentially very important to Maine's marine resources: freshwater runoff and nutrient loading from onshore sources.

1. Freshwater runoff is typically more acidic than seawater. Two of the most concerning impacts of climate change affecting ocean acidification in the Northeastern United States are greater annual precipitation and more frequent extreme precipitation events. Adding to the difficult task of understanding how Maine's marine environment is acidifying, the dominant source of freshwater to the larger Gulf of Maine comes from watersheds and melting ice to the north entering from the Scotian Shelf.

2. Organic matter entering Maine's coastal waters can also increase acidity. For example, large phytoplankton blooms resulting from the addition of excess nutrients eventually decompose and release CO_2.

One of the most important and urgent challenges facing Maine as we try to understand and prepare for the impacts of ocean acidification is to determine how and where these inshore causes of acidification contribute to Maine's "acidification budget."

The increasing rate of acidification will most heavily impact those marine organisms that produce calcium carbonate hard parts, such as clams, lobster, mussels, shrimp, scallops, sea urchins and cold water coral (see State of the Science report, Appendix C). Research and monitoring efforts have shown that there are mud flats in Casco Bay where juvenile softshell clams struggle to survive in acidified sediments. Perhaps the most alarming of the commission's findings is how much we do not know about ocean acidification and how it will affect Maine's commercially important species, including the iconic lobster. It is these gaps in our understanding that form the focal point for actions that can and must be taken to understand, prevent, reduce and mitigate the negative impacts of ocean acidification.

Maine is working with regional, state and local entities to address ocean acidification through existing programs related to climate change, air quality and water quality. Both the State and municipalities can enhance and increase this ongoing work to reduce possible sources of acidification through the adoption of land use practices that maximize recharge of precipitation to groundwater and reduce point and nonpoint nutrient discharges that can lead to acidification.

The commission arrived at its goals and recommendations based on the state of ocean acidification science, which is a nascent area of scientific inquiry. These goals and recommendations are made in light of practical, economic and political realities and after consideration of various viewpoints on the causes, levels, trends and significant gaps in our understanding of ocean acidification. The commission strongly believes its unanimous recommendations reflect a balance of those considerations.

The commission identified and unanimously adopted six overarching goals and twenty-five recommendations to achieve those goals. A synopsis of the recommendations can be found in Appendix E. The commission identified and adopted the following six goals:

1. Invest in Maine's capacity to monitor and investigate the effects of ocean acidification and determine impacts of ocean acidification on commercially important species and the mechanisms behind the impacts;

2. Reduce emissions of carbon dioxide;

3. Identify and reduce local land-based nutrients and organic carbon that contribute to ocean acidification by strengthening and augmenting existing pollution reduction efforts;

4. Increase Maine's capacity to mitigate, remediate and adapt to the impacts of ocean acidification;

5. Inform stakeholders, the public and decision-makers about ocean acidification in Maine and empower them to take action; and

6. Maintain a sustained and coordinated focus on ocean acidification.

The commission is proposing legislation to create an ongoing ocean acidification council to continue the commission's efforts to identify, study, mitigate and prevent the effects of coastal and ocean acidification on species commercially harvested and grown in Maine's marine environments. The proposed council would have the authority to advise on matters of ocean acidification and to respond to advances in ocean acidification science and to shifts in the economic and political landscapes. It would also have the authority to submit legislation regarding ocean acidification matters directly to the Legislature. This proposed legislation can be found in Appendix D.

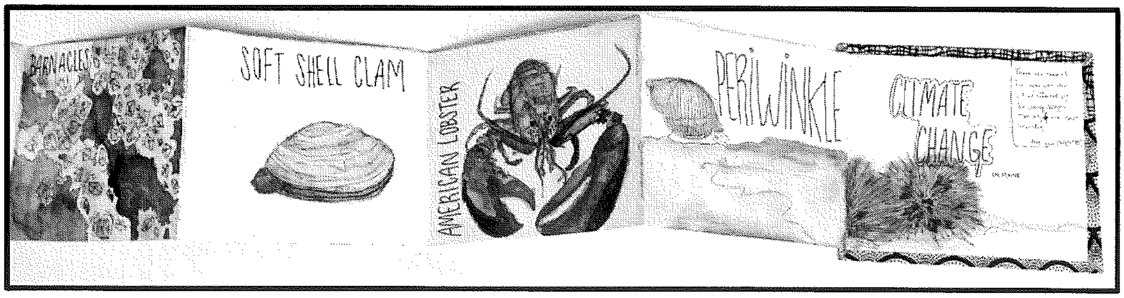

Image courtesy of the artist Olivia Dwyer

I. Introduction

With the 2014 passage of Resolve 2013, chapter 110, the 126th Maine Legislature established the Commission to Study the Effects of Coastal and Ocean Acidification and Its Existing and Potential Effects on Species That Are Commercially Harvested and Grown Along the Maine Coast. The resolve provided for a 16-member commission, specified its duties and directed the commission to submit its report to the joint standing committee having jurisdiction over marine resource matters by December 5, 2014. Resolve 2013, chapter 110 is included as Appendix A.

The President of the Senate, the Speaker of the House of Representatives and the Governor completed their appointments to the commission during the early summer of 2014. The members include two state senators, three state representatives, two representatives of an environmental or community group, one person who fishes commercially, two aquaculturists, three scientists who have studied coastal or ocean acidification, the Commissioner of Marine Resources, the Commissioner of Environmental Protection and the Commissioner of Agriculture, Conservation and Forestry or those commissioners' designees. A list of the commission's membership is included as Appendix B.

The commission met on August 1, September 4, September 18, October 10, October 21, November 10 and December 1, 2014. The August 1, 2014 meeting was held at the Darling Marine Center, University of Maine's Marine Laboratory in Walpole, Maine where the commission received presentations by scientists and other experts on ocean acidification and the economic and policy implications for Maine. This meeting was made possible by an in-kind contribution from the University of Maine's Darling Marine Center, through the Maine Sea Grant program, to pay for facility and luncheon costs. The remaining meetings were held in the Cross State Office Building in Augusta and were broadcast through the Legislature's public internet system. Summaries of the commission's meetings can be found at http://legislature.maine.gov/legis/opla/oceanacidificationmtgmatrls.htm.

To facilitate the commission's work, two subcommittees were created: the State of the Science, Research and Monitoring Priorities Subcommittee (State of the Science Subcommittee), to delve into the scientific literature and data pertaining to ocean acidification; and a subcommittee to review the Washington State Blue Ribbon Panel of Ocean Acidification report and to determine the applicability of panel's recommendations to the conditions in Maine. The State of the Science Subcommittee's report is a comprehensive review of the scientific literature and data pertaining to ocean acidification and can be found in Appendix C.[1]

A known contributor of ocean acidification is atmospheric carbon dioxide (CO_2), which forms carbonic acid when it dissolves in water. Globally, the increased atmospheric input of CO_2 can explain the observed multidecadal change in the acidity of the seawater. Nutrient (including organic matter) and freshwater runoff from land-based point and nonpoint sources are additional drivers of acidification in Maine's estuary and inshore waters (see State of the Science Subcommittee report, Appendix C). While the increase in freshwater runoff is documented, the history and trends in nutrient influx from land into inshore waters is not known.

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[1] A glossary of terms can be found in Appendix F.

It is well established that ocean acidification is occurring globally and proceeding at an increasing rate. Scientific data indicate the rate of acidification is at least 100 times faster at present than at any other time in the last 200,000 years and may be unprecedented in earth's history.[2] This rapid rate of change in ocean chemistry is a threat to the continued success of marine life; including Maine's commercially valuable marine species (see State of the Science Subcommittee report, Appendix C).

The importance of the commission's directive is highlighted by research that demonstrates the cold waters of the Gulf of Maine are more susceptible to ocean acidification than other regions in the United States because these waters are less buffered.[3] Additionally, carbon dioxide is more soluble in cold water, resulting in a faster rate of acidification than in warmer waters. Maine's heavy economic reliance on a single species, the American lobster (69% of the value of all of Maine's 2013 landings), which is thought to already be threatened by warming water temperatures, creates a heightened risk for devastating socio-economic impacts should increasing ocean acidity also prove to negatively impact lobsters.[4] In 2014, the Island Institute conducted a workshop to discuss potential impacts of ocean acidification on coastal communities, to learn about vulnerability assessment techniques and to discuss possible mitigation and adaptation strategies for Maine to consider. An executive summary of that report can be found in Appendix G. The full report is available at: www.islandinstitute.org/OceanAcidification.

While scientific research on the effects of ocean acidification on marine ecosystems and individual organisms is still in its infancy, Maine's coastal communities need not wait for a global solution to address a locally exacerbated problem that is compromising their marine environment.

Maine is working with regional, state and local entities to address ocean acidification through existing programs related to climate change, air and water quality. Both the State and municipalities can enhance and increase this ongoing work to reduce possible sources of acidification. Such efforts could include, but are not limited to, adopting land use practices that maximize recharge of precipitation to groundwater, and reducing point and nonpoint nutrient discharges that can lead to acidification. Additionally, municipalities, in coordination with regulatory agencies, could conduct pilot projects using shell hash (crushed shells) as a buffering "agent" in clam flats to determine if it is effective in restoring recruitment of softshell clams.

Despite data gaps, the existing scientific research on ocean acidification is already compelling and the commission strongly urges that steps be taken immediately to implement its recommendations. The commission arrived at its goals and recommendations based on the state of ocean acidification science and in light of practical, economic and political realities and after

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[2] Honisch et al. 2012. The geological record of ocean acidification. Science 335 pp.1058–1063.

[3] Wang et al. 2013. The marine inorganic carbon system along the Gulf of Mexico and Atlantic coasts of the United States: Insights from a transregional coastal carbon study. Limnol. Oceanogr. 58(1) pp. 325–342.

[4] In 2013, there were 125,953,876 pounds of lobster landed in Maine with a value of $364 million, representing 69% of the total value of all of Maine's commercially harvested marine species based on ex-vessel value (the price received by the captain at the point of landing for the catch). See http://www.maine.gov/dmr/news/2014/2013Landings.htm; http://www.maine.gov/dmr/commercialfishing/documents/2013ValueBySpecies.Pie.Graph.pdf.

consideration of various viewpoints on the causes, levels and trends of ocean acidification. The commission strongly believes its unanimous recommendations reflect a balance of those considerations.

II. Resolve 2013, Chapter 110

Resolve 2013, chapter 110, directed the commission to meet a minimum of four times to review, study and analyze existing scientific literature and data on coastal and ocean acidification and how it has affected or potentially will affect commercially harvested and grown species along the coast. The resolve also requires the commission to address the following:

1. The factors contributing to coastal and ocean acidification;

2. How to mitigate coastal and ocean acidification;

3. Critical scientific data and knowledge gaps pertaining to coastal and ocean acidification as well as critical scientific data and knowledge gaps pertaining to the effects of coastal and ocean acidification on species that are commercially harvested and grown along Maine's coast;

4. Ways to strengthen existing scientific monitoring, research and analysis regarding the causes of and trends in coastal and ocean acidification; and

5. Ways to increase public awareness of coastal and ocean acidification.

III. Executive Summary of State of the Science, Research and Monitoring Priorities Subcommittee Report

To focus the efforts of the commission, the State of the Science, Research and Monitoring Priorities Subcommittee was established to delve into the scientific literature and data pertaining to ocean acidification. This 6-member subcommittee produced a report (see Appendix C) that discusses the processes and impacts of ocean acidification, monitoring needs, mitigation options and provides a comprehensive review of relevant scientific literature. This summary provides a broad overview of that report. [5]

The world's oceans are becoming more acidic. While ocean acidification science is still in its infancy, especially in the Gulf of Maine, it is clear that rapid changes in seawater chemistry related to acidification are occurring on a global scale. Applicable scientific research suggests that in the Gulf of Maine, such changes are likely having an impact on commercially important species.

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[5] A glossary of terms can be found in Appendix F.

Of the processes that cause acidification of marine waters, the most documented and best-understood is the uptake of carbon dioxide (CO_2) from the atmosphere by the ocean, which results in the formation of carbonic acid (acidification). The increased uptake of CO_2 in recent decades is clearly linked to the increasing usage of fossil fuels. The waters of the Gulf of Maine are more susceptible to ocean acidification than other regional waters surrounding the United States for two main reasons. First, because of the relative freshness of waters entering the Gulf of Maine, its waters tend to be less chemically buffered against increasing acidity. Secondly, because CO_2 is more soluble in colder water, our region tends to absorb more atmospheric CO_2.

Freshwater runoff from Maine's rivers and streams is typically more acidic than ocean waters due to the local geology, land use patterns and relatively high acidity of precipitation. For Maine, increases in both the average annual rainfall and the frequency of extreme precipitation events are resulting in higher rates of runoff.

Large variations in pH (the scale used to measure acidity) within marine ecosystems also occur because of the balance between photosynthesis and respiration. Photosynthesis raises pH making water less acidic by taking up CO_2, and respiration produces CO_2, lowering pH, thus making water more acidic. This CO_2 balance between photosynthesis and respiration is threatened by the addition of nutrients, such as nitrogen and phosphorus from land use activities. These nutrients can boost biological productivity resulting in large swings in the concentration of CO_2 in marine waters that can be detrimental to marine organisms. Nutrient loading can also result in eutrophication (when large phytoplankton blooms die and release CO_2 as they decompose), which can be lethal to marine life.

While ocean acidification studies have provided some insights into the causes and effects of ocean acidification, they fail to provide sufficient information to adequately understand or predict how acidification will impact Maine's commercial species. Furthermore, the vast majority of studies only consider one species or even one life stage (see Table 1 in Appendix C). To assess and prepare for the impacts of ocean acidification on Maine's commercially valuable species, more research is needed that investigates multiple life stages, the impact of multiple climate change stressors and the effects on whole ecosystems.

To date, single species studies indicate that Maine species most impacted by acidified ocean waters are those that calcify, or produce calcium carbonate hard parts, including crustaceans (e.g., lobster, crabs, shrimp), mollusks (e.g., clams, mussels, oysters, scallops, periwinkles), echinoderms (e.g., sea urchins, sea cucumbers), calcareous macroalgae and plankton. The formation of calcium carbonate is particularly sensitive to changes in pH; however, the mechanisms of calcification are both species specific and not always well understood. In Maine, 87% of the landings value of harvested or grown species comes from organisms that make calcium carbonate shells.

- **Crustaceans:** Accounting for 69% of the landed value of Maine's fisheries in 2013, the American lobster is by far the most critical species to Maine's marine economy; however, there is very little known about how the lobster will react to a more acidic marine environment. Only two studies have examined the American lobster, each finding differing effects from increased pCO_2.[6] While these studies provide a starting point, they were conducted at water temperatures significantly warmer than those typical in Maine and did not study lobsters from Maine's gene pool. How Maine's lobster population will respond to ocean acidification is still very much an open question.

Northern shrimp appear to be resilient to ocean acidification, except that under elevated pCO_2 conditions larval development takes longer, making this species more susceptible to predation.

Of Maine's two commercially important crab species, the rock crab and the Jonah crab, there have been no studies investigating the effects of ocean acidification. However, two studies looking at other closely-related crabs found one species, the Dungeness crab, to have the ability to compensate for increased exposure to pCO_2, whereas the European edible crab was unable to tolerate warmer temperatures when exposed to high CO_2 conditions.

- **Bivalves:** Bivalves are a significant component of Maine's marine fishery and include softshell clams, sea scallops, eastern oysters, blue mussels, mahogany quahogs, hard clams and surf clams. Most bivalves are susceptible to ocean acidification. While adult bivalves in Maine can generally survive in more acidic conditions, during larval stages bivalves are more sensitive to ocean acidification. This sensitivity can largely be attributed to the fact that bivalves build their larval shells from more soluble forms of calcium carbonate, which is more readily dissolved in acidic conditions. In extreme cases, such as on the west coast where there was a near collapse of the oyster industry during the middle part of the last decade, fertilized eggs never developed into normal larvae that were able to feed and grow. The ocean conditions (the pCO_2 levels) at which this occurs are not uncommon in Maine's inshore waters.

  Studies have also shown that some bivalve larvae and small juveniles exposed to acidified conditions are smaller, less fit, slower to develop and show significantly greater mortality than larvae exposed to ambient conditions. The acidity of sediments can also influence the bivalve larval settlement behavior of softshell clams. In more acidic sediments, it is more likely the larvae will swim back into the water column rather than settle into the acidic mud. When settlement in more acidic sediment does occur, significantly higher mortality can result.

- **Other species:** Researchers have also studied the effects of ocean acidification on various commercially important species, such as polychaete worms, green sea urchins, Atlantic herring, Atlantic halibut, Atlantic cod, red algae, brown algae and green algae, as well as phytoplankton and zooplankton. The impacts of ocean acidification on these differing marine species are variable. In species like Atlantic cod sourced from the Norwegian coast, negative effects, such as an increase in tissue damage and a decrease in movement have been observed, whereas some species of fleshy macroalgae have

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[6] pCO_2 is the partial pressure of carbon dioxide. The value of pCO_2 depends on the amount of total carbon in the water, its buffering capacity and the water temperature.

responded positively to an increase in acid conditions by showing an increase in productivity.

Maine needs to promote and act on research and monitoring priorities suggested by the State of the Science, Research and Monitoring Priorities Subcommittee (see Appendix C) in order to properly adapt to, mitigate and remediate the impacts of ocean acidification on Maine's commercially important marine species. The better the understanding of how acidification will impact commercially valuable species throughout their life stages, as well as the marine ecosystem as whole, the more prepared Maine will be to find effective and efficient solutions.

IV. Goals and Recommendations[7]

Maine must make hard decisions to effectively address the rapidly increasing rate of acidification of its marine environments. Ocean acidification and its effects are not readily observable by the general public, underscoring the importance of education and outreach efforts to illuminate the seriousness of this issue and its importance among other issues that capture the public's attention. Maine decision-makers are often faced with competing economic and political issues but share a deep commitment to, and understanding of, the economic and cultural importance of the State's fisheries. The gravitas of ocean acidification must be understood by both Maine's leaders and the public to ensure the long-term stability of its commercially-harvested species, which are vital to the State's economy.

The commission's unanimous support for its goals and recommendations are the culmination of four months of in depth discussions, involving the review and analysis of highly technical scientific data, federal and state ocean acidification studies and programs and policy considerations. For Maine and its commercial fisheries, addressing ocean acidification has become an urgent matter and the commission emphatically supports the immediate implementation of its recommendations. The goals and recommendations in this report represent a starting point for efforts that this commission believes will put Maine on a path to identify, mitigate and remediate the impacts of ocean acidification and to take advantage of the opportunities it may afford us. While the commission understands that some of its recommendations have significant financial and time implications, preliminary actions can still be taken towards fulfilling those recommendations.

As used in this section, "shellfish" means the American lobster, crabs, oysters, mussels, clams, scallops, sea urchins, northern shrimp and periwinkles unless otherwise indicated by the context.

Goal 1: Invest in Maine's Capacity to Monitor and Investigate the Effects of Ocean Acidification and Determine the Impacts of Ocean Acidification on Commercially-Important Species and the Mechanisms Behind Those Impacts

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[7] The commission's recommendations dovetail with many of the recommendations from the 2012 report of the Washington State Blue Ribbon Panel on Ocean Acidification. The Washington State report can be found at http://www.ecy.wa.gov/water/marine/oceanacidification.html.

To date, most experiments have focused on single-species responses to ocean acidification in laboratory settings. Given the current rate of acidification, we must move beyond a single-species approach and consider how ocean acidification impacts the structure of marine ecosystems as a whole and over time. Filling this knowledge gap will require the expansion of monitoring and multispecies experiments that bring a small part of the natural environment under controlled conditions for study. Multispecies food-web models should be developed to obtain a better understanding of the direct and indirect impacts acidification is having on our commercial species.

Recommendations

1.1. Enhance monitoring and create a database sufficient to support the development of regulatory and non-regulatory approaches to reduce and limit nutrients and organic carbon from sources that are contributing significantly to the acidification of Maine's marine waters. Enhanced monitoring should begin in one or more pilot estuaries where impacts are presently occurring.

To support new or strengthened pollution reduction efforts, Maine industries, landowners and policy-makers need to understand if and how public and private investment in pollution controls will deliver the desired reduction in nutrients and the acidification they may cause in coastal waters. Inputs from land-based sources (wastewater treatment plants, industrial point sources, urban runoff and agricultural and silvicultural practices) need to be better understood. Maine does not currently monitor nitrogen production or its biological impact.

The commission recommends instituting pilot projects that involve monitoring key estuaries around Maine to learn more about how specific pollutants and freshwater runoff conditions are contributing to ocean acidification. While much work has been done in Casco Bay, more data is needed in that location as well as in other important locations along Maine's coast to better understand acidification processes in those areas.

1.2. Expand monitoring of ocean acidification to establish its natural variability and to detect trends in water chemistry and related biological responses.

There is a dearth of information on the impact of acidification on Maine's commercial species, especially under environmental conditions found in Maine. There is also a lack of high-resolution data on the present state of the carbonate system of coastal waters in Maine, making it difficult to know what conditions commercial species currently experience and how those conditions are expected to change in coming years. The commission recommends that the following research and monitoring activities be priorities for the state:

1. Monitor/sample watershed fluxes of materials affecting pH and the carbonate system. These materials include carbon compounds and nutrients such as nitrogen;

2. Resolve the acidification attributable to nitrogen and phosphorus fluxes;

3. Monitor the carbonate system of inshore and offshore water column and benthic habitats;

4. In conjunction with water quality/carbonate chemistry data collection, monitor larval abundance and recruitment success for commercially important shellfish species;

5. Conduct modeling and laboratory based efforts to understand how or if ocean acidification affects our most important species (lobsters, Jonah crabs, spider crabs and rock crabs, sea scallops, elvers and other finfish, sandworms and blood worms);

6. Conduct more in-depth experiments including multi-stressors, multiple life stages/multiple generations or predator-prey interaction studies;

7. Research mitigation, specifically regarding sediment buffering, algal growth and harvest (phytoremediation techniques to better understand the mitigation potential provided by upland and marine vegetation) and animal rearing; and

8. Conduct experiments to provide a better mechanistic understanding of how ocean acidification impacts marine organisms.

It is difficult to adapt to or mitigate acidification if it cannot be detected. Maine requires more "eyes" on its coastal waters to see where and when acidification occurs. These eyes will likely include fixed measurement platforms, research cruises and citizen monitoring efforts to measure more extensive areas. Time series using reproducible methods will be vital to find trends associated with ocean acidification.

Measurements of both water quality and biological indications of acidification are technical and, at present, expensive. More extensive measurements need to be made by less expensive means. Five strategies to extend these measurements include:

1. Expand monitoring capabilities within the context of the Northeastern Regional Association of Coastal and Ocean Observing Systems (NERACOOS) and the National Oceanic and Atmospheric Administration's Ocean Acidification Program;

2. Empower and assist citizens, singly (e.g., individuals on fishing vessels) or in organized groups, such as environmental monitoring groups (e.g., Maine Coastal Observation Alliance) to make measurements as extensive as possible. Reliability of data should be ensured via practices such as training in and adoption of Quality Assurance Project Plans overseen by the Environmental Protection Agency or the Department of Environmental Protection;

3. Support the development and take advantage of rapidly evolving technology such as new sensors to bring down the costs of direct or indirect measures of acidification (or proxies, see Recommendation 1.3) of waters or sediments;

4. Take advantage of existing platforms such as hatcheries, shoreside laboratories and moorings to deploy sensors; and

5. Continue the Department of Environmental Protection's work with regulated entities to obtain additional monitoring data regarding nutrient loading, specifically phosphorus, nitrogen and fixed nitrogen.

Detection of biological impacts from acidification is difficult because there are many stressors that may account for biological problems. Considerable research will be needed to develop indices of stress that are attributable to acidification.

Monitoring efforts will need to be coordinated and data compared between places and times. Central data-gathering groups, such as NERACOOS, coalition groups of citizen monitors (e.g., Maine Coastal Observation Alliance) and state agencies with water quality databases will all be vital to this networking. It is important that scientific data on ocean acidification from various sources be centralized and made readily available to all researchers.

1.3. Develop new tools with which to assess and understand acidification and its impacts in Maine waters.

The science and technology of assessing acidification impacts are developing rapidly. Maine needs to both keep up with this rate of evolution as well as develop tools appropriate to its local waters and species. Maine is in a position to be a leader in the development of new technologies related to ocean acidification and to realize the economic opportunities presented by burgeoning technologies.

Water quality and biological indicators of acidification need to be enhanced. Expensive chemical measurements of acidification will need to be supplemented by less expensive ways of measuring the same properties (e.g., pH). Similarly, impacts on organisms will be increasingly measured by automated methods such as genetic and image recognition technologies.

New tools will be developed by the assessment of chemical or biological proxies that signal the onset of acidification, such as dissolved oxygen or indicator bacteria. Such indicators need development not only for present and future conditions, but also to allow us to reach into the past so that we can understand how changing water quality has affected commercial species in prior times. Basic oceanographic sensing will enable detection of water masses that set the stage for acidification, whether it is salinity sensors inside estuaries or offshore buoys/glider systems that sense different water masses entering the Gulf of Maine.

Models are needed that connect the atmosphere, water masses and their chemistry, impacts on organisms, and linkages to socio-economic processes. This modeling extends the results of data gathering into times and places not measured. Modeling should proceed first at the level of individual components and later in linked forms as the components are proven. As understanding improves from experiments, field studies and models, sensing systems will need expansion or reorganization to detect acidification effects in the actual ocean.

1.4. Determine the causes and relative importance of acidification in the waters and sediments of Maine.

The commission recognizes three primary sources of acidification in Maine waters: (1) enrichment of atmospheric CO_2 via fossil fuel combustion; (2) eutrophication via nutrient additions; and (3) increased inputs of low-pH freshwater. The importance of these sources will vary with place and time. For example, freshwater inputs will likely be most important where rivers lower the salinity of marine waters, and nutrient controls will be strongest near sources of nutrients. The separate and combined roles of each, including relative contributions, should be assessed for a more complete understanding of the acidification budget.

Acidification of patterns of pelagic (open ocean) waters may be different from acidification patterns at the benthic boundary (water located directly above the bottom). Sediments will experience a suite of different processes, such as those mediated via biologic activity over a wide range of oxygen concentrations.

While ocean acidification is occurring very rapidly on a geologic time scale, detectable acidification caused by increasing atmospheric CO_2, as experienced by Maine's commercially important marine species, will continue to take place over decades. It is very likely that this will lower pH to levels potentially harmful to Maine's commercial species. Careful time series of appropriate measurements should be enhanced, as well as explorations of past conditions via proxy measurements. Modeling should be fairly successful at predicting CO_2 derived acidification trends because the physics and chemistry of ocean acidification by atmospheric CO_2 are relatively well understood.

Nutrient-derived acidification will be more variable, and increased acidification via this pathway will require studies of nutrient-driven cycles, such as photosynthesis and subsequent respiration. Nitrogen is likely to be the principal nutrient of concern, but the role of other nutrients, such as phosphorous, should also be assessed. The contributions of various sources of these nutrients to the inshore waters, including atmospheric, sewage, land use, river, oceanic source waters and others sources should be determined to plan future adaptive and remediation actions. Changing patterns of freshwater inputs into marine waters should be monitored and evaluated.

1.5. Identify the impacts of acidified waters and sediments on Maine's commercial species.

Maine must develop better information on the impacts of acidification on wild and cultured commercial species using Maine's environmental conditions. Because acidification is one of many environmental challenges faced by Maine's commercial species, its impacts should be considered both separately and in conjunction with other stressors, such as warming, disease, invasive species and fishing pressure. Differences between water and sediment ecosystems mean that acidification of water inputs to hatchery bivalves may differ considerably from acidification affecting natural sets of bivalves in adjacent coves.

These impacts may occur in direct and indirect ways. Direct impacts on species should be studied in well-controlled experimental systems capable of evaluating the combined effects of climate change parameters, such as dissolved oxygen and temperature. These studies should include impacts on both physiology and behavior and should assess the ability of various species to adapt to changing conditions. Acidification may also affect ecosystems in ways that indirectly affect commercially important species. For example, plankton that serve as food may change in quality or quantity, or disease-causing organisms may become prevalent. Studies of overall impacts of acidification on commercial species must remain sensitive to these possibilities.

Studies should address whether the impacts found in experiments appear in organisms in the field, and should also address the success of larval recruitment to natural populations, especially in conjunction with water quality measurements. Researchers should develop markers of acidification impacts that can be used in subsequent field monitoring.

Goal 2: Reduce Emissions of Carbon Dioxide

While the acidification of the Gulf of Maine is the result of several processes, the increased atmospheric input of CO_2 can explain the observed multidecadal change in acidity of the seawater. The Gulf of Maine is colder than most coastal areas in the United States and CO_2 is more soluble in colder water, thereby facilitating a higher rate of CO_2 uptake causing an accelerated rate of acidification. Furthermore, Gulf of Maine waters are less buffered than other regions, resulting in a greater increase in acidity from the same uptake of carbon dioxide (see State of the Science Subcommittee report, Appendix C). Reducing global atmospheric carbon dioxide levels should be an immediate priority. While ocean acidification from atmospheric carbon dioxide is largely recognized as a result of global activities (of which Maine has a small proportional impact), Maine can still have a discernable impact in reducing atmospheric carbon dioxide by implementing the following recommendations.

Recommendations

2.1. Strengthen coordination and continue participation with existing national, state and regional initiatives regarding the reduction of atmospheric CO_2 levels.

In recent years, emphasis has been placed on climate change resulting in resolutions pertaining to energy, alternative fueled vehicles, transportation and other matters related to climate change.

Maine is currently involved with several initiatives to help reduce atmospheric CO_2 levels and other greenhouse gases[8] at both the regional and state level. At the regional level, Maine is a member of the Regional Greenhouse Gas Initiative (RGGI). This initiative is the first market-based regulatory program in the United States designed to reduce greenhouse gas emissions and is a cooperative effort among the states of Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island and Vermont to cap and reduce CO_2 emissions from the power sector. It is critically important for Maine to continue its efforts as part of this regional group approach to ensure that RGGI is effective.

Maine is also a member of the Transportation and Climate Initiative of Northeastern and Mid-Atlantic States. Its mission is to develop the clean energy economy and reduce greenhouse gas

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[8] The term "greenhouse gases" includes CO_2, as well as methane (CH_4), nitrous oxide (N_2O), hydroflourocarbons (HFCs), perflourocarbons (PFCs) and sulfur hexafluoride (SF_6).

emissions in the transportation sector. Since 1973, Maine has participated in the partnership and annual conferences of the six New England Governors and the five Eastern Canadian Premieres (NEGECP). This partnership is meant to encourage cooperation by focusing on developing networks and relationships, taking collective action, engaging in regional projects and endorsing projects by others, undertaking research and increasing public awareness of shared interests. Additionally, the NEGECP adopted a 2013 Climate Action Plan at its 37th conference and has since developed a work plan for 2014 and 2015.

In 2013, Maine established the Environmental and Energy Resources Working Group whose purpose is to ensure effective cross-coordination and integration of programming among Maine's agencies regarding reduction of greenhouse gases, as well as adaptive measures taken to mitigate environmental or climate changes. The results of this group have been released and call for efficient mechanisms for collaborating to reduce redundancies and duplication of efforts among state and local agencies. The report, "Monitoring, Mapping, Modeling, Mitigation and Messaging: Maine Prepares for Climate Change" is available at http://www.maine.gov/dep/sustainability/climate/Working%20Group%20maine%20prepares.pdf Efforts to work on reducing greenhouse gases as part of an ocean acidification mitigation strategy should be coordinated with the results of the Environmental and Energy Resources Working Group.

As outlined in the report referenced above, a number of Maine's state agencies are working on ways to reduce greenhouse gases. Many of these efforts started as a result of the 2004 Climate Action Plan and the 2010 Climate Adaptation Plan. These efforts include but are not limited to: the monitoring and reporting of greenhouse gas emissions, regulating greenhouse gas emissions at permitted facilities, encouraging both energy efficiency and investments into renewable energy, managing a "cleaner" fleet of state cars and promoting new technologies to capture greenhouse gas emissions. State agencies that are involved include the Department of Environmental Protection, the Public Utilities Commission, the Department of Transportation, the Efficiency Maine Trust and the Governor's Energy Office. Results of these programs include several recurring reports that are delivered to the Legislature, for example, The Fifth Biennial Report on Progress toward Greenhouse Gas Reduction Goals (available at http://www.maine.gov/tools/whatsnew/attach.php?id=611577&an=1) and the 2014 Regional Greenhouse Gas Initiative Annual Report (available at http://www.maine.gov/tools/whatsnew/attach.php?id=616525&an=1).

Other organizations and academic institutions throughout Maine are also focusing on the reduction of atmospheric CO_2 levels and may also serve as useful resources in determining additional strategies. An example of such an institution is the University of Maine Climate Change Institute.

Moving forward and in coordination with the existing initiatives outlined above, Maine should continue to work with federal and state agencies, other coastal states, Eastern Canadian Premieres and other international governments as applicable to promote effective strategies and comprehensive approaches to reduce atmospheric levels of CO_2 by:

1. Sharing knowledge, data, scientific expertise and establishing potential policy initiatives with partners;
2. Participating in joint actions to protect oceans and other marine waters from acidification;
3. Pursuing agreements with other partners to cooperate in scientific initiatives that will better define the impacts of atmospheric CO_2 on marine fisheries, seafood supplies and water quality; and
4. Building public awareness by using intergovernmental compacts and joint outreach and education efforts.

2.2. Encourage key leaders and policymakers to synchronize in establishing a comprehensive and unified strategy to reduce carbon dioxide emissions.

Since Maine is already actively taking a variety of steps and engaging in multiple initiatives to reduce atmospheric CO_2 levels, it is critically important that Maine's legislators, congressional delegation, Governor, community stakeholders and academic and business leaders come together with state agencies to establish a comprehensive path forward on the best approaches and strategies for reduction. Better coordination of these efforts is important to avoid duplication, to ensure entities are not acting at cross purposes, and to ensure that Maine's leaders can effectively serve as ambassadors to promote the reduction of CO_2 levels with a unified voice. To effectively carryout this recommendation, elected officials and other key leaders should be periodically briefed on ocean acidification issues to stay current on CO_2 levels and trends, ocean acidification science and impacts relevant to Maine's commercial fisheries.

2.3. Expand actions at the state and local level that may help in reducing CO_2 emissions.

Although Maine acting individually or alone will lessen only a small proportion of the overall levels of atmospheric carbon dioxide (as compared to the global contribution), Maine can still help to increase public awareness and set a good example by supporting regional or national initiatives. A considerable amount of work has been conducted on the reduction of greenhouse gases and the commission strongly recommends that this work be drawn upon and integrated with other related ongoing efforts, including the state's Comprehensive Energy Plan. Perhaps the most effective way for Maine to contribute to global greenhouse gas reduction is through the identification and development of relevant new technologies that have global marketability and which would have the added benefit of creating economic opportunities here in Maine. An integrated approach may allow Maine to take the following actions at the state and local levels:

1. Provide additional funding to existing state air quality emissions, monitoring and climate change mitigation and adaptation programs;
2. Continue support for existing air quality programs pertaining to transportation fuel efficiency, including:
    - Requiring the use of cleaner-burning fuels;

- Implementing motor-vehicle emission standards (meeting the California Low Emission Vehicle standards); and
- Administering the Maine Clean Diesel Program and the Maine Clean Marine Engine Program;

3. Continue support for existing programs pertaining to point of use energy generation;

4. Create additional incentive programs to encourage energy conservation and efficiency and the use of renewable energy sources as well as clean technologies;

5. Set policies and establish programs that will encourage the creation and expansion of new technologies and innovations to reduce greenhouse gas emissions;

6. Provide educational and outreach materials to demonstrate the benefits of reducing greenhouse gases; and

7. Expand local energy conservation boards.

Collaborating with other states to take the actions listed above will increase their potential impact.

Goal 3: Identify and Reduce Local Land-Based Nutrient Loading and Organic Carbon Contributions to Ocean Acidification and Freshwater Runoff by Strengthening and Augmenting Existing Pollution Reduction Efforts and Making Groundwater Recharge a Land Use Priority

Maine's numerous rivers and streams provide an influx of freshwater that typically has a lower pH than ocean waters and are also a possible source of excess nitrogen and phosphorus, both of which can be contributors to ocean acidification. While the proportion of impact or relative contribution by these sources is unknown, the influx of additional nutrients and lower pH waters are generally understood to adversely impact commercially valuable species, especially in estuaries.

An increase in nutrients boosts biological productivity but in larger amounts may lead to oxygen depleted waters, toxic algae blooms and the acidification of marine waters. An increase in the frequency and severity of storms and anticipated trends in precipitation are likely to result in lower pH water entering rivers and streams and ultimately estuaries. While it is recognized that both of these factors contribute to ocean acidification, it is not understood to what extent marine species are stressed by acidification alone as compared to other competing factors, including, but not limited to, invasive species (green crabs), other water quality parameters (temperature), low levels of dissolved oxygen and overfishing.

Recommendations

3.1. Identify and reduce nutrient loading and organic carbon from point source and nonpoint discharges determined to cause or contribute to ocean acidification.

Nutrient and organic carbon originating from a variety of point sources (including municipal wastewater treatment facilities or publicly owned treatment works (POTWs));[9] industrial point source discharges; industrial, municipal, agricultural or construction storm water discharges; and on-site sewage discharges,[10] such as overboard discharges and septic failures as well as nonpoint source discharges (runoff) likely account for the majority of local nutrient inputs into Maine's marine waters. Discharges from most point sources are regulated by individual or general permits issued by the Department of Environmental Protection under the Maine Pollutant Discharge Elimination System program.

Point source permits typically impose specific effluent limits, monitoring and reporting requirements and other conditions on permitted discharges. At this time, however, specific nutrient criteria (i.e., nitrogen and phosphorus) are typically not included in permits as these criteria are not yet developed in Maine.[11] In addition, the extent of the relative contribution of impacts on estuaries from specific point sources is not well understood.

As compared to point sources, nonpoint source discharges are typically not licensed, but the Department of Environmental Protection and the Department of Agriculture, Conservation and Forestry have programs to help landowners with reducing runoff and restoring impacted areas to improved environmental health. Several programs to help with planning and implementing best management practices are already in place.

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[9] When properly designed and installed, POTWs provide a high level of treatment for bacteria and other pollutants including pH. The allowable limits of pH in wastewater discharges are governed by statute and legislation would be required to change those limits. Nutrients like nitrogen are not removed unless nitrogen-reducing technologies are used. Because POTWs are considered to be permanent infrastructure, they are costly to construct, maintain and operate. Reducing nitrogen from these sources will require technology that must be tailored to location conditions and the actual facility design to work properly. The cost of the advanced treatment of nutrients will generally fall on individuals as POTWs are managed and funded at the municipal level. If it is shown to be effective and reliable, nitrogen-removal technologies ought to be considered as an option in areas where it is determined that nutrients from POTWs are contributing significantly to ocean acidification.

[10] In addition to POTWs, other smaller on-site sewage systems are in operation around the state. Continued efforts to improve technologies and mitigate these localized sources where opportunities are available is still worthwhile. These include residential sewage and septic systems. Provided that funding is available, Maine offers several programs to assist qualifying homeowners with replacement of failing on-site septic systems and overboard discharge systems.

[11] Numeric nutrient criteria provide the basis for regulations to reduce nutrient loading to water bodies from licensed (or permitted) point source discharges. In 2004, the Environmental Protection Agency directed states to develop numeric nutrient criteria for nitrogen and phosphorous to protect aquaculture, shellfish harvesting/propagation and habitats for aquatic marine life. For marine waters, Resolve 2007, chapter 49, required the Department of Environmental Protection to create a work plan and timeline leading to approved nutrient standards and a report on technological innovations to (total nitrogen) nutrient reduction/wastewater treatment. Significant point and non-point sources of nutrients flowing into Casco Bay were subsequently inventoried. The Department's June 2008 report is available at http://www.maine.gov/dep/water/nutrient-criteria/nutrient_criteria_report_2008.pdf. The Department's deadline for completing this work is currently 2015 (extended from 2012 by the Legislature).

The commission recommends additional research and monitoring to determine the extent to which point sources of nutrients and organic carbon cause significant acidification. Using that research, the commission recommends that more clarity be provided on nutrient criteria and how they might be incorporated into both regulations and the permitting process. Concurrently, sources that significantly contribute to nutrient loading should be required to reduce their contributions when feasible by instituting new technologies.

Additionally, state agencies should enhance their efforts to remediate sources of pollution, especially in the watersheds of shellfish growing areas and in pilot ocean acidification watersheds, emulating successful efforts such as the Department of Agriculture, Conservation and Forestry and the Department of Environmental Protection memorandum of agreement that outlines the responsibilities of both agencies to assist with agricultural runoff.

3.2. Assess the need for additional water quality criteria[12] relevant to ocean acidification.

The commission recommends that the Environmental Protection Agency and other federal agencies, in conjunction with the Department of Environmental Protection, take the lead on evaluating existing standards and the need for new standards (e.g., pH, oxygen, temperature and conductivity) to address ocean acidification. Cost effectiveness of the standards should be considered. If it is determined that existing standards are insufficient to control the impacts of local sources, the Environmental Protection Agency should evaluate the applicability of pH and other water quality criteria identified by recent research or recommended by scientific experts in the fields of ocean acidification and water quality. Recent scientific research suggests that other ocean chemistry parameters such as dissolved oxygen and biological indicators may be relevant to local acidification.

Currently, pH is the only water quality criteria that can be readily associated with ocean acidification. It is conceivable that changing existing regulatory limits may have an effect on pH in the inshore waters depending on the volume of effluent being discharged and the diluting characteristics of the receiving water. The allowable limits of pH in wastewater discharges are governed by statute and legislation would be required to change those limits.

The commission encourages the Department of Environmental Protection to meet its June 2015 deadline for establishing numeric nutrient criteria (see footnote 10).

3.3. Ensure that state staff and other practitioners are working with the best information and most effective technology.

To ensure that the people of Maine are getting access to the most effective technologies, the commission recommends continuing and enhancing current best management practices (BMPs) workshops and training sessions on storm water runoff, erosion control and sedimentation. These workshops and training sessions should continue to provide information about the most

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[12] Water quality criteria under Goal 3 refers to regulatory criteria or standards set to guide the regulated community regarding their discharge limits and what is allowable under their licenses. This is different from the criteria and information outlined in Goal 1 that will help in understanding more generally the chemical and biological indicators of ocean acidification.

effective existing and emerging tools that remove or reduce nutrients, organic carbon and help minimize land use changes that increase freshwater dilution of seawater.

There is a critical need for better technologies to address nutrient loading, especially from nonpoint sources such as new septic system technologies that more effectively treat nutrients. Where demonstrated to have an impact (based on the understanding of relative contributions of nutrients), the State should seek to establish private partnerships to identify, promote and support new and improved technologies that remove or reduce nitrogen and organic carbon from both point and nonpoint sources.

Maine should also continue to enforce BMPs written into licensed entities' permits to ensure the BMPs are followed and required technologies are installed and effective in achieving demonstrated reductions in nutrient loading. For those entities that are not required to be licensed, Maine can enhance public education and outreach on the importance of BMPs and how to voluntarily implement them.

3.4. Investigate incentive programs for pollution and freshwater runoff reduction.

The design of best management practices is often site-specific, and existing financial incentives are often insufficient to warrant landowner participation. Maine should investigate the use of effective incentives for landowners to participate in activities that will contribute toward water quality improvements.

3.5. Support and reinforce current planning efforts and programs that address the impacts of nutrients and organic carbon and freshwater runoff into coastal waters.

Local, state and federal programs are already working collaboratively to protect and improve water quality through storm water management, land use planning and land conservation. Land conservation programs conserve forests, marshes and agricultural lands, all of which can function as natural filters to remove nutrients and sequester carbon and help minimize fluctuations in seawater dilution (lowers pH levels) from freshwater runoff in estuaries.

Land use planning that encourages the use of "green infrastructure" practices reduces the amount of impervious surface and assists in groundwater recharge.[13] State and local government should advance the use of incentives and continue efforts to working with other non-regulatory tools to promote and conserve forest and agricultural land uses, promote reduction in impervious surfaces and encourage use of green infrastructure and other sustainable practices.

Maine state agencies, county soil and water conservation districts, watershed groups and other qualified organizations should continue existing planning, technical, and financial assistance programs to help rural and urban landowners, farmers and others properly manage nutrients and reduce organic carbon.

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[13] Per the Environmental Protection Agency, at the lot or neighborhood level, "green infrastructure" refers to storm water management systems that mimic nature by soaking up and storing water. At the municipal or regional scale, green infrastructure refers to the patchwork of natural areas that collectively provide habitat, flood protection, cleaner air and cleaner water.

3.6. Enhance education and outreach programs that provide landowners with information about best practices for reduction of nutrient pollution.

While the relative contributions of nitrogen loading from the use of fertilizers are not certain, they are believed to have an impact. In some watersheds, the impact may be more than in others depending on the specific characteristics of the coastal watershed.

The commission recommends that outreach and education programs be instituted in areas where it is demonstrated that commercial and residential fertilizers are impacting the nutrient levels coming out of coastal watersheds into estuaries. Based on the characteristics of individual coastal watersheds, the impact of nutrient pollution from fertilizer use on residential and commercial properties may be noteworthy. Other states have led successful outreach and education programs encouraging home and business owners to make optimal choices about the types and quantities of fertilizers needed. In the aggregate, the possibility of communities and individuals lessening their use of certain fertilizers and pesticides may help reduce nutrient loading in their watersheds.

Goal 4: Increase Maine's Capacity to Mitigate, Remediate and Adapt to the Impacts of Ocean Acidification

Ocean acidification is occurring in our ocean and coastal waters. Scientific data suggest that the rate of acidification will continue to increase and further alter ocean chemistry. The rate of change to ocean chemistry represents the most stressful impact of ocean acidification on marine species. In light of these data, the commission makes the following recommendations to mitigate the current effects of ocean acidification and to begin to research mechanisms and methods that may enhance the adaptability of commercial species and those industries that depend upon them, thereby improving their resilience to changes in ocean chemistry.

Recommendations

4.1. Preserve, enhance and manage a sustainable harvest of kelp, rockweed and native algae and preserve and enhance eelgrass beds.

Because plants absorb carbon dioxide through photosynthesis, they have the potential to locally remediate acidification by drawing down carbon dioxide in the surrounding seawater, a process known as "phytoremediation." Acquisition of CO_2 by marine macrophytes (sea grass, seaweeds) represents an important sink for anthropogenic CO_2 emissions. The remediation benefits are likely to be more apparent in areas of slower circulation. Growing and harvesting macroalgae could play a considerable role in carbon sequestration. Determining the benefits of co-culturing macroalgae, such as kelp and shellfish, should be a research priority.

Currently, the process for obtaining a permit for new or expanded aquaculture sites can be quite lengthy. The commission recommends that the Department of Marine Resources work to identify ways to streamline the permit and leasing processes to facilitate and promote the development and use of vegetation-based remediation efforts. Eelgrass restoration efforts are already underway and the state can build off of these existing efforts.

4.2. Encourage bivalve production to support healthy marine waters.

Sustaining shellfish production in Maine helps to protect healthy seawater chemistry and marine ecosystems from acidification. Productive shellfish beds provide natural treatment of some water quality conditions. By the very act of feeding, bivalves filter the water, clean and clarify it. Clearer water allows more sunlight to penetrate, which aids in the growth of seagrasses, including eelgrass. Seagrasses, in turn, take up carbon dioxide and sequester it deep in their root systems, reducing carbon dioxide levels in the water. Different mechanisms exist for maintaining and expanding shellfish beds and the commission recommends that the State promote shellfish production to support heathy marine waters.

4.3. Spread shells or other forms of calcium carbonate ($CaCO_3$) in bivalve areas to remediate impacts of local acidification.

Re-depositing shell hash (pulverized bivalve shell) or other sources of calcium carbonate on mudflats can effectively buffer mudflats, reducing corrosive conditions and improving chances for shellfish recruitment. The spreading of shell material in intertidal zones requires permits through the Department of Environmental Protection and Department of Marine Resources. If this process is determined to be effective, these departments should adopt rules to provide a streamlined permitting process for such remediation measures.

Currently, tons of shells leftover from the consumption of shellfish in Maine restaurants are disposed of in landfills, but these shells may be useful for ocean acidification mitigation and remediation efforts. In accordance with the Department of Environmental Protection's solid waste rules for appropriate handling, storage, collection, treatment and processing protocols, a shell collection and deposition program could help protect cultivated and native oysters and clams from acidification and engage citizens and businesses in mitigating local impacts of acidification.

The commission strongly encourages the creation and promotion of shell collection programs and best management practices for carrying them out safely and effectively. To properly process shell material, centralized stockpiling locations should be identified (likely in association with shellfish growing operations) to "season" the shells sufficiently to meet state standards for prevention of disease and exotic organisms. Initially, such programs should be carried out on a "pilot study" scale to identify any unforeseen negative impacts of spreading crushed shells on mudflats.

4.4. Increase the capacity of the fishing and aquaculture industries to adapt to ocean acidification.

As acidification intensifies, hatcheries may become refuges where huge quantities of larvae can be raised in a controlled environment. The creation of this capacity would be an economic development opportunity for the private sector. The commission encourages efforts to examine the feasibility of growing species in this controlled environment until the species reach a point at which they are less vulnerable to acidification. To accomplish this, better information about the tolerances of individual species in combination with rigorous monitoring and maintenance of hatchery water is essential. Hatcheries may require technical support for monitoring and buffering methodology. Furthermore, the development of models to forecast future carbonate chemistry scenarios and the sharing of these results with industry will give business owners some predictive capacity when it comes to investing.

4.5. Identify refuges and acidification hotspots to prioritize protection and remediation efforts. Vulnerability assessments identify species and habitats in the path of disturbance as well as those less likely to be affected and can help develop site specific adaptation strategies within the priority areas. Once locales are identified as being at high risk from increased CO_2 (hotspots), steps can be taken to mitigate the impacts through habitat restoration, phytoremediation or other measures.

To identify refuges (areas at less risk from ocean acidification because of physical features, remoteness to sources of acidification or because of biological activity utilizing CO_2) or acidification hotspots, monitoring of critical locations must be a priority. A set of criteria should be developed with which to rank different areas. The rankings should guide management efforts by providing a framework with which to focus on the most vulnerable regions first.

4.6. Encourage the enhancement and creation of research hatcheries.

Hatcheries with a focus on research can both maintain and improve genome data of commercially valuable shellfish, including crustaceans, mollusks and echinoderms. The development and testing of technology to improve large scale commercial hatchery production should be supported. Hatcheries should place a high priority on the exploration of genetic adaptive capacity within these populations, selectively breed for resistance to ocean acidification and maintain these selected lines.

Goal 5: Inform Stakeholders, the Public and Decision-Makers about Ocean Acidification in Maine and Empower Them to Take Action

The effects of acidification on marine organisms have been a topic of scientific inquiry for only a little more than 10 years. Calcifiers (e.g., organisms that produce shells) account for approximately 87% of landing value of Maine's commercial fisheries and research suggests that these marine resources are at risk. Maine's leaders at all levels of government, those whose livelihoods depend on marine species and the general public must have a better understanding of ocean acidification, not only in terms of what is known but also in terms of the gaps in scientific data. Information is a crucial requirement to empower stakeholders to take appropriate action. A sustained and coordinated effort will be necessary to understand the risks and appropriately address the causes and effects of ocean acidification. Given the high stakes associated with the changes in ocean chemistry, stakeholders, managers, water quality monitoring groups, conservation organizations and scientists must work together to develop a roadmap that will guide Maine's efforts to cope with the uncertainties associated with ocean acidification.

Recommendations:

5.1. In addition to providing the commission's report, its key findings should be communicated to the Governor, Maine's legislative leaders, Maine's Congressional delegation, the press and the general public in a series of briefings by commission members.

5.2. Continue efforts to increase the understanding of ocean acidification among key stakeholders, targeted audiences and local communities to help implement the commission's recommendations.

Leadership amongst nongovernmental organizations and community networks, such as the Maine Sea Grant and the Maine Coastal Observing Alliance, should take steps to help meet this goal by building on existing outreach and education efforts (workshops, multi-media tools and informational mailings) and improving educational materials developed in conjunction with stakeholders. Those stakeholders include, but are not limited to, the Maine Lobstermen's Association, the Maine Lobstermen's Union, the Maine Coast Fishermen's Association, the Maine Clammer's Association, the Maine Aquaculture Association, the Maine Soil and Water Conservation Districts, the Maine Farm Bureau, Agricultural Council of Maine, Maine Water Environment Association and Maine Rural Water Association. Information regarding ocean acidification science, remediation and adaptation strategies should be shared at existing conferences, for example, the Maine Fishermen's Forum, the Maine Water and Sustainability Conference, Northeast Coastal Acidification Network's stakeholder workshops and the Northeast Aquaculture Conference and Exposition.

5.3. Enhance the existing communication network of engaged stakeholders, state agency representatives and the research community.

A number of entities in Maine are important stakeholders in disseminating information about marine research in Maine, including ocean acidification information. For example, the Maine Sea Grant offers educational programs and resources for the general public and in schools. It also sponsors scientific research related to Maine's coastal and marine resources. There is also an online group called the Maine Ocean Acidification Google group. This is a group of over 110 individuals who have collaborated to stay informed about ocean acidification, and the group is currently managed by the Island Institute.

The commission encourages broader and more active participation in these groups to share information about the latest educational opportunities, research findings, mitigation, remediation and adaptation strategies related to ocean acidification. The commission also supports continuing Maine's representation within the Northeast Coastal Acidification Network.

5.4. Develop, adapt and use curricula on ocean acidification in K-12 schools and institutes of higher education and increase interdisciplinary university programs to equip young leaders with the skills to find solutions to complex multidisciplinary problems such as ocean acidification.

Maine educators should be encouraged to include curricula related to ocean acidification in their K-12 classrooms and college level courses. Ocean acidification educational efforts should include hands-on experimentation and exploration at all age levels, making the subject more engaging. Where possible, students should be encouraged to participate in Maine's volunteer monitoring efforts and to join citizen volunteer groups to learn about this issue first-hand.

There are existing ocean acidification materials available from multiple sources on the Internet. To promote the most efficient and effective uses of these materials they should be compiled into one database that is readily available to teachers who will be able to select materials suitable to their class. Prior to inclusion in the central database, the materials should be evaluated and revised if necessary to make sure they are aligned with the *National Next Generation Science and Common Core Standards.* The easier it is for educators to incorporate ocean acidification materials into their required curricula, the more likely they are to do so.

Educational, research and non-profit organizations around Maine, including but not limited to, the Maine Sea Grant, the Gulf of Maine Research Institute, the Gulf of Maine Marine Education Association, Bigelow Laboratory for Ocean Sciences and the Island Institute could hold symposia for educators to learn more about ocean acidification and how they can incorporate ocean acidification lessons into their curricula. Such events could also serve to connect students directly with researchers. Maine Sea Grant may provide funding to support low-cost, big-impact school and community partnerships. The creation of university programs, such as the University of Maine's School for Marine Sciences Dual Master's Degree program that link marine policy and marine science education should be encouraged.

Goal 6: Maintain a Sustained and Coordinated Focus on Ocean Acidification

The state's effectiveness in addressing the impacts of changing ocean chemistry and acidification on our marine ecosystems and coastal communities requires sustained leadership and support by the Governor and other state officials and an entity to coordinate and facilitate implementation of the commission's recommendations. The commission's recommendations touch on a wide range of ocean and coastal activities involving multiple entities. Coordinating all actions related to ocean health and coastal resources, including collaboration among scientists and decision-makers, should minimize redundancies and inefficiencies.

Recommendation

6.1. Create an ongoing ocean acidification council.

The commission strongly recommends the creation of an on-going ocean acidification council to facilitate its recommendations and to accomplish the following goals:

1. Establish partnerships with state agencies involved with ocean acidification matters;

2. Coordinate the implementation of the commission's recommendations with other ocean and coastal actions;

3. Incorporate refinements and updates to the recommendations according to the latest science on ocean acidification;

4. Bridge ocean acidification related science and policy needs by supporting continued productive interaction between scientists and policymakers;

5. Coordinate with other states and key federal agencies, including the National Oceanographic and Atmospheric Administration, the Environmental Protection Agency and the Department of the Interior and work within the framework of the National Ocean Policy and with the National Ocean Council, the Northeast Regional Planning Body, the Northeast Regional Ocean Council and the Northeast Coastal Acidification Network, while sharing data with the Northeast Ocean Data Portal.[14] This can be done by developing memoranda of understanding or other mechanisms among partners to support data sharing, collaboration and leveraging and prioritizing of funding;

6. Identify and promote economic development opportunities afforded by ocean acidification through development and commercialization of new technologies and businesses; and

7. Build public awareness, support and engagement to advance public understanding of the importance of a healthy ocean and of the most pressing challenges facing the ocean and to engage citizens and various stakeholders in the development of and support for actions and solutions needed to address those challenges.

V. PROPOSED LEGISLATION

The commission strongly believes that an ongoing entity must be created to implement its goals and recommendations. Ocean acidification is a long-term issue that will evolve in ways this commission cannot foresee or have the ability to address during its limited existence. The creation of an ongoing ocean acidification council is therefore paramount to protecting our commercially valuable species from the deleterious effects of acidification. The commission's proposed legislation can be found in Appendix D.

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[14] The Northeast Ocean Data Portal is a decision support and information system which provides centralized access to ocean data, interactive maps, tools and other information to a broad range of government and non-government entities, scientists, and other ocean stakeholders. See http://northeastoceandata.org.

APPENDIX A

Authorizing Legislation
Resolve 2013, Chapter 110

Resolve, Establishing the Commission to Study the Effects of Coastal and Ocean Acidification and Its Existing and Potential Effects on Species That Are Commercially Harvested and Grown along the Maine Coast

Emergency preamble. Whereas, acts and resolves of the Legislature do not become effective until 90 days after adjournment unless enacted as emergencies; and

Whereas, the Commission To Study the Effects of Coastal and Ocean Acidification and Its Existing and Potential Effects on Species That Are Commercially Harvested and Grown along the Maine Coast is established to identify the actual and potential effects of coastal and ocean acidification on commercially valuable marine species, to identify the scientific data and knowledge gaps that hinder Maine's ability to craft policy and other responses to coastal and ocean acidification and prioritize the strategies for filling those gaps and to provide policies and tools to respond to the adverse effects of coastal and ocean acidification on commercially important fisheries and Maine's shellfish aquaculture industry; and

Whereas, the study must be initiated before the 90-day period expires in order that the study may be completed and a report submitted in time to be considered in the next legislative session; and

Whereas, in the judgment of the Legislature, these facts create an emergency within the meaning of the Constitution of Maine and require the following legislation as immediately necessary for the preservation of the public peace, health and safety; now, therefore, be it

Sec. 1 Commission established. Resolved: That, notwithstanding Joint Rule 353, the Commission To Study the Effects of Coastal and Ocean Acidification and Its Existing and Potential Effects on Species That Are Commercially Harvested and Grown along the Maine Coast, referred to in this resolve as "the commission," is established; and be it further

Sec. 2 Commission membership. Resolved: That the commission consists of the following members:

1. Two members of the Senate appointed by the President of the Senate, including one member from each of the 2 parties holding the largest number of seats in the Legislature;

2. Three members of the House of Representatives appointed by the Speaker of the House, including at least one member from each of the 2 parties holding the largest number of seats in the Legislature;

3. Eight members appointed by the Commissioner of Marine Resources, including:

A. Two representatives of an environmental or community group;

B. Three persons who fish commercially, including at least one aquaculturist; and

C. Three scientists who have studied coastal or ocean acidification; and

4. Three members as follows:

A. The Commissioner of Marine Resources or the commissioner's designee;

B. The Commissioner of Environmental Protection or the commissioner's designee; and

C. The Commissioner of Agriculture, Conservation and Forestry or the commissioner's designee; and be it further

Sec. 3 Chairs. Resolved: That the first-named Senate member is the Senate chair and the first-named House of Representatives member is the House chair of the commission; and be it further

Sec. 4 Appointments; convening of commission. Resolved: That all appointments must be made no later than 30 days following the effective date of this resolve. The appointing authorities shall notify the Executive Director of the Legislative Council once all appointments have been completed. After appointment of all members, the chairs shall call and convene the first meeting of the commission within 45 days. If 30 days or more after the effective date of this resolve a majority of but not all appointments have been made, the chairs may request authority and the Legislative Council may grant authority for the commission to meet and conduct its business; and be it further

Sec. 5 Duties. Resolved: That the commission shall meet a minimum of 4 times to review, study and analyze existing scientific literature and data on coastal and ocean acidification and how it has affected or potentially will affect commercially harvested and grown species along the coast of the State and shall address:

1. The factors contributing to coastal and ocean acidification;

2. How to mitigate coastal and ocean acidification;

3. Critical scientific data and knowledge gaps pertaining to coastal and ocean acidification as well as critical scientific data and knowledge gaps pertaining to the effects of coastal and ocean acidification on species that are commercially harvested and grown along Maine's coast. The commission shall include in its review of the relevant scientific literature and data the results of studies presented at conferences or workshops held in the New England or Northeast region that relate to coastal and ocean acidification, and the commission shall coordinate with the Northeast Coastal Acidification Network to prevent duplication of effort;

4. Steps to strengthen existing scientific monitoring, research and analysis regarding the causes of and trends in coastal and ocean acidification; and

5. Steps to take to provide recommendations to the Legislature and increase public awareness of coastal and ocean acidification; and be it further

Sec. 6 Staff assistance. Resolved: That the Legislative Council shall provide necessary staffing services to the commission; and be it further

Sec. 7 Outside funding. Resolved: That the commission shall seek funding contributions of $1,500 to fund the costs of the study in fiscal year 2014-15. All funding is subject to approval by the Legislative Council in accordance with its policies. If $1,500 to fund the study has not been received by July 1, 2014, no meetings are authorized and no expenses of any kind may be incurred or reimbursed in fiscal year 2014-15; and be it further

Sec. 8 Report. Resolved: That, no later than December 5, 2014, the commission shall submit a report of its findings and recommendations to date, including suggested legislation, to the joint standing committee of the Legislature having jurisdiction over marine resources matters. The joint standing committee is authorized to submit a bill to the First Regular Session of the 127th Legislature related to the subject matter of the report.

Emergency clause. In view of the emergency cited in the preamble, this legislation takes effect when approved.

APPENDIX B

Membership List

Commission to Study the Effects of Coastal and Ocean Acidification and Its Existing and Potential Effects on Species that are Commercially Harvested and Grown Along the Maine Coast

Resolve, Chapter 110

Tuesday, July 15, 2014

Appointment(s) by the President

Sen. Christopher K. Johnson – Chair 3230 Turner Ridge Road Somerville, ME 04348 207-632-6066 chris@dirigo.net	Senate Member
Sen. Brian D. Langley 11 South Street Ellsworth, ME 04605 207-667-0625 SenBrian.Langley@legislature.maine.gov	Senate Member

Appointment(s) by the Speaker

Rep. Michael Gilbert Devin – Chair 1 Hillcrest Road Newcastle, ME 04553 207-975-3132 mick@mickdevin.org	House Member
Rep. Wayne R. Parry 851 Alfred Road Arundel, ME 04046 207-286-9145 RepWayne.Parry@legislature.maine.gov	House Member
Rep. Joan W. Welsh 54 Sea Street Rockport, ME 04856 207-236-6554 joanwelsh08@gmail.com	House Member

Commissioner, Department of Agriculture, Conservation & Forestry

Kathleen Leyden Director, Maine Coastal Program Department of Agriculture, Conservation & Forestry 93 SHS Augusta, ME 04333-0093 207-287-3144 kathleen.leyden@maine.gov	Commissioner's designee

Commissioner, Department of Environmental Protection

Susanne Miller
Director, Eastern Maine Regional Office
Department of Environmental Protection
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Commissioner's designee

Commissioner, Department of Marine Resources

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Representing an environmental or community group

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Scientists who have studied coastal or ocean acidification

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Scientists who have studied coastal or ocean acidification

Dr. Meredith White
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Scientists who have studied coastal or ocean acidification

Dr. Mark A. Green
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278 Whites Bridge Road
Standish, ME 04084
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mgreen@sjcme.edu

Representing commercial fisherman, at least 1 aquaculturist

Jon Lewis Aquaculture Environmental Coordinator Department of Marine Resources PO Box 8 West Boothbay, ME 04575 207-633-9594 jon.lewis@maine.gov	Designee
Bill Mook Mook Sea Farm 321 State Route 129 Walpole, ME 04573 207-563-1456 bill@mookseafarm.net	Representing commercial fisherman, at least 1 aquaculturist
Richard Nelson F/V Pescadero PO Box 62 Friendship, ME 04547 207-832-6972 fvpescadero@yahoo.com	Representing commercial fisherman, at least 1 aquaculturist
Joe Payne Casco Baykeeper Friends of Casco Bay 43 Slocum Drive So. Portland, ME 04106 207-799-8574 jpayne@cascobay.org	Representing an environmental or community group

Staff:
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Office of Policy and Legal Analysis

APPENDIX C

State of the Science, Research and Monitoring Priorities Subcommittee Report

Maine Ocean Acidification Commission

State of the Science, Research and Monitoring Priorities Subcommittee Report

The full commission wishes to thank the members of its subcommittee, the State of the Science, Research and Monitoring Priorities Subcommittee for its invaluable contributions in producing this report. Subcommittee members include Dr. Suzanne N. Arnold, Dr. Mark A. Green, Dr. Lawrence M. Mayer, Bill Mook, Dr. Joseph E. Salisbury and Dr. Meredith M. White.

1. Introduction

Ocean acidification (OA), refers to the processes that lower the pH[15] of ocean water and is proceeding globally at an increasing rate. In the Gulf of Maine, OA arises from the combination of several processes. The best-understood and documented process is caused by the uptake of carbon dioxide (CO_2) from the atmosphere by the ocean, which takes up about 25% of atmospheric carbon dioxide (Le Quéré et al. 2014). This uptake has increased in recent decades due to increasing fossil fuel use. The atmospheric CO_2 concentration has increased at a geologically unprecedented rate since the beginning of the industrial revolution (Figure 1), resulting in a 30% increase in the average acidity of ocean waters (Orr et al. 2005), although the majority of that increase has occurred since about 1950 (Le Quéré et al. 2014). Preliminary analyses of CO_2 data in the Gulf of Maine suggest this increase is proceeding at a rate of 1.2 ppm per year (Figure 2).

The increased atmospheric input of CO_2 can explain the observed multidecadal change in acidity of the seawater. The Gulf of Maine is colder than most coastal areas in the United States, making carbon dioxide more soluble and enhancing this uptake. Colder waters are projected to acidify sooner from this atmospheric source than warmer waters (Orr et al. 2005). This increase is superimposed on daily and seasonal variations in carbon dioxide due to biological processes. Coastal and marginal waters such as Maine's estuaries, however, show more intense CO_2 variations than the open ocean due to greater influences of river flow, physical circulation, and nutrient inputs (Waldbusser & Salisbury 2014; Wang et al. 2013).

A more acidic ocean will not kill every marine species. However, the well documented, global increase in acidity is already affecting some marine species. As the ocean continues to acidify, more and more species will be impacted. One group of organisms that will be most heavily affected by an acidifying ocean is those that calcify or produce calcium carbonate hard parts. Calcium carbonate ($CaCO_3$) producing organisms include a diverse array of ocean life and include coral reefs (warm water and cold water corals similar to those found in Maine), crustaceans (lobsters, crabs, shrimp), mollusks (mussels, oysters, clams, scallops), echinoderms (sea urchins and starfish), calcareous macroalgae (some seaweeds) and plankton (pteropods, microalgae such as coccolithophores). Shells built out of $CaCO_3$ are particularly sensitive to

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[15] pH is a measure of the acidity or basicity of an aqueous solution. (See the glossary for further information.)

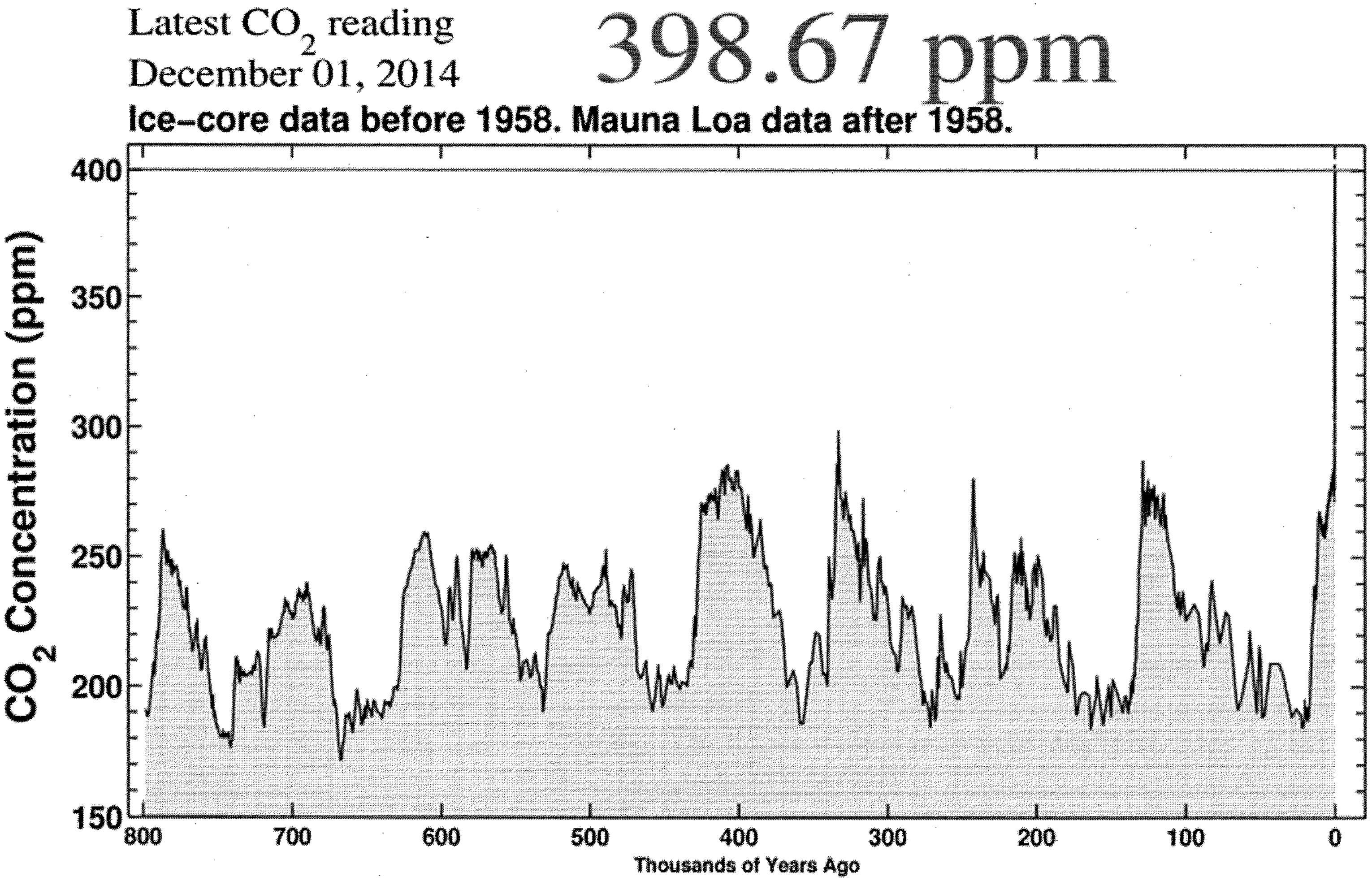

Figure 1. Atmospheric CO_2 concentration (ppm). Data prior to 1958 are measured from ice cores, data after 1958 were measured by Scripps Institution of Oceanography at the Mauna Loa Observatory in Hawaii. (Figure courtesy of Scripps Institution of Oceanography; https://scripps.ucsd.edu/programs/keelingcurve/wp-content/plugins/sio-bluemoon/graphs/co2_800k.png)

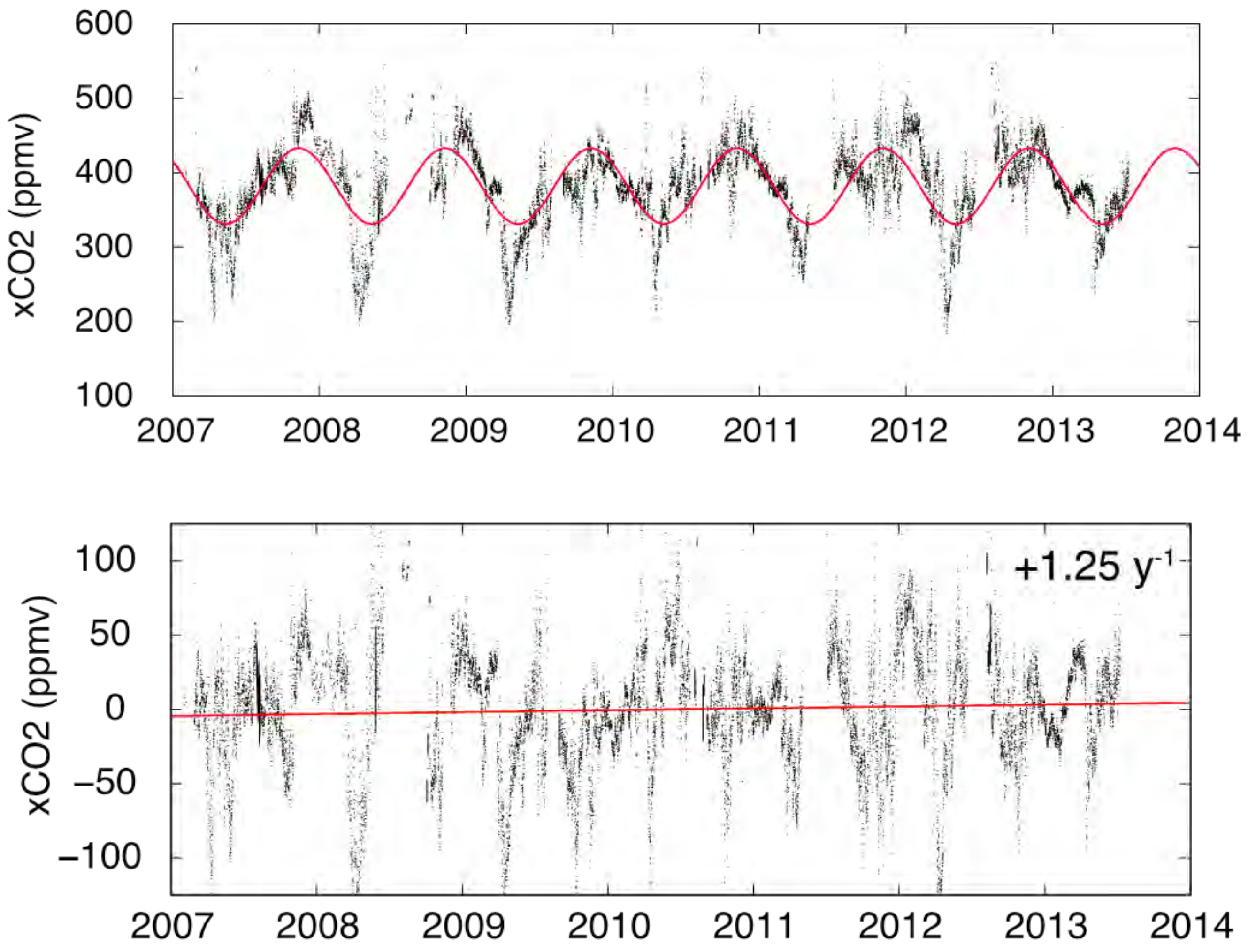

Figure 2. (Top Panel) Preliminary ocean surface mole fraction of CO_2 (xCO_2) data from the UNH-NOAA NERACOOS Acidification Buoy in the Gulf of Maine from 2007-2014. The red line is fitted to the data and highlights the seasonal cycle of xCO_2 **(Bottom Panel)** Data from the top panel are statistically reworked to remove seasonal patterns that occur each year. The trends in the residuals (redline) are positive for both parameters, with pCO_2 increasing 1.25 ± 0.34 ppm per year. During this time period, the atmospheric xCO_2 data from the NOAA Mauna Loa Observatory increased at a rate of 2.2 ppm per year. (Data from the UNH-PMEL-NERACOOS Acidification Buoy.)

changes in pH, with more acidic conditions making the formation of $CaCO_3$ in seawater considerably more difficult. Although the precise mechanisms of calcification are species-specific, and in some cases not well understood, calcification can be expressed in the most basic form as:

$$\text{Calcification: } Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$$

To make $CaCO_3$, organisms must combine ions of Ca^{2+} and CO_3^{2-} from seawater. The Ca^{2+} and CO_3^{2-} can combine to form different crystal structures, complicated by the addition of other ions from seawater (for example Mg^{2+}), resulting in different forms of $CaCO_3$, such as calcite, aragonite, high-magnesian calcite, and amorphous calcium carbonate. The solubility of these different forms of $CaCO_3$ is different with amorphous calcium carbonate being the most soluble, followed by high-magnesian calcite, aragonite and then calcite. So, the chemical type of $CaCO_3$ that an organism secretes will dictate the severity of acidification effects. In many parts of the ocean it is well-documented that high-magnesiam calcite and aragonite-bearing organisms are already being negatively impacted.

Just as Ca^{2+} is 'attracted' to CO_3^{2-}, so are hydrogen ions (H^+). However, H^+ has a greater affinity for CO_3^{2-} than Ca^{2+} does. As the ocean becomes more acidic and the concentration of H^+ increases, it will bind with CO_3^{2-} forming what is known as bicarbonate, HCO_3^-. As more of the carbonate ion (CO_3^{2-}) disappears from seawater it becomes less available for marine calcifiers to build and grow new shell. Even if there is enough CO_3^{2-} for shell formation, the diminishing amount means that more energy will be required for shell building in addition to energy normally allocated to activities like movement, reproduction, and feeding. The resulting metabolic stress may jeopardize survival. With the continued depletion of available CO_3^{2-} resulting from acidification, there reaches a tipping point where the $CaCO_3$ already formed by some organisms will actually start to dissolve.

These impacts on $CaCO_3$ make it important to assess the factors that control acidification throughout the Gulf of Maine and its estuarine embayments, which are essential habitats for many of Maine's commercial species. In this report we examine the aspects of this ocean environment that control pH variations.

2. Research and Monitoring Priorities

Adaptation to and mitigation of ocean acidification must rely on knowing how, where and when coastal waters reach dangerous levels of acidification. Acidification may result from local or regional causes, and we do not know their relative importance in inshore regions of the Gulf of Maine. We must therefore assess coastal patterns in the present day, using a range of measurement technologies and sampling approaches. Because we have no good records of acidification over time, we must reach into the past by studying either pH variations directly or processes related to them such as oxygen depletion. For example, emerging isotope techniques might be applied to fossil or long-lived organisms, analogous to the use of tree rings. Last, we must predict future acidification trends using present-day data coupled to models of the future. These models need to be validated and kept updated via consistent testing with new data.

Water inputs to the Gulf of Maine from atmospheric, freshwater, and oceanic sources need more attention, because they create the environment in which Maine's commercial species live. While there is good understanding of the fundamental properties and processes that control pH in such waters, there is much less information about how they are manifested in Maine's waters. Both water column and sedimentary environments should be studied, focusing on areas where vulnerable life stages of Maine's commercial species are found. By using combined chemical, biological and other oceanographic approaches, we can link observations of water quality with impacts on marine organisms.

There is a dearth of information on the impact of acidification on Maine's commercial species, especially under environmental conditions found in Maine. These impacts may occur in direct and indirect ways. Direct impacts on species should be studied in well-controlled experimental systems capable of evaluating the combined effects of climate change parameters such as dissolved oxygen and temperature. These studies should include aspects of both physiology and behavior. Other studies should address whether the impacts found in experiments appear in organisms in the wild. Acidification may also affect ecosystems in ways that indirectly affect commercially important species. For example, plankton that serve as food may change in quality or quantity, or disease-causing organisms may become prevalent. Studies of overall impacts of acidification on commercial species must remain sensitive to these possibilities.

2.1. Specific Research and Monitoring Priorities

1. Monitor/sample watershed fluxes of materials affecting pH and the carbonate system. These materials include carbon compounds and nutrients such as nitrogen.

2. Resolve the acidification attributable to nitrogen and phosphorus fluxes.

3. Monitor the carbonate system of inshore and offshore water column and benthic habitats.

4. In conjunction with water quality/carbonate chemistry data collection, monitor larval abundance and recruitment success for commercially important shellfish species.

5. Modeling and laboratory based efforts to understand how or if OA affects our most important species (lobsters, Jonah crabs, spider crabs and rock crabs, sea scallops, elvers and other finfish, sandworms and blood worms).

6. More in-depth experiments including multi-stressors, multiple life stages/multiple generations or predator-prey interaction studies.

7. Research into mitigation, specifically regarding sediment buffering, algal growth and harvest (phytoremediation techniques to better understand the mitigation potential provided by upland and marine vegetation) and animal rearing.

8. Experiments to provide better mechanistic understanding of how OA impacts marine organisms.

3. Acidification of Maine Waters: Causes and Trends

Maine's commercial species live in its estuaries and in the open Gulf of Maine. These ocean waters are replenished by a considerable tidal range but are somewhat separated from the open Atlantic Ocean by Georges Bank and Brown's Bank. Within the Gulf, the waters slowly circulate in large currents such as the Maine Coastal Current, which flows in a southwestern direction along the coast. Contributions from rivers and streams flowing into the Gulf of Maine through its estuaries are entrained in this current as it moves from northeast to southwest (Pettigrew et al. 2005). These inshore, estuarine waters do not have a consistent boundary with the open Gulf of Maine in an environmental sense, unlike legal definitions that use a fixed distance from land. The influence of freshwater from rivers affects acidification but varies enormously along Maine's coastline with its complicated shape and rivers of different size whose flow varies seasonally. We therefore use the term "inshore" in a relative sense, seeking to emphasize inshore influences of embayment and low salinity. Likewise, the term "offshore" implies open water conditions away from protective coastline and/or river inputs.

3.1. Freshwater Influences

3.1.1. Gulf of Maine Watersheds

Watersheds in the lands surrounding the Gulf of Maine supply acidity (H^+) to the ocean. The rivers and streams of Maine generally have lower pH values than are found in marine waters (Hunt et al. 2011; Figure 3). This is caused by several factors. Rainwater itself has low pH, due to the dissolution of atmospheric carbon dioxide, nitrate and sulfate, some of which have resulted from fossil fuel combustion. While sulfate and nitrate emissions and subsequent deposition in New England have decreased over the past three decades, the rise in pH of stream waters that would be expected from this trend has not materialized (Strock et al. 2014). It is most likely that the acidity of stream waters persists due to lag effects in soils, such as release of acidic organic substances or buffering of pH by aluminum compounds in soils. Indeed, surveys show considerable contribution of dissolved organic matter to the pool of potentially acidic compounds introduced to estuaries (Hunt et al. 2011). Other climatic and land-use factors may also be involved in this persistent acidification; for example, higher-intensity storm systems bring sea salt onto land as does increased use of road salt (Rosfjord et al. 2007). These added salts tend to enhance release of acidic organic substances from soils, and lower the pH of streamwater (Heath et al. 1992).

Surveys of tea-colored compounds (also known as *gelbstoff* or *colored dissolved organic matter*) in the waters of the Gulf of Maine (Balch et al. 2012) suggest that increased amounts of organic matter are being delivered to the ocean by streams due to some combination of increased rainfall or increased concentration of tea-colored compounds in the stream water. These compounds may provide extra acidity; they also provide competition for light that would otherwise be used for phytoplankton production.

As mentioned above, a principal threat of ocean acidification results from changes in the ability of calcareous organisms to precipitate their shells. The ability to calcify depends on the amounts of dissolved calcium and carbonate ions in the water. Freshwater dilution of seawater in the

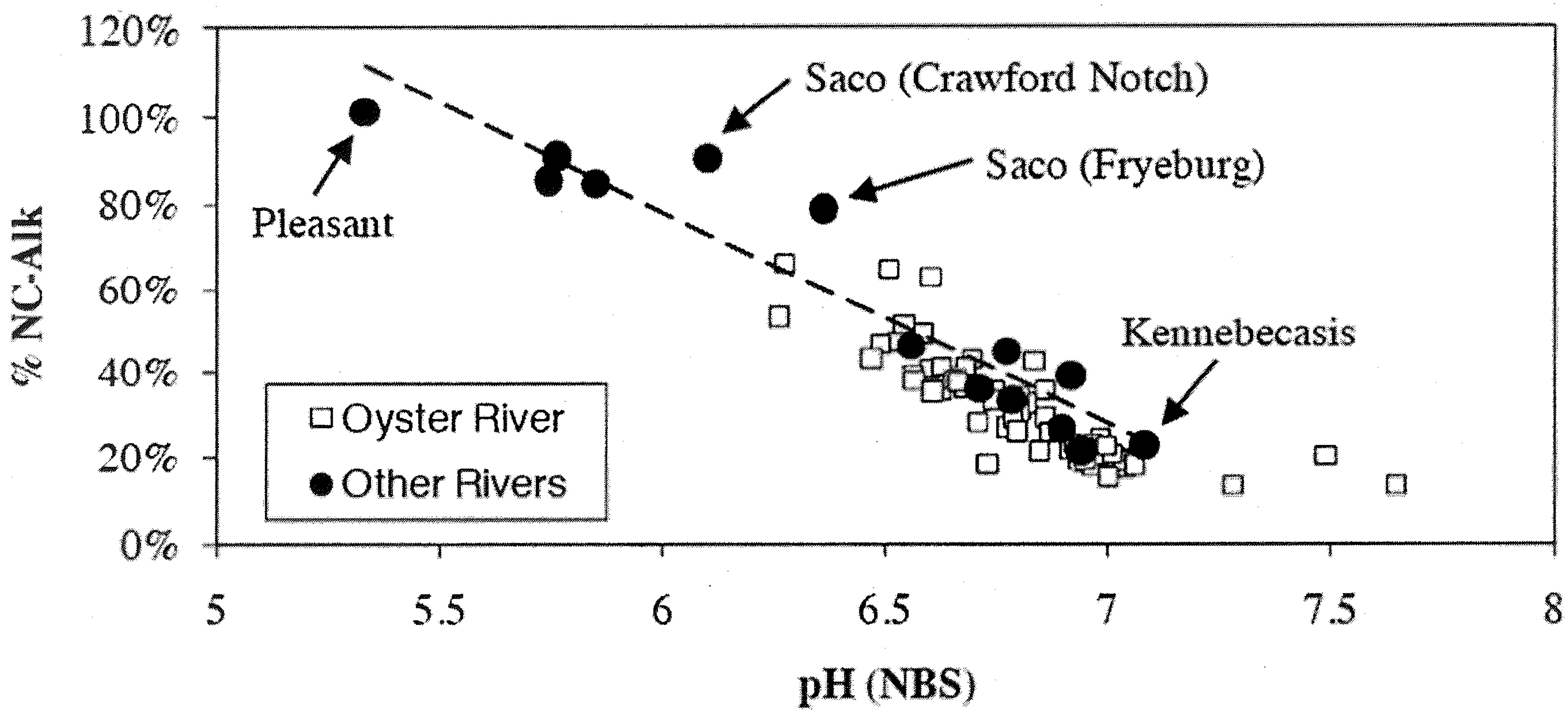

Figure 3. Relationship between pH (measured in the lab) and the calculated percentage of non-carbonate alkalinity (NC-Alk) in the Oyster River and in the sampled rivers in northern New England and Canada (Other Rivers). The dotted line shows the linear regression of the Other Rivers, having the equation %NC-Alk = −0.5*pH + 379. Copyright Hunt et al. 2011. This figure is distributed under the Creative Commons Attribution 3.0 License.

inshore regions affects this ability in two ways. First, by lowering pH it shifts the form of dissolved inorganic carbon to one that is less favorable for shell formation (i.e., it removes carbonate ions). In this manner it has an impact similar to that of acidification from carbon dioxide released to the atmosphere by fossil fuel combustion. Second, freshwaters in Maine contain less dissolved calcium and carbonate than seawater (Salisbury et al. 2008), and these freshwater concentrations vary among Maine rivers by as much as a factor of ten (Hunt et al. 2011). River pH, dissolved calcium, and carbonate values all vary along the coast, which affects the ability of marine organisms to form shells. These variations are caused by the type of bedrock in the watershed, neutralization of acidic rainwater by soil processes such as chemical weathering, and the extent to which this neutralization occurs among watersheds. This variability will control the degree to which the dilution of seawater by river waters will affect calcareous shell formation (Figure 4). Estuarine waters become undersaturated for shell formation at the lower salinities encountered in many Maine estuaries (Figure 5). There is sufficient chemical information on some Maine rivers to estimate these impacts, but better seasonal coverage is needed to better understand impacts on calcification by commercial species.

These freshwater variations will also affect the ability of ocean water to buffer itself against acidification by other processes, such as local estuarine eutrophication. This buffering capacity is controlled by parameters such as the total alkalinity and its makeup by carbonate and non-carbonate, acid-neutralizing compounds. These properties vary among watersheds. We have fewer data on these river variations in pH and acid-neutralizing substances among Maine rivers and even fewer that let us identify changes over time.

Amounts of freshwater entering the Gulf of Maine from its rivers are changing along with other climatic patterns. Warming over the past decades has been accompanied by increased precipitation and runoff (Huntington & Billmire 2014) and frequency of extreme precipitation events (NOAA NCDC; Figure 6). If this trend continues, significant increases in both temperature and seasonal precipitation are projected over the next 50 years (Rawlins et al. 2012; Figure 7).

Changing land use has and will continue to modify freshwater inputs to the Gulf of Maine. As dams are built or removed, the timing of runoff will change. Hardening the landscape during development, or changing agricultural practices will affect how much and how quickly rainfall turns into river flow. These changing freshwater distributions will doubtless affect the land fluxes of acidification-relevant substances and their distribution into receiving coastal waters. Studies of these hydrological impacts are rare in Maine but are emerging in the southwestern part of the state.

Variations in freshwater delivery to Maine's estuaries will change the distribution of salinity in these systems. These salinity distributions vary on many time scales, from hourly changes due to tides, up to decadal ones influenced by climate. While many salinity distributions have been measured in Maine's estuaries, almost all are short-term snapshots taken over several hours on one day, and we lack continuous records of salinity at different sites.

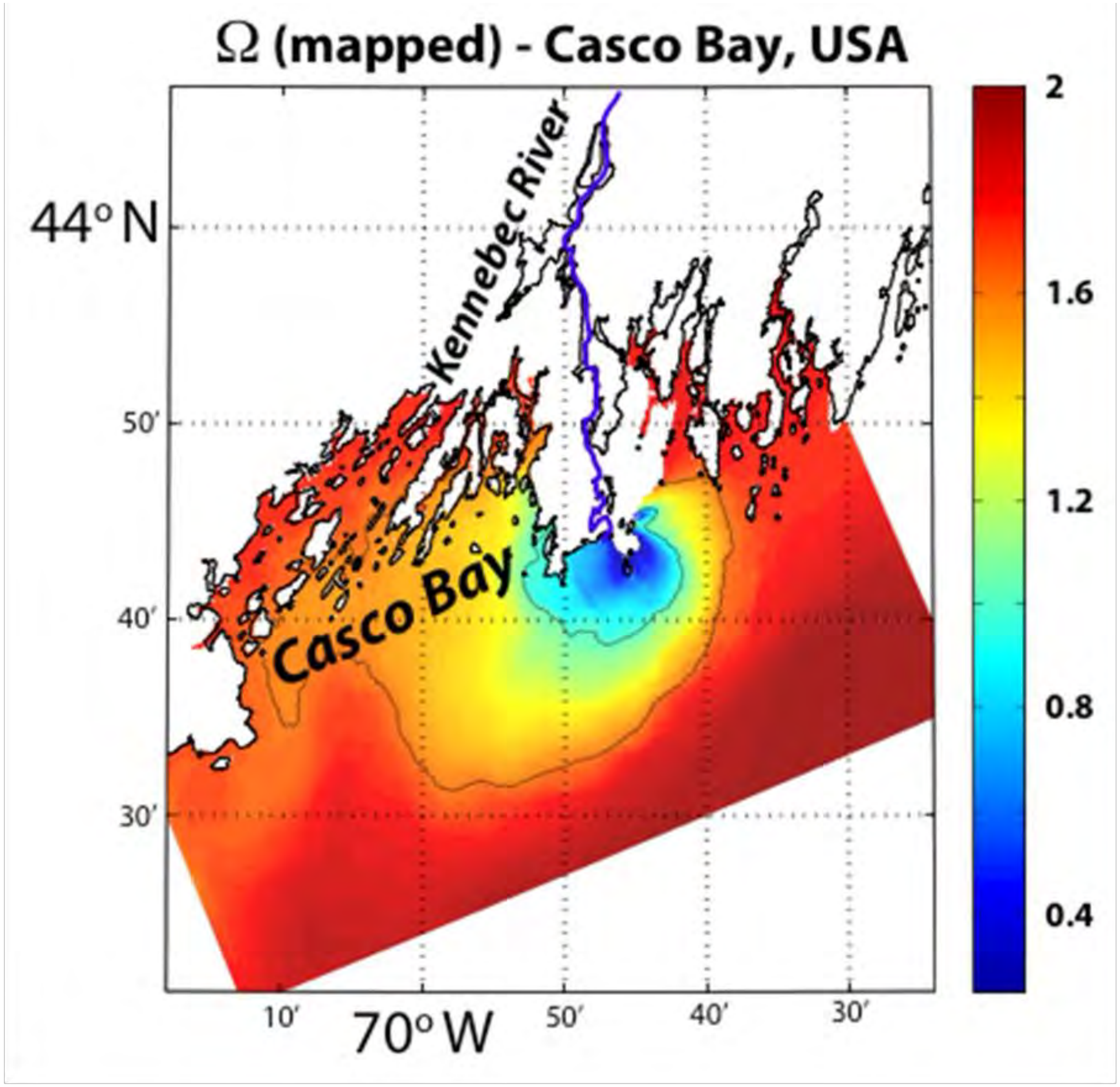

Figure 4. Mapped $\Omega_{aragonite}$ for the surface waters of the Kennebec Plume and Casco Bay, Gulf of Maine on June 20, 2005. Contours of $\Omega_{aragonite} = 1.0$ and $\Omega_{aragonite} = 1.6$ (outer) are shown. The 1.6 contour intersects the outer islands and peninsulas of Casco Bay. The Kennebec is a moderately-sized river system whose average discharge is 438 m^3s^{-1}. (Salisbury et al. 2008. Figure courtesy of American Geophysical Union)

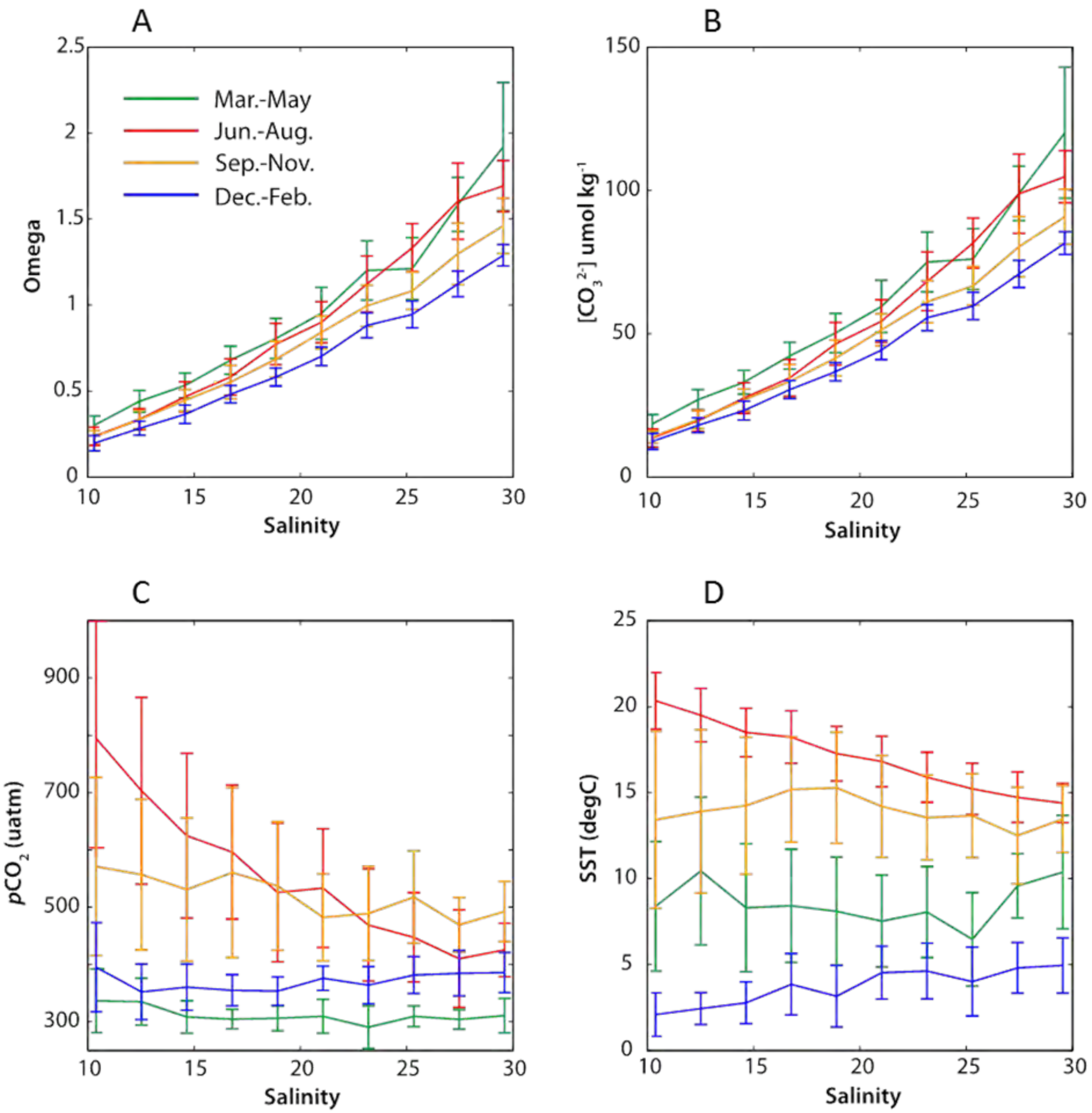

Figure 5. Carbonate parameters in the Kennebec Estuary, Maine (43.8 °N, 68.8 ◦W): (A) surface saturation state (Ω), (B) CO_3^{2-} concentration, (C) pCO_2, and (D) sea-surface temperature (SST). The data are from the University of New Hampshire's coastal transect database of 56 cruises from 2005 to 2009 (Salisbury et al. 2008a) and are averaged by season and salinity bin (2 psu). The Ω (±0.2) and CO_3^{2-} concentration (±2.1 μmol kg^{-1}) values are estimated from under-way salinity, temperature, pCO_2 (±3 μatm), and total alkalinity (±12.6 μmol kg^{-1}) estimated from salinity. Note the dependence of both Ω and CO_3^{2-} concentration on salinity. The remainder of the variability arises from seasonal heating and cooling that affects CO_2 solubility and from net community production that consumes or produces CO_2. (Reproduced with permission of Annual Review of Marine Science, Volume 6 © 2014 by Annual Reviews, http://www.annualreviews.org, Waldbusser & Salisbury 2014)

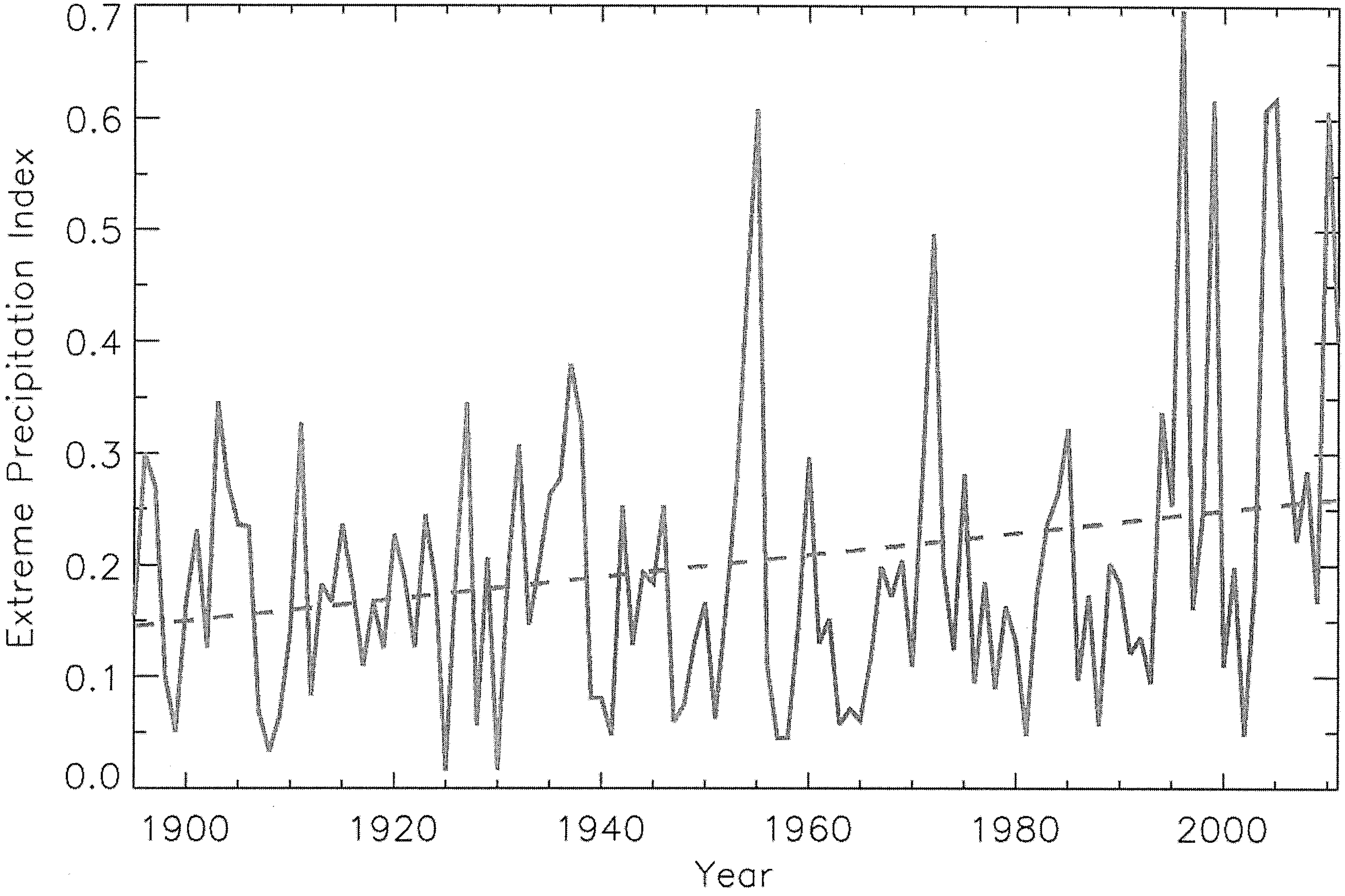

Figure 6. Time series of extreme precipitation index for the occurrence of 1-day, 1 in 5-year extreme precipitation, for the Northeast region. The dashed line is a linear fit. Based on daily COOP data from long-term stations in the National Climatic Data Center's Global Historical Climatology Network data set (Data courtesy of NOAA NCDC).

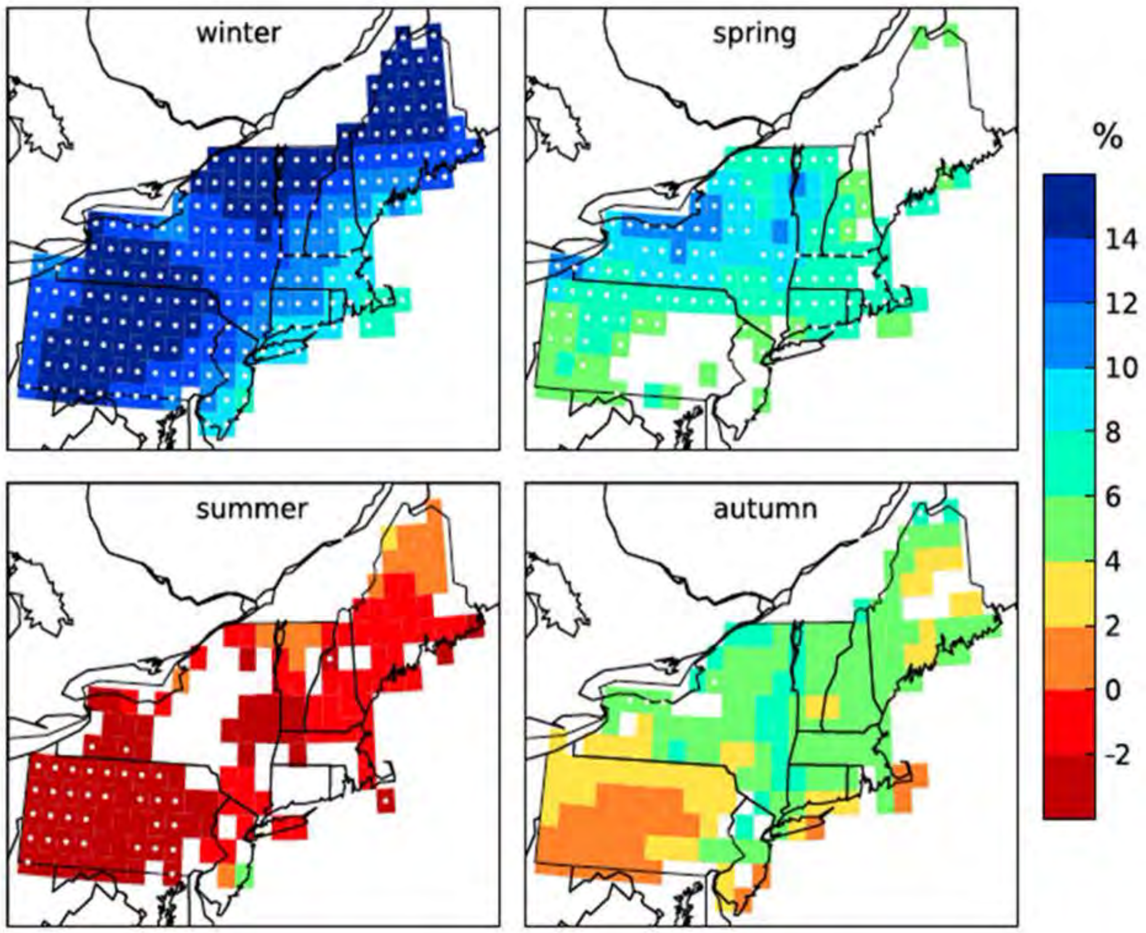

Figure 7. Projected relative percent change (%, $\Delta = P_{2041\text{-}2070} - P_{1971\text{-}2000} * 100\%$) in seasonal precipitation from the ensemble mean of nine model pairs. Units are percent of present-day precipitation. Note that precipitation is projected to increase in winter, spring, and autumn. Precipitation estimates for present and future periods were drawn from regional climate model outputs archived under the North American Regional Climate Change Assessment Program (NARCCAP). (Courtesy of the creators Rawlins et al. 2012)

Salinity has well-established impacts on biota, especially in estuaries, and often controls which organisms can live where. The fresher ends of estuaries are especially well-known as stressful for organisms for reasons besides lower pH, so that changing delivery of freshwater to estuaries will add to stresses imposed by acidification. These upper ends are also the zones most susceptible to dilution of seawater by freshwater flow events, in part because they are shallower and there is less seawater to be diluted. We anticipate especially acute impacts on commercial species living in these upper estuarine zones.

3.1.2. Remote Freshwater Sources

While rivers have a strong effect on estuaries and inshore, they are not the dominant freshwater source to the larger Gulf of Maine. Instead, freshwater input is dominated by watersheds and melting ice toward the north, which arrives as diluted seawater in the form of relatively cold, low salinity Scotian Shelf Waters (Smith 1983; Brown & Irish 1993). Shelf-sea exchanges, which occur largely through the narrow Northeast Channel, also bring in deeper, saltier waters that may come from north or south (Townsend et al. 2010). The mix of these inputs from the Atlantic varies on decadal scales and strongly influences the Gulf of Maine's circulation (Pringle 2006), nutrient levels (Townsend et al. 2010), productivity (O'Reilly et al. 1987) and acidification (Wang et al. 2013; Signorini et al. 2013; Figure 8).

3.2. The Cycle of Photosynthesis and Respiration

The discussion to this point has emphasized external influences on the acidity of the Gulf of Maine. However, most pH variations within its ecosystems are due to the balance between photosynthesis (the creation of organic matter that raises pH by taking up carbon dioxide) and respiration (the conversion of organic matter to energy, which lowers pH by producing carbon dioxide). Indeed the atmospheric CO_2 that is acidifying world oceans today comes from the combustion of organic matter (analogous to respiration) that was photosynthesized millions of years ago and stored as fossilized plant and animal material (e.g., coal and oil). In today's ocean we observe rises in pH when modern phytoplankton bloom in the surface waters. In the daytime when light is abundant, the pH often rises with the sun angle. At night, the pH drops with the waning light as photosynthesis gives way to respiration. This separation in time can also occur in space. Higher pH values are often found at the well-lit surface of the ocean, while lower values are found in darker waters beneath. Any process that separates these two opposing processes – such as time or allowing dead phytoplankton to settle to a different depth before they are respired – will accentuate the swings in pH associated with this biological cycle. Likewise, processes that make the cycle more intense, such as added nutrients, can also widen the pH swings. We next consider the factors that influence this balance.

3.2.1. Nutrient Additions

Addition of nutrients to marine waters enhances their biological productivity by increasing photosynthesis. In small to moderate amounts, the higher productivity can benefit commercial species, but in larger amounts it can result in a variety of negative outcomes that can hurt those same species. Examples of negative outcomes can include harmful algal blooms, eutrophication (severe oxygen depletion stimulated by nutrient enrichment) and acidification of marine bottom

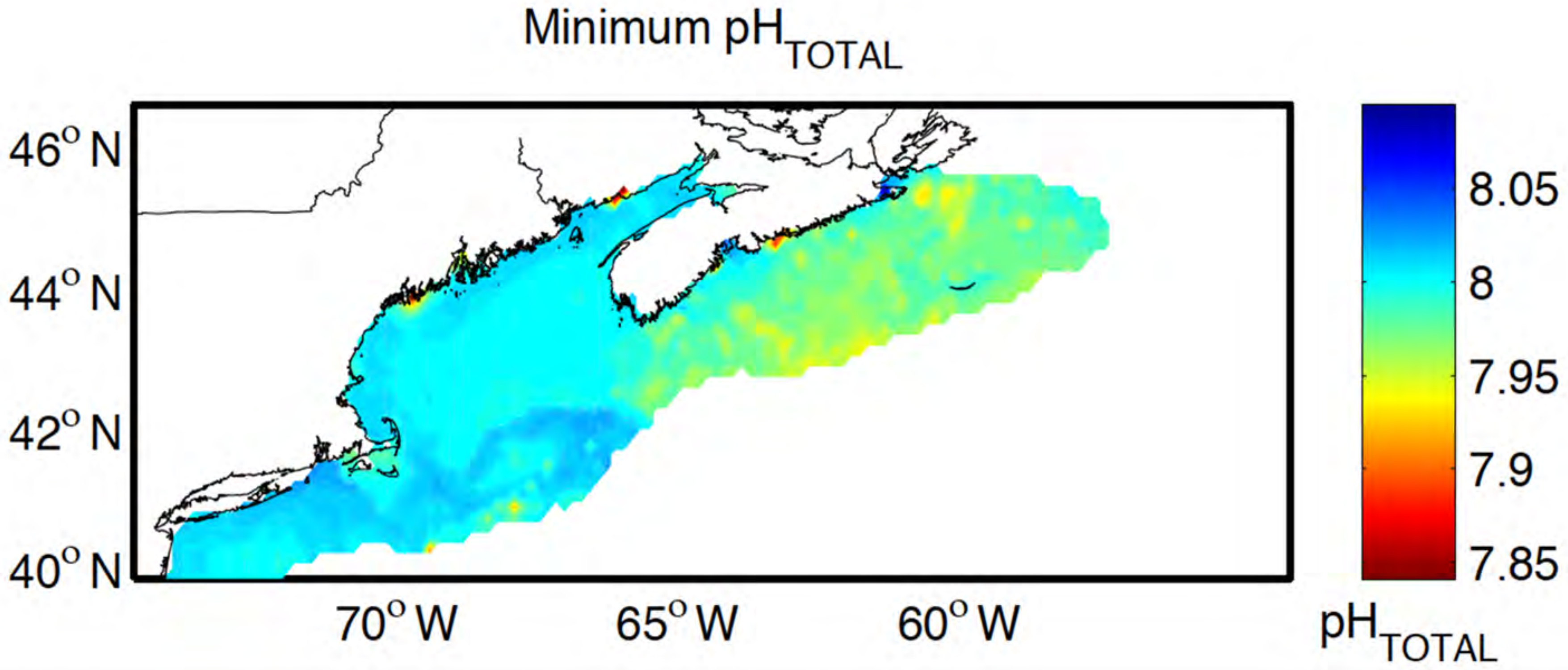

Figure 8. An analysis of data from Signorini et al. (2013) shows that water entering the Gulf of Maine from the Scotian Shelf can have a considerable lower pH than Gulf of Maine waters. (Salisbury & Hunt unpublished)

waters. Combinations of these stresses can be particularly threatening to commercial species. A classic Maine example might be the shellfish die-off in Maquoit Bay in 1988, in which some combination of oxygen depletion and harmful algae is thought to have killed off 30-40% of shellfish within a few days (Heinig & Campbell 1992).

In the simplest case, as noted above, nutrient addition can raise pH in waters by removing carbon dioxide where algae are actively photosynthesizing. Unless the organic matter produced is rapidly and deeply buried in ocean sediments, this pH rise will be local and temporary. Virtually all of the photosynthesized organic matter will return to enrich the waters with carbon dioxide and lower the pH. The question is where and when this will happen.

Scientists often address the question of whether a coastal ecosystem has greater total photosynthesis or respiration, and this question is important for various reasons. However, for the life-cycles of individual species of commercial value it is more important to determine if acidification caused by respiration occurs in isolated times or places that prevent these species from reaching a certain life stage. As discussed below, factors such as physical mixing of the water column are very important in answering this type of question.

Coastal marine ecosystems under high nutrient loading clearly show enhanced cycles of increased and decreased pH in response to photosynthesis and respiration respectively (Nixon et al. 2014). In highly eutrophic estuaries in southern New England, Wallace et al. (2014) found elevated pH in surface waters close to nutrient sources in early-mid summer and decreased pH values in waters that were deeper and later in the season when respiration became more dominant. These trends are evident in their transects from western to eastern Long Island Sound (Figure 9). The ability of calcifying organisms to make shells, expressed as carbonate saturation values ($\Omega_{aragonite}$), ranged from very favorable in zones of active photosynthesis to very unfavorable in the zones of active respiration and oxygen depletion. It is therefore the latter conditions to which we must be attentive.

As with direct additions of acidity to estuaries, nutrient inputs vary in quality and quantity. For the purposes of this review, human-derived nutrients are of special concern. It is clear that concentrations of nutrients in rivers respond to human population density in the watershed and the burden of the atmospheric nitrogen deposited throughout the watershed. The export of nitrogen from land to sea, per area of watershed, tends to follow the population gradient along Maine's coast (Figure 10). Direct flow of nutrients to coastal waters (e.g., sewage outfalls or atmospheric deposition) adds to these riverine contributions. Further direct deposition to coastal waters, which occurs in both wet and dry phases, can be highly episodic and thus difficult to characterize. For example, storm events providing nutrients in excess of 1mmol N m^{-2} d^{-1} have been reported in the coastal Gulf of Maine (Jordan & Talbot 2000), and these events were associated with increased phytoplankton growth.

While eutrophication histories of Maine estuaries are poorly documented, data suggest significant nutrient additions beginning over a century ago (Koster et al. 2007). However, it also appears that nitrogen and phosphorus delivery to the coastal zone across the Northeast has decreased over at least the last decade or two (Hale et al. 2013). Nitrogen and phosphorus concentrations in the Merrimack River have strongly decreased over recent decades (Robinson et

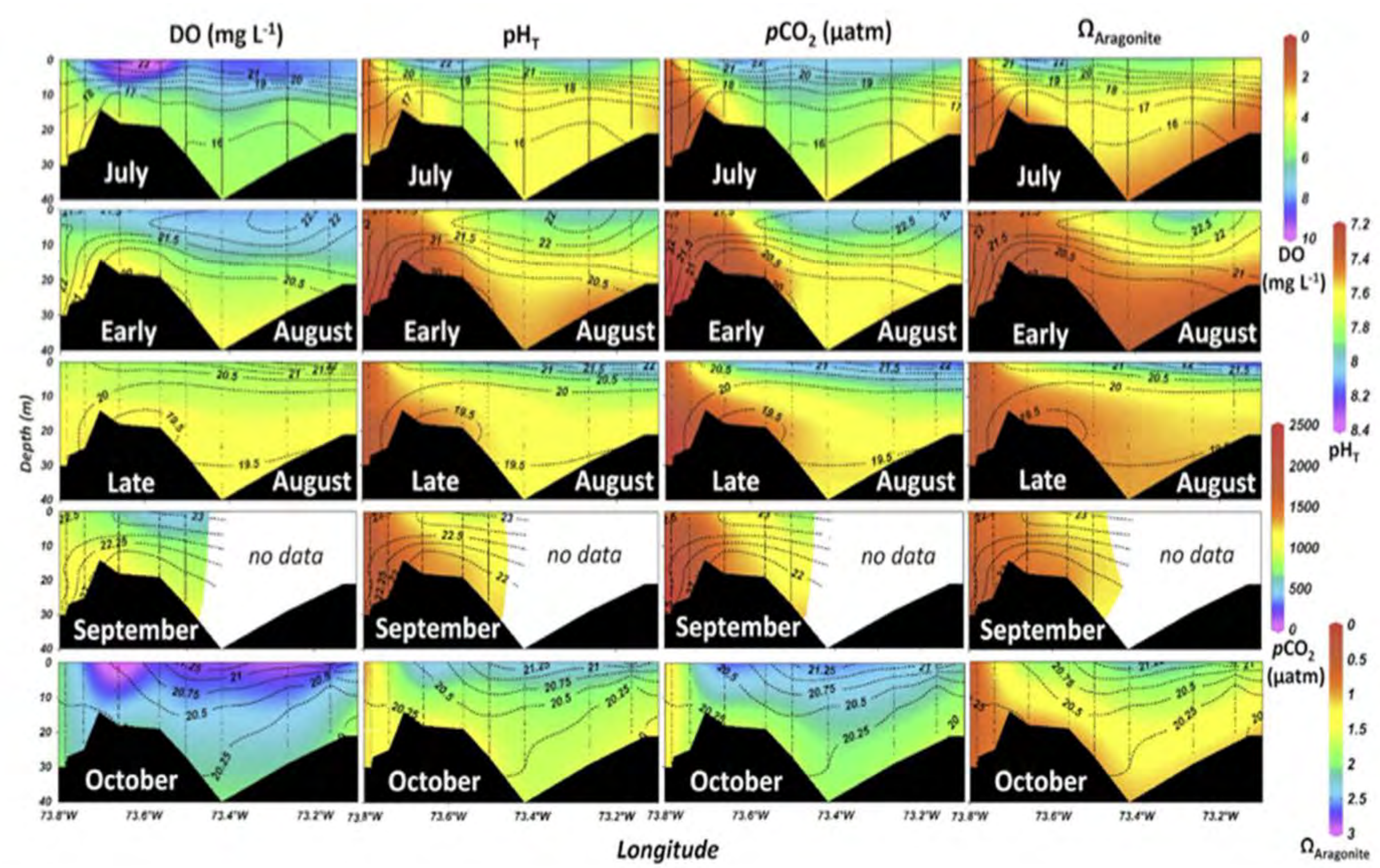

Figure 9. Monthly vertical section plots of dissolved oxygen, pH, pCO_2, and $\Omega_{aragonite}$ with temperature (°C) contour lines during July, early August, late August, September, and October of 2013 in Long Island Sound. Vertical lines represent CTD profiles. Depth is 0-40 m. (Reprinted from Estuarine, Coastal and Shelf Science, Volume 148, Wallace et al., Coastal ocean acidification: The other eutrophication problem, pages 1-13, © 2014 with permission from Elsevier.)

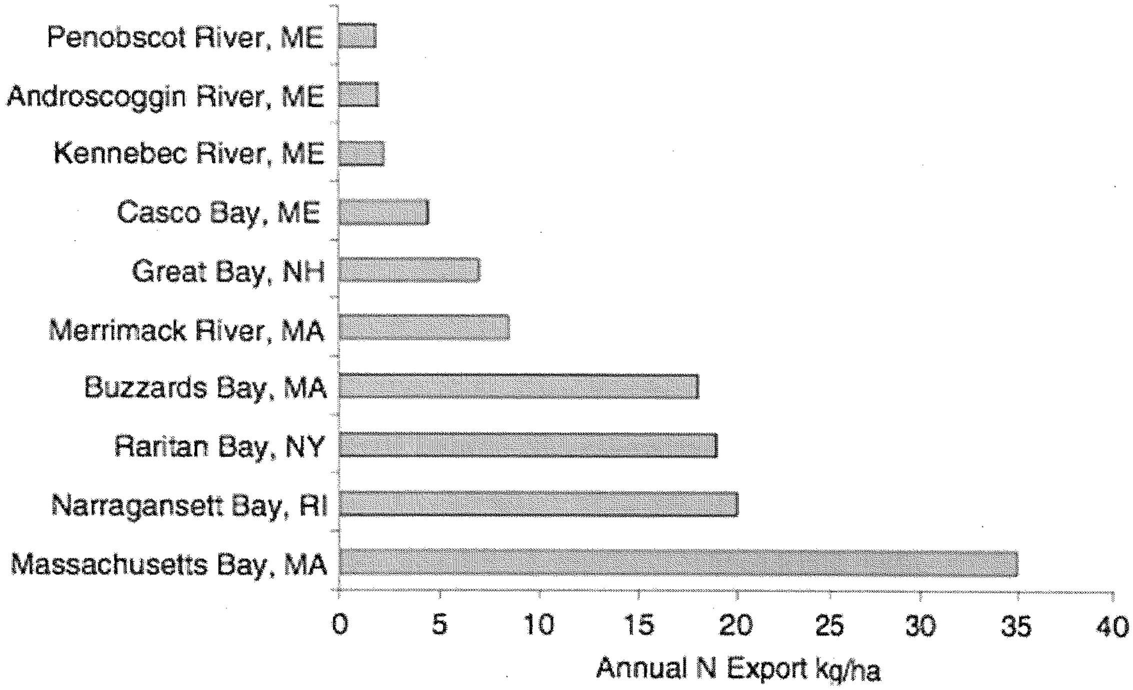

Figure 10. Mean annual unit area exports of nitrogen from a variety of watersheds along the northeastern coasts of the USA. Values for the Penobscot, Androscoggin, and Kennebec River watersheds are from Cronan et al. (2012); other values are from Driscoll et al. (2003). (Reprinted with the kind permission from Springer+Business Media: *Environmental Monitoring and Assessment.* Biogeochemistry of the Penobscot River watershed, Maine, USA: nutrient export patterns for carbon, nitrogen, and phosphorus. **184**, p. 4286, Cronan et al. 2012, figure 4 © Springer Science+Business Media B.V. 2011.)

al. 2003). This is likely the case in Maine too, where the decreasing atmospheric inputs of nitrogen are even more important fractions of the total loads (Moore et al. 2011).

3.2.2. Water Column Stratification

The separation of respiration from photosynthesis becomes greater when the upper waters, where phytoplankton grow, are separated from deeper waters where the food settles and is respired. This separation occurs within the water column most strongly when water masses of different density are separated by sharp changes; oceanographers use the term "stratification" for this process, and it is seen also in lakes that stratify during summer warming of the surface. In the open ocean this stratification can also result from warming of the surface. In the coastal zone, stratification is more strongly influenced by low-density freshwater from rivers, which can rest above saltier layers for extended times without mixing. Such stratification, especially if combined with excess nutrients from land, can result in high rates of respiration in the bottom waters or sediments (eutrophication). Carbon dioxide can build up, and oxygen disappears, with little opportunity for exchange with the atmosphere. Stratification is often the trigger for periods of oxygen depletion in deeper waters, in areas with high nutrient loading. Well-known examples come from the Chesapeake Bay and Mississippi Delta (Rabouille et al. 2008; Schubel & Pritchard 1986).

Because oxygen depletion is accompanied by acidification (see above), there is a high likelihood that stratification conditions will enhance acidification of bottom waters, where many commercially important species live. Furthermore, oxygen consumption can also decrease the buffering capacity of seawater against other forms of acidification (Cai et al. 2011). Although to our knowledge there are no data demonstrating acidification resulting from stratification in Maine waters, this physical mixing should be studied as possible contributors to future acidification.

3.2.3. Sediment Processes

Sediments act as the compost pile for the coastal ocean. Because the ocean is relatively shallow compared to the deep sea, a significant fraction (usually around 10 percent) of the organic matter produced by photosynthesis in the overlying waters is respired in coastal sediments. In the deep ocean this percentage is much smaller. The sediment environment is thus a food-rich one with certain kinds of stability that make it home for many commercial species. Again, respiration is an acid-producing process, so that sediments are usually more acidic than the overlying water column.

While water column respiration is usually dominated by animals, phytoplankton, and bacteria that use oxygen, sediment respiration can often be dominated by bacteria that use compounds other than oxygen to perform their respiration. The sulfurous smell of some mudflat sediments results from such bacterial respiration. Many of these non-oxygen respiration processes also add acid to the water column and in some cases can produce significantly more acid than oxygen-based respiration. Others, such as denitrification, can instead increase total alkalinity or the buffering capacity of the contact water (Gazeau et al. 2014). Either set of processes may affect biological calcification by commercial species.

The type of respiration occurring in any given patch of sediment is affected by many different factors, such as the amount of organic matter, resident animal communities and the frequency and severity of physical disturbance (e.g., storm resuspension, bottom-fishing, activities such as clamming or trawling, sediment runoff from land). As a result, acid production in sediments and its contribution to the overlying water column is extremely complex and varies widely with time and place. This complexity is evident on small and large scales. For example, within a small region of a few inches, consider the pH range of 6.2-8.2 found around common worm burrows (Figure 11).These pH values show similar variation at even smaller size scales (< 1 mm). For example, pH increases to very high values at the sediment surface as benthic microalgae carry out photosynthesis (Revsbech et al. 1988). In Maine, across a 2m x 5m rectangle in Portland Harbor, Green et al. (2013) found a wide range of pH and hence aragonite saturation values (Figure 12). The interface between sediments and the overlying water column is a mosaic of environments, varying in their acidic character, and it emerges as a critical zone for biological calcification reactions. The history of such measurements in Maine made with appropriately calibrated instruments is very recent, so we have no data to assess whether this distribution of pH values has changed over recent decades.

Significantly, most of the values measured by Green et al. (2013) indicate that the calcareous shells of organisms settling from the water column would be susceptible to dissolution. The

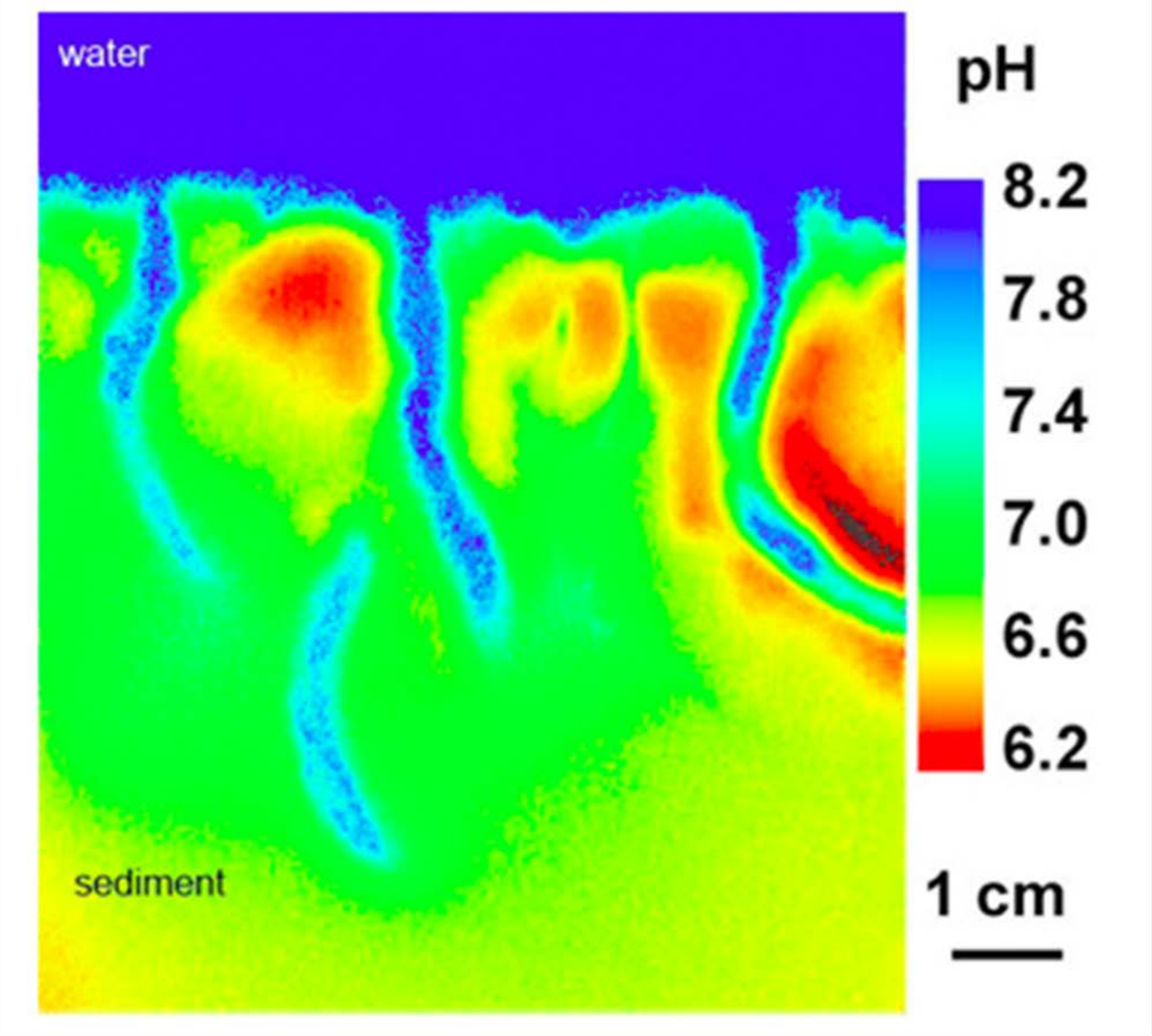

Figure 11. Sediment-water interface pH values, highlighting the roll of worm burrows in creating regions of higher pH in the sediment.(From et al. 2006) (Reprinted from Geochimica et Cosmochimica Acta, Volume 70, Zhu et al., Two-dimensional pH distributions and dynamics in bioturbated marine sediments, pages 4933-4949, © 2006 with permission from Elsevier.)

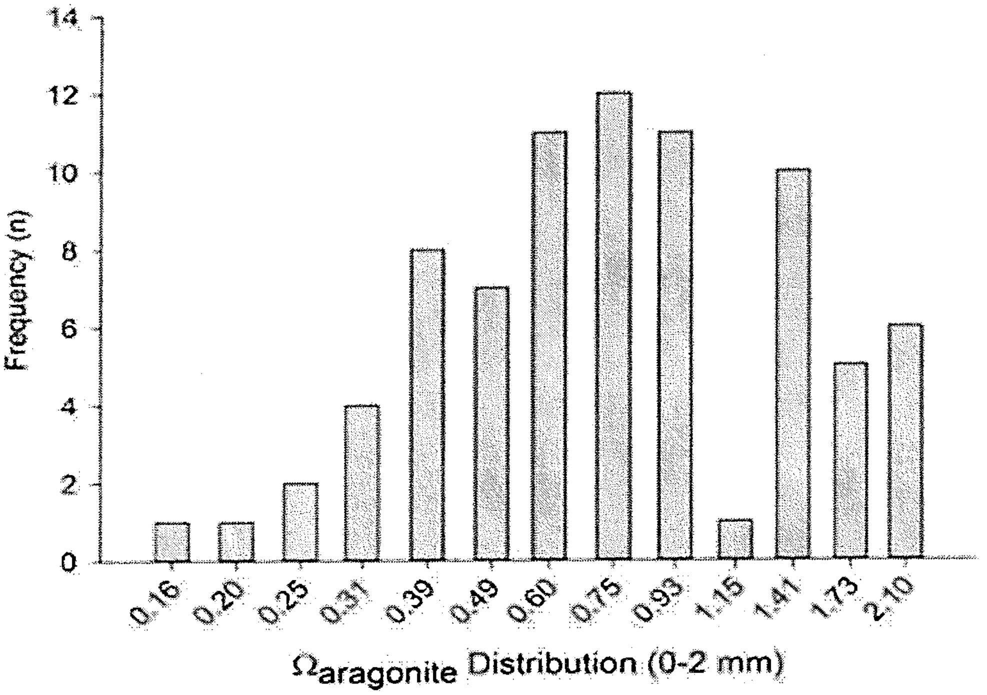

Figure 12. Frequency distribution plot of surface sediment saturation state ($\Omega_{aragonite}$ 0-0.5 cm) in South Portland, Maine. (Reprinted with the kind permission from Springer+Business Media: *Estuaries and Coasts*, Carbonate mineral saturation state as the recruitment cue for settling bivalves in marine muds. Volume 36, page 21, Green et al. 2013, figure 1 © Coastal and Estuarine Research Foundation.)

complex mosaic of pH values therefore implies that the success of organisms will depend on the coincidence of harmful conditions and the susceptible stages of organisms. For example, the settlement of clam spat may depend the local timing of strongly acidifying processes in the sediment and arrival of spat. It will be important to match up assessment of sedimentary conditions with life cycles of susceptible organisms.

Adding calcium carbonate to sediments can buffer the sediment to acid production by respiration processes, as seen in an experiment in which ground up clam shells were added to intertidal sediment (Green et al. 2013). Most Maine sediments contain very little calcium carbonate, reflecting the lack of limestone in most Maine landscapes. Possible exceptions are areas such as the St. George estuary, where limestone quarrying may have led to spillage of mine tailings.

3.2.4 Timing of pH changes

The wide swings in pH on short time scales, due to factors such as annual photosynthesis-respiration cycles or freshwater discharge, mean that the threat to commercial species from acidification will occur as relatively short timescale events which add to the large scale and longer-term trends, such as buildup of atmospheric CO_2 (Waldbusser & Salisbury 2014). The shorter cycles will drive acidification in different parts of the Gulf of Maine at different times and for different reasons. For example, acidification of the more offshore waters of the Gulf is likely dependent on the global atmospheric increase in carbon dioxide, a long-term, slow and continuous trend, as well as decadal changes in the circulation patterns of water entering the Gulf of Maine. Acidification of the estuarine waters of the urbanizing western part of Maine's coast will likely be more dependent on water and nutrient management. Toward the east, climate-induced changes in rainfall, with their accompanying acidification due to low-pH streamflow, may be more important in controlling acidification events. These geographic trends do not imply that nutrient management is, for example, unimportant for the open Gulf of Maine or eastern estuaries; rather, these trends emphasize the importance of budgeting different factors contributing to acidification in Maine.

Temperature strongly affects the relationships among pH, carbon dioxide content and saturation state in Maine waters (Waldbusser & Salisbury 2014), so climate change will affect saturation in complex ways. In the simplest case, warming oceans will increase mean saturation states, but these effects will also be affected by temperature impacts on processes such as freshwater flow and stratification. Temperature also has important biological implications, in addition to impacts on pH, and is addressed below in the section on multi-stressors.

Acidification events will occur when these various pressures coincide, much as coastal damage is greatest when storm waves and tides align. In order to predict these alignments, data on variability in pH or properties related to it such as salinity or oxygen, will be needed. Such data will be needed on shorter and longer time scales. Careful searches for older, archived information on similar properties would aid immensely in assessing longer term trends.

4. Biological Impacts of Ocean Acidification

Current CO_2 concentrations in the atmosphere are higher than at any time in the last 800,000 years and possibly higher than at any time in the last 10-15 million years (Tripati et al. 2009). Based on current CO_2 emission scenarios, surface water pH by 2050 in the world's ocean will be lower than anything experienced in the last several million years (Royal Society 2005). By 2100, the current pH trajectory means that ocean pH will be lower than at any time in the last 300 million years (Honisch et al. 2012). One of the most important factors to consider when contemplating the biological impacts of ocean acidification is not just the absolute pH of seawater, but the rate at which ocean pH is changing.

The current rate of acidification is faster than during any period in the last 300 million years, a period that includes four mass extinctions and, very possibly is unprecedented in Earth's history (Honisch et al. 2012, Zeebe 2012). So, while no past events can exactly predict what changes we can expect, we do know that many marine organisms have not responded well to high CO_2 events in geologic history. The closest analog is thought to have occurred approximately fifty-six million years ago, during the Paleocene-Eocene Thermal Maximum (PETM) (Kerr 2010).

During the PETM, the Earth warmed by 6°C and the pH declined by approximately 0.4 units. The PETM is recognized as a period during which one of the major coral reef crises occurred, and other marine life like calcifying plankton went extinct (Ridgwell & Schmidt 2010). These changes happened over the course of many thousands of years (20,000 years according to Cui et al. (2011)). Today, scientists predict pH declines in the world's oceans of 0.4 units by the end of this century (Feely et al. 2009) – a mere 85 years from now. This rate of change in ocean chemistry undoubtedly represents one of the most stressful aspects of ocean acidification on marine life.

Marine organisms have evolved and adapted to tolerate small, natural variations that occur in ocean pH. However, evolution and adaptation take considerable time to occur in nature. The current rate of change in oceanic pH is likely well outside the capacity of many marine organisms to adapt and will negatively affect many present-day species (Ries et al. 2009) but we cannot predict with any certainty which ones are likely to go extinct. Analyzing the "paleo-record" or the skeletons or shells of dead organisms, like corals, mollusks or calcified algae, can reveal past responses that can inform future impacts. This information can be combined with modern laboratory and field studies to identify the most vulnerable species.

4.1. Mechanisms of Impacts on Organisms

4.1.1. Calcification

Decreased rates of calcification are the most documented effect of ocean acidification. Nearly all marine calcifying organisms studied to date show decreases in the ability to form shells with decreasing pH. This includes larval and juvenile shellfish, (mussels, hard clams, soft shell clams and oysters) marine plankton such as coccolithophores, sea urchins, corals and coralline algae (Fabry et al. 2008). For a variety of species, significant decreases in calcification are noted with pH declines of 0.2-0.4, which falls within the range of expected pH levels in many locations of the ocean as soon as 2050 (Ries et al. 2009) and are already seen in some estuaries (Wallace et al. 2014). Decreases in calcification can result in thinner shells in mollusks (Talmage & Gobler 2009), deformed external plates in coccolithophores (Langer et al. 2006), thinner tests in foraminifera (Moy et al. 2009), higher mortality in juvenile hard clams (*Mercenaria mercenaria*, Green et al. 2004) and slower growth in mollusks (Waldbusser et al. 2010). A relatively large number of studies have looked at coral reefs and nearly all show a reduction in calcification rate of 10-60% when exposed to seawater with CO_2 concentrations doubled from pre-industrial levels (Langdon & Atkinson 2005).

Considerable work is still needed to understand how acidification of seawater impacts rates of shell formation. Calcification is an internal process and occurs by an organism's ability to supersaturate seawater with respect to $CaCO_3$ compared to external CO_3^{2-} concentrations. What is known is that shell building is an energetically costly endeavor and likely becomes more energetically demanding when external concentrations of CO_3^{2-} are lowered relative to concentrations that must be achieved within cells (Cohen & Holcomb 2009).

In general, ocean acidification is likely to have the most direct impact on calcifying marine organisms. Many of these species are small and ubiquitous throughout the ocean and provide valuable food resources for many other species. The cascade effect through multiple marine food webs will likely have significant negative impacts on many other marine species.

4.1.2. Photosynthesis

Over 99% of the organic matter in the ocean and used by marine food webs come from photosynthetic marine organisms that take nutrients, inorganic carbon (CO_2) and water (H_2O) to produce glucose and oxygen (O_2). Marine photosynthesis represents just under half of the total photosynthesis that occurs on Earth (Field et al. 1998). Most of the photosynthesis in the ocean is from phytoplankton, including both calcifying and non-calcifying organisms such as coccolithophores, foraminifera, diatoms, dinoflagellates and cyanobacteria (Falkowski et al. 1998). Benthic photosynthetic organisms can be important in shallow water regions where light penetrates to the sea floor. These organisms include benthic microalgae, seagrasses, seaweeds and corals. Although their net primary productivity is about fifty times less than phytoplankton (1 gigaton/year compared to 50 gigatons/year), they are important in coastal ecosystems, for example providing food and habitats for other species as well as recycling nutrients. For this reason and because organic matter produced by photosynthetic plants is ultimately consumed by other organisms in the ocean, it is important to know the impact of an acidifying ocean on photosynthesis.

Researchers have begun to evaluate the effect of changing ocean pH on photosynthetic organisms. Increasing pCO_2 in the surface water of the ocean will likely impact photosynthesis in two primary ways. First, an increase in H^+ will result in a corresponding decrease in CO_3^{2-}. As discussed, this will harm calcifying photosynthetic organisms that require $CaCO_3$ to build their external structures. Secondly, an increase in CO_2 and HCO_3^- will in fact tend to slightly increase rates of primary production in non-calcifying organisms if they are somewhat limited by the availability of inorganic carbon. However, these increased photosynthetic rates appear to be small, generally 10% or less (e.g. Giordano et al. 2005). The lack of significant response from the non-calcifiers is due mostly to the presence of carbon concentrating mechanisms by various photosynthetic species so that CO_2 concentrations, even today, are saturated within the photosynthetic structure of the organism. In an extensive review by Kleypas et al. (2006) nearly all carbonate bearing photosynthetic organisms showed significant declines in calcification with increasing pCO_2 and decreasing saturation states. Likewise, most showed significant decreases in photosynthetic rates as well, although some species showed increased photosynthetic rates even while calcification rates were diminished.

Most work on ocean acidification has focused on phytoplankton with less research considering how increases in CO_2 and HCO_3^- will impact growth rates of seaweeds and seagrasses. In the species studied to date it appears that compared to phytoplankton, growth rates will tend to increase as CO_2 increases in the ocean (Palacious & Zimmerman 2007). More work is needed to draw any conclusions about the impact of CO_2 on growth of marine phytoplankton and seaweeds. Although multiple species have been tested, there is no clear pattern as to how an acidifying ocean will impact primary producers (e.g, phytoplankton, algae and seagrass). Some work gives results that contradict previous sets of experiments, in some cases by the same scientists (Royal Society 2005). Likewise, few experiments to date have been long enough to determine if adaptation is possible. In addition, experiments are just beginning to show how an increase in CO_2 in conjunction with the other changing environmental conditions (temperature, nutrient availability, hypoxia, metal speciation and toxicity) will impact various species. Multi-factorial studies that include other parameters related to climate change must continue in order to better our understanding of how ocean acidification will impact marine primary producers in the ocean. Because of the immense importance of photosynthetic organisms in the cycling of carbon throughout every food web in the ocean, it is imperative we continue to learn about their responses as even small changes in their productivity could have dramatic implications in the ocean.

4.1.3. Effects on Multicellular Organisms

Larger marine organisms in the ocean that do not breathe air (i.e., fish, invertebrates) take up O_2 and lose CO_2 from seawater through their gills. These organisms could be significantly impacted by rising ocean CO_2. There is considerably less O_2 in seawater than in air due to its low solubility. The mechanisms that larger marine organisms use to take up O_2 are also designed to remove more CO_2 from body fluids. As a result, water breathing marine organisms are very sensitive to changes in seawater CO_2.

Increased CO_2 will acidify body tissues and fluids (known as hypercapnia or acidosis) and affects the ability for blood to carry oxygen. Research on the effect of hypercapnia on fish is still in its infancy. Some research shows that respiratory activity decreases with the onset of acidosis in tissues and that this can occur rapidly, within hours (Pörtner et al. 2004). Experiments by Kikkawa et al. (2004) showed that hypercapnia can cause significant mortality in some fish species.

Some species of animals such as squid and fish that reside in the deep sea appear particularly vulnerable to ocean acidification. Highly muscular and oxygen demanding species such as squid and tuna require a high concentration and steady supply of O_2. This O_2 is carried by respiratory proteins (for example, hemoglobin). However, increasing CO_2 in body fluids lowers the affinity of O_2 to these respiratory proteins and therefore reduces bloods ability to carry O_2. This will cause a decrease in overall metabolism, a decrease in aerobic activities, and will make it more difficult to meet all day-to-day metabolic demands, thus becoming a significant stressor on these organisms (Pörtner et al. 2000).

In addition to internal pH control, there will presumably be other effects of acidosis on larger marine species. For example, higher seawater CO_2 has been shown to impair the olfactory discrimination and homing ability of the orange clownfish, *Amphiprion percula* (Munday et al. 2009).

Currently, many of the effects of ocean acidification on larger marine organisms remain unknown. However, work to date clearly shows the potential for significant impacts on the acid-base chemistry of many marine species. We know that the tolerance for acidification varies considerably among the species studied and appears tightly coupled to metabolic rate with more energetically-demanding species at greater risk. Very little is known about the capacities for different life stages of a specific species to tolerate ocean acidification and how additional stressors in the ocean will compound the impact of acidification. Multi-factorial studies are necessary to elucidate this.

4.2. Experimental Determination of Ocean Acidification Impact on Marine Species

For the past decade, scientists have been experimentally studying how ocean acidification will affect marine organisms. Typically, these experiments happen in a laboratory, focusing on a single species and usually on a single life stage of that species. Some early studies changed the pH of the seawater by adding acid (Riebesell et al. 2000), but it is now widely recognized that a more realistic approach for creating experimental pH conditions is to add CO_2 directly to seawater (Riebesell et al. 2010).

As has been discussed, the addition of CO_2 reduces the pH of the seawater. Scientists choose target pH levels or target pCO_2 levels based either on projected atmospheric CO_2 levels or on the conditions naturally experienced by the organism. The latter rationale is applicable when the organism lives in an environment where the natural pCO_2 level or variability exceeds the predicted pCO_2 for the future atmosphere. This is often the case for coastal and estuarine regions. After exposing the organisms to the high CO_2 conditions for a predetermined amount of time, scientists evaluate the organisms' response to those OA conditions by taking measurements of the organisms' growth, development, physiology or other characteristics.

Due to the costs and technical difficulties of raising animals, plants, and algae in the laboratory for extended lengths of time, most OA studies have been fairly short (months or less) and have focused on a single life stage of the species, although some have considered multiple life stages. Faster developmental time makes it easier to work with multiple life stages. For example, copepods, a type of zooplankton, often reach sexual maturity in as little as 14 days, so there have been several studies investigating the effects of OA on multiple generations of copepods (Pedersen et al. 2014; Kurihara & Ishimatsu 2008; Fitzer et al. 2012). A large percentage of OA studies have focused on larval or juvenile life stages, as these early life stages of marine invertebrates can be highly vulnerable to environmental stressors (Pechenik 1987).

To date, studies considering the effects of OA on marine organisms have often focused on organisms that are considered most vulnerable to OA (mainly calcifying organisms), not necessarily organisms that are most commercially important. This makes it extremely difficult to predict the impact of OA on Maine's harvested and farm raised marine resources. Table 1 shows the number of OA studies that have been performed on these species broken down within a species into the number of studies on different life stages. Many have not been studied with respect to ocean acidification at all, while others have been considered in only one or two studies, some of which were not designed to test acidification effects under environmental conditions found in Maine.

A great amount of work on Maine species has been done in European laboratories using European populations. These results may or may not be relevant to Maine populations because the response of a species to OA is sometimes population-specific, usually determined by the pH variability that the population naturally experiences. For example, studies of Atlantic cod (*Gadus morhua*) sourced from Baltic Sea populations were found to be fairly resilient to OA conditions (Frommel et al. 2010; Frommel et al. 2013). However, when the cod were sourced from the Norwegian coast, the larvae showed tissue damage and decreased movement (Frommel et al. 2012; Maneja et al. 2013a; Maneja et al. 2013b). The Baltic Sea has naturally higher pCO_2 levels

Table 1. Number of studies investigating organismal responses of Maine species to increased $p\mathrm{CO}_2$ conditions. The number of studies are broken down into the distinct life stages of the organisms. The total number of studies may not equal the sum of studies for all life stages or the sum of the references listed because some studies consider multiple life stages and some references include multiple studies. We thank Allison C. Candelmo, R. Christopher Chambers, Christopher J. Gobler, Andrew L. King, Nichole N. Price, Richard A. Wahle, and Jesica D. Waller for their contributions towards compiling data from the studies referenced in this table.

Common Name *Scientific Name*	**2013 Landings Value ($)**	**Life Stages**				**Total Studies**	**References**
		Reproduction/ Fertiliztion/ Eggs	**Larvae**	**Juveniles**	**Adults**		
American lobster *Homarus americanus*	378,736,030	0	1	1	0	2	Keppel et al. 2012, Ries et al. 2009, Ries 2011
Elvers (American eel) *Anguilla rostrata*	32,926,991	0	0	0	0	0	
Soft shell clam *Mya arenaria*	16,915,005	0	0	3	1	4	Green et al. 2009, Green et al. 2013, Clements & Hunt 2014, Ries et al. 2009
Atlantic Herring *Clupea harengus*	15,391,192	2	2	0	0	2	Frommel et al. 2014, Franke & Clemmesen 2011
Total Groundfish	**7,626,795**						
Pollock *Pollachius virens*	2,560,807	0	0	0	0	0	
White hake *Urophycis tenuis*	1,477,447	0	0	0	0	0	
Atlantic cod *Gadus morhua*	736,154	2	4	3	0	8	Frommel et al. 2010, Frommel et al. 2012, Frommel et al. 2013, Maneja et al. 2013a, Maneja et al. 2013b, Melzner et al. 2009, Moran & Støttrup 2011
Monkfish *Lophius americanus*	726,130	0	0	0	0	0	
Plaice *Hippoglossoides platessoides*	779,015	0	0	0	0	0	
Witch flounder *Glyptocephalus cynoglossus*	576,799	0	0	0	0	0	
Atlantic halibut *Hippoglossus hippoglossus*	328,587	0	0	2	0	2	Bresolin de Souza et al. 2014, Gräns et al. 2014

Common Name *Scientific Name*	2013 Landings Value ($)	Life Stages				Total Studies	References
		Reproduction/ Fertiliztion/ Eggs	Larvae	Juveniles	Adults		
Haddock *Melanogrammus aeglefinus*	211,279	0	0	0	0	0	
Acadian redfish *Sebastes fasciatus*	170,134	0	0	0	0	0	
Cusk *Brosme brosme*	17,618	0	0	0	0	0	
Winter flounder *Pseudopleuronectes americanus*	Not enough data to report	0	0	0	0	0	
Yellowtail flounder *Limanda ferruginea*	Not enough data to report	0	0	0	0	0	
Bloodworm *Glycera dibranchiate*	5,627,577	0	0	0	0	0	
Green sea urchin *Strongylocentrotus droebachiensis*	5,291,790	1	4	2	6	11	Dupont & Thorndyke 2012, Dupont et al. 2013, Holtmann et al. 2013, Siikavuopio et al. 2007, Spicer et al. 2011, Stumpp et al. 2012a, Stumpp et al. 2012b, Stumpp et al. 2013
Sea scallop *Placopecten magellanicus*	5,194,553	0	0	0	0	0	
Eastern oyster *Crassostrea virginica*	2,415,764* *Landings value represents *C. virginica* and *Ostrea edulis*. Only *C. virginica* has been studied with respect to ocean acidification.	0	2	4	8	13	Beniash et al. 2010, Dickinson et al. 2012, Gazeau et al. 2007, Gobler & Talmage 2014, Götze et al. 2014, Ivanina et al. 2013a, Ivanina et al. 2014, Matoo et al. 2013, Ries et al. 2009, Talmage & Gobler 2009, Talmage & Gobler 2011, Waldbusser et al. 2011a, Waldbusser et al. 2011b

Common Name *Scientific Name*	2013 Landings Value ($)	Life Stages				Total Studies	References
		Reproduction/ Fertiliztion/ Eggs	Larvae	Juveniles	Adults		
Blue mussel *Mytilus eduli*	2,340,965	1	0	1	13	14	Asplund et al. 2014, Beesley et al. 2008, Berge et al. 2006, Bibby et al. 2008, Gazeau et al. 2007, Hiebenthal et al. 2013, Hüning et al. 2012, Mackenzie et al. 2014a, Mackenzie et al. 2014b, Melzner et al. 2011, Ries et al. 2009, Thomsen & Melzner 2010, Thomsen et al. 2010, Thomsen et al. 2013
Mahogany quahog *Arctica islandica*	1,378,491	0	0	0	2	2	Hiebenthal et al. 2013, Stemmer et al. 2013
Sand worm *Alitta virens* (formerly *Nereis virens)*	1,372,283	0	0	0	1	1	Widdicombe & Needham 2007
Northern shrimp *Pandalus borealis*	1,008,766	1	2	0	1	3	Arnberg et al. 2013, Bechmann et al. 2011, Hammer & Pedersen 2013
Common periwinkle *Littorina littorea*	869,083	0	0	0	4	4	Bibby et al. 2007, Melatunan et al. 2013, Ries et al. 2009, Russell et al. 2013
Hard clam *Mercenaria mercenaria*	502,004	0	3	6	6	15	Dickinson et al. 2013, Gobler & Talmage 2013, Gobler et al. 2014, Götze et al. 2014, Green et al. 2004, Green et al. 2009, Green et al. 2013, Ivanina et al. 2013a, Ivanina et al. 2013b, Ivanina et al. 2014, Matoo et al. 2013, Ries et al. 2009, Talmage & Gobler 2009, Talmage & Gobler 2010, Waldbusser et al. 2010

Common Name *Scientific Name*	**2013 Landings Value ($)**	**Life Stages**				**Total Studies**	**References**
		Reproduction/ Fertiliztion/ Eggs	**Larvae**	**Juveniles**	**Adults**		
Total Macroalgae	**464,728**						
Rockweed *Ascophyllum nodosum*		0	N/A	N/A	1	1	Longphuirt et al. 2013
Bladderwrack *Fucus vesiculosus*		0	N/A	N/A	1	1	Gutow et al. 2014
Sugar kelp *Saccharina latissima*		1	N/A	N/A	2	2	Longphuirt et al. 2013, Swanson & Fox 2007
Horsetail kelp *Laminaria digitata*		0	N/A	N/A	0	0	
Wing kelp *Alaria esculenta*		0	N/A	N/A	0	0	
Irish Moss *Chondrus crispus*		0	N/A	N/A	4	4	Hofmann et al. 2012b, Sarker et al. 2013
Nori *Porphyra umbilicalis*		0	N/A	N/A	0	0	
Dulse *Palmaria palmata*		0	N/A	N/A	0	0	
Graceful Redweed *Graciliaria tikvahiae*		0	N/A	N/A	0	0	
Sea cucumber *Cucumaria frondosa*	288,541	0	0	0	0	0	
Surf clam *Spisula solidissima*	Not enough data to report	0	0	0	0	0	

Common Name ***Scientific Name***	**2013 Landings Value ($)**	**Life Stages**				**Total Studies**	**References**
		Reproduction/ Fertiliztion/ Eggs	**Larvae**	**Juveniles**	**Adults**		
Non-Commercially Important Species							
European lobster *Homarus gammarus** (Maine Congener: American lobster *Homarus americanus*)	N/A	1	2	1	0	2	Agnalt et al. 2013, Arnold et al. 2009
Green crab *Carcinus maenas*	N/A	0	0	0	3	3	Appelhans et al. 2012, Fehsenfeld et al. 2011, Landes & Zimmer 2013
Dungeness crab *Cancer magister** (Maine Congers: Jonah crab *Cancer borealis* and Rock crab *Cancer irroratus*)	N/A	0	0	0	1	1	Pane & Berry 2007
European edible crab *Cancer pagurus** (Maine Congers: Jonah crab *Cancer borealis* and Rock crab *Cancer irroratus*)	N/A	0	0	0	1	1	Metzger et al. 2007
Summer flounder *Paralichthys dentatus** (Maine Congener: Winter flounder *Pseudopleuronectes americanus*)	N/A	1	2	0	0	2	Chambers et al. 2014

Common Name ***Scientific Name***	**2013 Landings Value ($)**	**Life Stages**				**Total Studies**	**References**
		Reproduction/ Fertiliztion/ Eggs	**Larvae**	**Juveniles**	**Adults**		
Bay scallop *Argopecten irradians** (Maine Congener: Sea scallop *Placopecten magellanicus*)	N/A	0	7	2	1	8	Gobler & Talmage 2013, Gobler et al. 2014, Ries et al. 2009, Talmage & Gobler 2009, Talmage & Gobler 2010, Talmage & Gobler 2011, White et al. 2013, White et al. 2014
Kelp *Laminaria hyperborea** (NECAN congener *Laminaria digitata*)	N/A	1	N/A	N/A	1	1	Olischläger et al. 2012
Nori *Porphyra haitanensis** (Maine Congener: *Porphyra umbilics*)	N/A	0	N/A	N/A	1	1	Liu et al. 2013
Nori *Porphyra linearis** (Maine Congener: *Porphyra umbilicus*)	N/A	0	N/A	N/A	1	1	Israel et al. 1999
Nori *Porphyra leucosticta** (Maine Congener:	N/A	0	N/A	N/A	1	1	Mercado 1998
Graceful Redweed *Gracilaria lemaneiformis** (NECAN Congener: *Gracilaria vermiculophylla*)	N/A	0	N/A	N/A	2	2	Yang et al. 2013, Xu et al. 2010

Symbol explanation
* This species does not live in Maine, but is related to a Maine species.

and variability than the Norwegian coast, so cod from the Baltic Sea are more acclimated to higher pCO_2 conditions than cod from the Norwegian coast.

These studies highlight the uncertainty in making predictions on how OA will affect Maine's commercially important species based on research using populations from outside of Maine. With this in mind, below we review what is known about OA impacts on those species, grouping taxonomically-similar species together.

4.3. Effects of OA on Maine's Commercially Important Species

4.3.1. Effects on Crustaceans

Maine's most iconic marine species is surely the American lobster (*Homarus americanus*). Considering that the landed value of lobster was 10-times the value of any other commercially harvested species in 2013 (DMR 2013), we know extremely little about how lobsters will fare in a high CO_2 world. Only two studies have considered this species (Table 1), and these studies found different effects of increased pCO_2. Studying juvenile lobsters, Ries et al. (2009) found increased calcification at a pCO_2 level of ~2850 ppm (pH = 7.31). This response has been highlighted in the media as an indication that lobsters will be better off in a high CO_2 world, but it is important to point out that the temperature used in this study (25°C, 77°F) is not reflective of temperature that Maine lobster populations experience. Ries et al. (2009) conducted their research on the southern shore of Cape Cod, Massachusetts where lobsters are exposed to temperatures this high during summer months. Temperatures recorded from 2001-2015 at a depth of 50 m at Buoy E on the Central Maine Shelf typically range from about 3 °C during spring months to about 10 °C during autumn months (Pettigrew & UMOOS Buoy E).

The only other lobster OA study worked with larval lobsters from the northern coast of Nova Scotia. Keppel et al. (2012) found that the carapace lengths of stage II, III, and IV larvae were significantly smaller when exposed to high pCO_2 conditions (1200 ppm, pH = 7.7) compared to larvae exposed to ambient pCO_2 conditions. Furthermore, the larvae exposed to high pCO_2 took significantly longer to molt than larvae exposed to ambient conditions. Smaller size and longer development time can both directly and indirectly affect survival. Larval lobsters develop as plankton in the water column, where they are exposed to numerous predators with no way to hide. The longer they spend as plankton up in the water, the more likely they are to be eaten. Additionally, smaller larvae are also more vulnerable to predation than larger larvae.

Keppel et al. (2012) performed their study at 20°C (68 °F), which was the ambient water temperature of Northumberland Strait during the experimental period. This temperature is also higher than is typically experienced by Maine lobster larvae, but not as extreme as the previous example. Lobster larvae develop during summer months in the water column, which is generally warmer than bottom waters. Temperatures recorded from 2001-2015 at a depth of 1-4 m at Buoy E on the Central Maine Shelf typically reached 17 °C during summer months (NERACOOS Buoy E).

We report the results of Keppel et al. (2012) and Ries et al. (2009), because they are the only existing studies of OA effects on American lobsters. However, we caution that in order to understand how Maine juvenile lobsters will respond to OA, studies using Maine populations with ecologically relevant temperatures should be performed.

The Northern shrimp (*Pandalus borealis*) appears to be somewhat resilient to increased pCO_2. Exposure of egg-bearing mothers to elevated pCO_2 produced no effects on time to first hatch, hatching rate or duration of hatching (Arnberg et al. 2013). Similarly, larval survival, feeding rate, and oxygen consumption were unaffected (Arnberg et al. 2013; Bechmann et al. 2011), although the larval development time increased. Increased development time can result in increased predation and should be considered a negative effect of exposure to increased CO_2. Hammer and Pedersen (2013) suggest that for adults, this resiliency may be due to the ability of Northern shrimp to partially compensate under extreme pCO_2 conditions by accumulating bicarbonate ions in their hemolymph (fluid in its open circulatory system, similar to blood). Bicarbonate ions provide buffering capacity for the shrimp's hemolymph when acidosis occurs. Furthermore, adult shrimp did not experience increased respiration rates, which would have been a sign of physiological stress.

No studies have investigated the effects of ocean acidification on Maine's two commercially important crab species, the rock crab (*Cancer irroratus*) and the Jonah crab (*Cancer borealis*), but two studies have considered other crabs of the same genus: the Dungeness crab (*Cancer magister*) and the European edible crab (*Cancer pagurus*). Similar to Northern shrimp, the Dungeness crab was able to compensate for exposure to high pCO_2 conditions by buffering its hemolymph with bicarbonate ions (Pane & Barry 2007). Compensation for high CO_2 conditions is a promising response as it indicates the organism has some innate ability to deal with this stressor. However, Metzger et al. (2007) found when the European edible crab was exposed to high CO_2 conditions, its upper thermal tolerance decreased by 5 °C, which means the crab could not tolerate warmer temperatures. This is another example of why it is so important to study the effects of multiple stressors.

Much more work is necessary in order to understand and predict the effects of ocean acidification on Maine's commercially important crustaceans. Thousands of Maine people and the communities they live in from Kittery to Eastport depend upon the lobster fishery, yet we know next to nothing about how they will be affected by ocean acidification. While some crustaceans are able to compensate for acidosis of their hemolymph, it is unknown whether lobsters can perform a similar compensation. Furthermore, none of these species have been studied throughout an entire life cycle or for multiple generations, and the effects of OA on individual life stages may not accurately portray the species' response to ocean acidification.

4.3.2. Effects on Finfish

While lobsters account for 69% of the landed value of Maine's fisheries, finfish represent a significant portion of the remaining landings. Elvers, an early life stage of the American eel (*Anguilla rostrata*), and Atlantic herring (*Clupea harengus*) have the second and fourth highest landed values, respectively (Table 1). However, only three Maine finfish species have been studied with respect to ocean acidification: Atlantic herring, Atlantic halibut (*Hippoglossus hippoglossus*), and Atlantic cod (*G. morhua*).

For both herring and cod, the impact of high CO_2 was dependent on the fish population source. As pointed out above, larvae from cod sourced from the Baltic sea with naturally high and variable pCO_2 conditions experienced few, if any, negative effects of high CO_2 conditions in the laboratory (Frommel et al. 2010, Frommel et al. 2013), while larvae from cod sourced from the Norwegian coast showed increased tissue damage, decreased RNA:DNA ratio (a measure of nutritional condition) and decreased movement (Frommel et al. 2012, Maneja et al. 2013a, Maneja et al. 2013b). Herring from the Baltic Sea were negatively impacted by high CO_2 only when the treatment level reached 4625 ppm (pH = 7.05), which is a very extreme treatment level (Franke & Clemmesen 2011). However, 25-day-old herring larvae from the Norwegian coast had increased abnormalities of their kidneys, liver, pancreas, and fins at CO_2 conditions as low as 1881 ppm (pH = 7.45), but not of their heart, gills, or skeletons (Frommel et al. 2014). At 39 days old, the larvae exposed to high CO_2 were smaller, had slower development, and decreased nutritional condition than larvae raised at ambient CO_2 conditions (Frommel et al. 2014).

Exposure to OA conditions affected regulation of proteins involved in immune function, energy production, cytoskeleton, and cellular turnover in juvenile halibut (Bresolin de Souza et al. 2014). While no OA studies have been performed on Maine flounder species, there have been two studies of summer flounder (*Paralichthys denatus*), which lives further south. Survival of embryos was reduced at intermediate (1808 ppm, pH = 7.5) and high (4714 ppm, pH = 7.1) pCO_2 conditions (Chambers et al. 2014). Summer flounder larvae were larger when exposed to intermediate and high pCO_2 conditions; they also metamorphosed at an earlier age and had increased liver abnormalities compared to larvae raised at ambient conditions.

While these are the only studies of commercially important species, we can also learn about general effects of OA on finfish from studies on non-commercially important species, some of which can be important forage for commercially harvested fish. One extremely important observation is that sensitivity to increased pCO_2 can vary with parental exposure. Murray et al. (2014) found that Atlantic silverside (*Menidia menidia*) larvae had reduced survival and growth when exposed to high CO_2 *only* when they were obtained from adults collected early in the season, and not when they were obtained from adults collected later in the season. Adults collected at different times in the season were naturally exposed to different pCO_2 conditions. Early in the season, the pCO_2 level was naturally lower, and later in the season, the pCO_2 level was naturally higher. This is an example of a maternal effect (Marshall et al. 2008), where the mother can respond to environmental cues and signals by conditioning her eggs differently to better prepare the offspring to cope with those environmental conditions.

4.3.3. Effects on Mollusks

Mollusks are the group of Maine's commercially important species that have been studied the most with respect to ocean acidification. This is likely because they are considered one of the more vulnerable groups since they form calcium carbonate shells and because upwelling of acidic water caused the near collapse of the oyster industry in the Pacific Northwest during the early-mid 2000's. Maine's commercially harvested mollusks are mostly bivalves: softshell clams (*Mya arenaria*), sea scallops (*Placopecten magellanicus*), eastern oysters (*Crassostrea virginica*), blue mussels (*Mytilus edulis*), mahogany quahogs (*Actica islandica*), hard clams

(*Mercenaria mercenaria*), and surf clams (*Spisula solidissima*); with one gastropod, the common periwinkle (*Littorina littorea*).

The effects of ocean acidification on mollusks are overwhelmingly negative. Multiple studies using pCO_2 levels predicted for the coming centuries (and currently present during summer months in some estuaries (Wallace et al. 2014)) have shown slowed shell growth and/or decreased calcification, sometimes across multiple life stages (Table 1). The mahogany quahog (*Arctica islandica*) remains Maine's only commercially important mollusk for which no negative effect of OA has been documented (Hiebenthal et al. 2013; Stemmer et al. 2013). There haven't been any published studies on the effects of OA on sea scallops, likely because they are extremely difficult to culture in the laboratory. However, multiple studies have investigated the response of bay scallops (*Argopecten irradians*), a more southern species, to OA. The results of those studies are included below.

In general, adult bivalves can survive up to extreme pCO_2 conditions (>3500 ppm, pH < 7.0). However, larval stages appear to be more sensitive to OA conditions. Larval sensitivity to OA conditions is in part due to the mineralogy of larval shells. Bivalve larvae form the earliest portions of their larval shell from amorphous calcium carbonate (Weiss et al. 2002), which is the most soluble form of calcium carbonate, before switching to calcification of aragonite, which is still more soluble than calcite. Research has shown increased mortality for larval hard clams and eastern oysters at pCO_2 levels 750-1500 ppm. Hard clam, oyster, mussel, and scallop larvae exposed to OA conditions have been shown to be smaller, less fit, and slower to develop than larvae exposed to ambient conditions (Talmage & Gobler 2009; Talmage & Gobler 2010; Talmage & Gobler 2011; White et al. 2013; White et al. 2014; Thomsen et al. 2013; Gobler & Talmage 2013; Gobler & Talmage 2014). Waldbusser et al. (2013) suggest, through stable isotope analysis, that disruption of bivalve initial shell formation during early development is most likely due in part to energetics (i.e. limited supply of energy from maternal stores). All of these traits can indirectly affect larval survival and can lead to high mortality during metamorphosis to the juvenile stage.

When bivalve larvae are competent to settle, meaning that they are ready to transition from the planktonic larval stage to the benthic juvenile stage, they sink out of the water column and use their foot to 'test' a substrate. They can swim back into the water column if the substrate is not suitable. Work has shown that the saturation state of sediments can influence larval settlement behavior of softshell clams, with the clams preferring to settle out of the water column to metamorphose in sediment with higher saturation states, which are less acidic (Clements and Hunt 2014). When the saturation state of sediment is raised by the addition of ground aragonite, recruitment of juvenile softshell clams increased (Green et al. 2009; Green et al. 2013). Similarly, Friends of Casco Bay has found a correlation between sediment pH and the presence of juvenile softshell clams with more juvenile clams in mudflats with higher pH. If the sediment pH and saturation state is too low, the shells of clams can actually dissolve (Figure 13), leading to juvenile mortality (Green et al. 2004; Green et al. 2009).

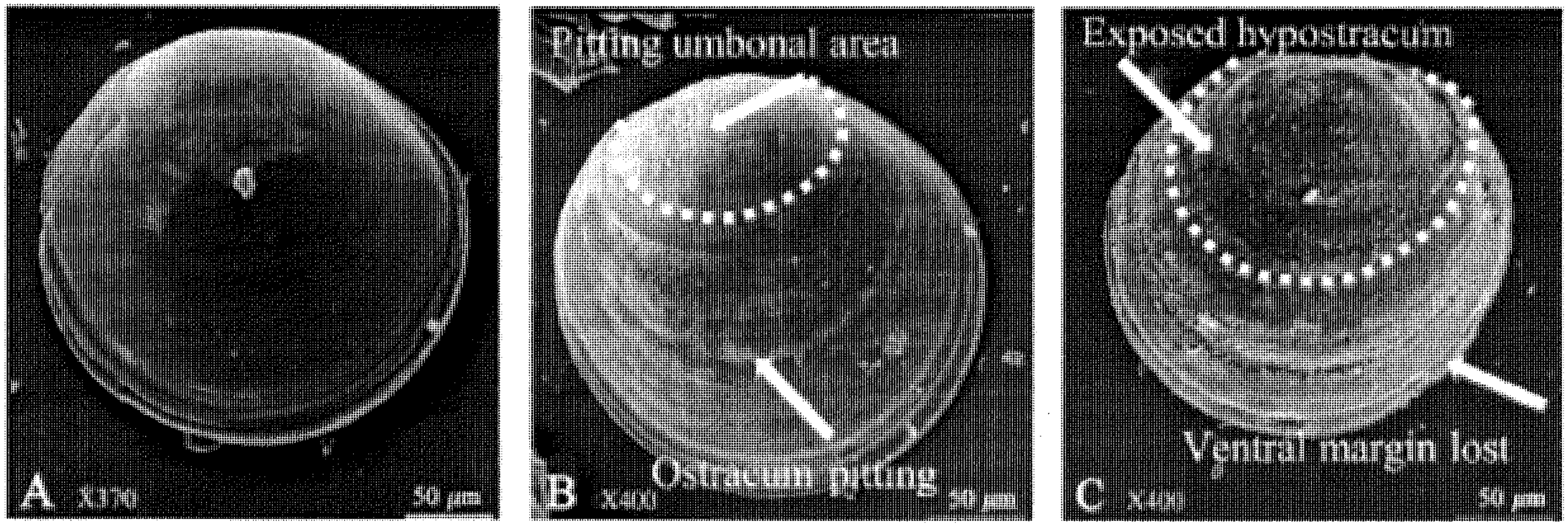

Figure 13. Scanning electron micrographs (SEM) of representative 0.2 mm *M. mercenaria* reared in sediments maintained at $\Omega_{aragonite} = 0.6$. Clams were maintained in these conditions for 0, 4, and 7 days (A, B, and C, respectively). Magnification and scale bars are shown, as well as significant dissolution to various parts of the shell. (From Green et al. 2009).

4.3.4. Effects of Ocean Acidification on Annelids

Two species of polychaete worms are commercially important in Maine: bloodworms (*Glycera dibranchiate*) and sandworms (*Alitta virens*, formerly *Nereis virens*). Neither of these worms calcifies and only sandworms have been studied with respect to ocean acidification. The results of this one study found that neither survival of the worms nor the size or shape of the burrows were affected by pH levels as low as 5.6 (Widdicombe & Needham 2007). However, this study did not investigate any physiological response that the worm may have had, so we cannot rule out the possibility that OA may affect either species.

4.3.5. Effects of Ocean Acidification on Echinoderms

Maine has two commercially important echinoderm species: the green sea urchin (*Strongylocentrotus droebachiensis*) and the orange-footed sea cucumber (*Cucumaria frondosa*). These species differ in the degree to which they calcify. Sea urchins form their test (shell) out of five ossicles, which (along with their spines) are calcium carbonate. Sea cucumbers have greatly reduced microscopic ossicles. The orange-footed sea cucumber has not been studied with respect to ocean acidification, but the green sea urchin has been reasonably well-studied.

The effects of OA on the green urchin are largely negative at all life stages (larval, juvenile, and adult), although most studies have considered only adults. Adult green urchins have been shown to have reduced growth, reduced ingestion of food and increased dissolution of test ossicles and spines (Stumpp et al. 2012b; Holtmann et al. 2013; Siikavuopio et al. 2007). Like northern shrimp and some crabs, green urchins are able to compensate for decreased pH in their perivisceral coelomic fluid when exposed to OA conditions by accumulating bicarbonate ions (Stump et al. 2012b), but this process shifts the overall energy budget, possibly diverting energy away from growth or reproduction.

Larval urchins are negatively impacted by increased $p\mathrm{CO}_2$, resulting in smaller size and decreased digestion rates (Stumpp et al. 2013). Only one group has considered multiple life stages of the green urchin in one experiment (Dupont et al. 2013). They found that larval $p\mathrm{CO}_2$ exposure has legacy effects on juvenile survival but not on juvenile settlement success or growth rate (so there was increased mortality after settlement; however, the survivors grew just as well as those exposed to ambient $p\mathrm{CO}_2$). None of these studies were performed on sea urchins that came from Maine populations.

It is possible that sea urchins like finfish could respond to OA differently, depending on the natural conditions that their population experiences. Therefore, we may not be able to rely on these observations holding true for Maine populations.

4.3.6. Effects of Ocean Acidification on Macroalgae

Maine has multiple species of macroalgae that are wild-harvested or farmed. These species represent all three phyla of macroalgae: red algae (Rhodophyta), brown algae (Ochrophyta) and green algae (Chlorophyta). Macroalgae can be broken into two major functional groups:

calcareous species that calcify and 'fleshy' species (commonly referred to as seaweed) that do not calcify. These groups typically show different responses to OA conditions.

All of Maine's commercially important macroalgae species are fleshy algae, which have been shown to increase productivity and growth in response to increased pCO_2 (Kroeker et al. 2010, Kroeker et al. 2013). One hypothesis for this is that the algae may be growth-limited by inorganic carbon (CO_2) and the increase in CO_2 associated with OA relieves this carbon limitation. Most fleshy algae that have been studied with respect to OA have shown increased growth (or increased biomass) under high CO_2 conditions, but two species of brown algae that are commercially important in Maine, sugar kelp (*Saccharina latissima*) and bladderwrack (*Fucus vesiculosus*), actually lost biomass under increased pCO_2 conditions (Swanson & Fox 2007; Gutow et al. 2014).

Because fleshy algae, such as kelp, typically have enhanced growth under OA conditions, these algae could help efforts to reduce the impacts of OA on coastal areas. The idea is that the macroalgae can assimilate excess CO_2 into their tissue, taking advantage of their relatively fast growth rates. Then the algae can be harvested and that CO_2 would be removed from the local ecosystem (Chung et al. 2011). This represents a temporary sequestration of the CO_2, since many of the current uses for macroalgae (such as biofuel) result in the re-release of that CO_2. Nonetheless, when biofuels are produced and consumed, release of CO_2 from fossil fuels is reduced.

4.3.7. Effects of Ocean Acidification on Phytoplankton and Zooplankton

Phytoplankton (single-celled algae) and zooplankton (microscopic animals living in the water column) are generally not considered to be commercially important species, although phytoplankton are increasingly grown in controlled environments for use in biofuels. However, these organisms are absolutely essential to our marine ecosystem. Phytoplankton are primary producers, performing photosynthesis to convert the sun's energy along with CO_2 to usable energy and oxygen. Half of the world's oxygen is produced by marine phytoplankton.

Aside from that critical role that phytoplankton play in providing us with oxygen, they are the base of the marine food web. Phytoplankton are eaten by zooplankton, which are in turn eaten by larger organisms. At least 17-32% of primary production by phytoplankton is consumed by copepods (Hernández-León & Ikeda 2005), but that number could be as high as 30-50% (David Fields, unpublished data). Many marine invertebrate larvae and adult bivalves also consume phytoplankton. Therefore, we cannot begin to fully understand the effects of OA on commercially important marine species without understanding the effects of OA on phytoplankton and zooplankton.

The response of phytoplankton to OA seems to be species-specific, meaning that not all phytoplankton respond the same way. Phytoplankton are very diverse and even within one species, the response can be population-specific, based on the natural CO_2 conditions from where that population was isolated. In general, it appears that at CO_2 predicted for the year 2100, the growth rate of several species of phytoplankton living in or around Maine waters will not be affected (King et al. in prep (a), King et al. in prep (b)). However, growth rate is not the only consideration. Nutrient uptake, photosynthetic rate and nutritional composition are all factors that are potentially affected by ocean acidification. In section 4.4.1., we introduce an example of how changes in the nutritional composition of phytoplankton impact higher trophic levels.

With regard to zooplankton, there are two major functional groups, copepods and pteropods, which have received the most attention in the context of OA. Copepods are microscopic crustaceans living throughout the world's oceans. Like other crustaceans, their exoskeleton is formed of a polysaccharide known as chitin with variable amounts of calcium carbonate. Pteropods are planktonic snails, some which have aragonite shells and some that do not. Both copepods and pteropods are important links in the ocean food web. Their responses to ocean acidification are generally different from each other.

Copepods appear to be fairly resilient at pCO_2 levels up to about 2500 ppm (an approximate prediction for the year 2300). Survival of one of the most common copepods species, *Calanus finmarchicus*, is not affected by pCO_2 less than 7000 ppm (Pedersen et al. 2013, Pedersen et al. 2014). Similarly, *Acartia tonsa* juvenile and adult survival is not affected by pCO_2 less than 3000 ppm, although larval survival decreases at 1000 ppm (Cripps et al. 2014b). However, while survival may not be affected by high pCO_2, Rossell et al. (2012) found that *A. tonsa* egg production, hatching success and growth were significantly reduced to 750 ppm.

Pteropods, however, seem to be highly sensitive to increased pCO_2 with negative effects seen on larval, juvenile and adult life stages. Calcification has been shown to be negatively impacted by OA in both larvae (Comeau et al. 2010b) and adults (Comeau et al. 2009, 2010a), possibly because their shells are formed from a particularly soluble form of calcium carbonate. In addition, larval, juvenile, and adult shells experience dissolution, which could have ecological impacts for pteropods (Comeau et al. 2009, Comeau et al. 2010a, Comeau et al. 2010b, Busch et al. 2014, Bednaršek et al. 2012).

4.4. Other Considerations of the Effects of Ocean Acidification on Marine Organisms

4.4.1. Ocean Acidification Effects on Trophic Interactions

In the laboratory, experiments typically consider only one species at a time. This completely misses any interactive effects of OA on predator-prey relationships. For example, it makes sense that bivalves with thinner shells due to OA would be more susceptible to predation, but their predators may also be weakened by OA, resulting in no net change in the predation rate. Only a handful of studies have considered predator-prey interactions, also known as trophic interactions, and these studies highlight the importance of further investigation into this field of research. One example showed that the diatom phytoplankton species *Thalassiosira pseudonana* produced less polyunsaturated fatty acids, which are nutritionally important to the copepod *A. tonsa*, when it was grown at ~740 ppm pCO_2 (Rossoll et al. 2012). While this may not have impacted the phytoplankton, it had a significant impact on *A. tonsa* eating the phytoplankton grown at 740 ppm. These copepods developed slower and had significantly reduced egg production (5 eggs per female per day compared to 34 eggs per female per day for copepods eating phytoplankton raised at ambient pCO_2). These results are extremely important, because the majority of work considering the impact of high CO_2 on copepods suggests they are not greatly affected by OA conditions, but in most of these studies copepods are fed food grown at ambient CO_2.

4.4.2. Exposure of Multiple Life Stages or Multiple Generations

The vast majority of experiments investigating the effects of OA on marine organisms have considered only one species, and typically only one life stage of that species. This approach fails to address links between the organism's different developmental life stages or the influence that parental exposure to high $p\mathrm{CO}_2$ conditions may have on the organism's response. These single-life-stage studies can be useful to determine the mechanisms by which OA affects an organism, but to accurately project a population's response to OA we need to increase the number of multi-life-stage and multi-generational studies. Relying on single-life-stage exposure studies to make forecasts of how a species will fare will not accurately reflect the species' true vulnerability to OA.

From the few multi-life-stage studies that have been performed on marine organisms, it is clear that exposure during one life stage can affect the response of a later life stage. For example, Gobler & Talmage (2013) found that when larval bay scallops were exposed to high $p\mathrm{CO}_2$ conditions and then raised in ambient conditions as juveniles, the juveniles experienced carry-over effects of the larval exposure, resulting in smaller juveniles. Smaller juveniles are more vulnerable to predation, so the carry-over effects of the larval exposure to high CO_2 could have implications for population success. This is an example of how multiple life stage studies produced unanticipated negative effects. However, multiple life stage exposure can also show unanticipated *positive* effects. Adult barnacles exhibited compensatory calcification when they had been exposed to high $p\mathrm{CO}_2$ since their larval stage (McDonald et al. 2009). In this case, adult barnacles that had been exposed to high $p\mathrm{CO}_2$ their entire life calcified more than adult barnacles that had been exposed to ambient $p\mathrm{CO}_2$ for their entire life, which, from the organism's perspective, is a positive response to life-long exposure to high $p\mathrm{CO}_2$. Many studies have focused only on early life stages due to their vulnerability, but clearly, we cannot always extrapolate these results to later life stages and to population vulnerabilities.

In addition to exposing organisms to OA conditions for multiple life stages, there is a need for more experiments exposing the parental generation to OA conditions while they are developing their eggs and sperm (gametogenesis). Maternal exposure to stressful environmental conditions during this time can affect how much energy they put into reproduction, which can influence survival and fitness of their offspring. This phenomenon is known as 'maternal effects' (Marshall et al. 2008). Because egg development is more energetically-costly to the mother than sperm development is to fathers, it is generally accepted that any maternal effects would be greater than paternal effects. No studies of Maine's commercially important species have included parental exposure as part of the treatment.

However, because of their short generation time, several copepod experiments have included either maternal or both maternal and paternal exposure. A recent study considering the effects of both maternal and paternal exposure to OA conditions on the copepod, *Acartia tonsa* offspring (Cripps et al. 2014a) found, in addition to decreased egg production rate and naupliar production seen with maternal exposure, that combined maternal and paternal exposure also decreased hatching success at 1000 ppm and egg volume at 3000 ppm. This suggests that paternal exposure can affect reproductive success in copepods and highlights the need for experiments on Maine's commercial species to include parental exposure to OA treatments. Multi-generational exposure studies can also provide us with data that can be used to predict the ability of the organism to acclimate or adapt to OA conditions. Damselfish (*Acanthochromis polyacanthus*), a non-Maine species, continued to exhibit negative behavior as a result of exposure to increased $p\mathrm{CO}_2$ even when they came from parents who had been exposed to increased $p\mathrm{CO}_2$, indicating that they are not able to acclimate to OA conditions through parental exposure (Welch et al. 2014).

4.4.3. Ocean Acidification in the Context of Multiple Stressors

Coastal marine ecosystems are some of the most biologically productive regions on Earth. Globally, the world ocean contributes more than 20 billion $US in annual resources (Costanza et al. 1997). In New England alone, the value of commercial fish landings was $1.16 billion in 2013 (NMFS, Fisheries of the US 2013). However, with over 3 billion people living within 100 km of the coastline, it is also a region that experiences significant anthropogenic stressors. The stressors are numerous and include such things as intense nutrient loading and the resultant chronic low oxygen (hypoxia), rising temperature, overfishing, pollution, changes in ocean mixing and circulation and introduction of invasive species. Ocean acidification is an additional, more recently recognized stressor and must be considered with the co-occurrence of these other anthropogenic threats.

When considering the impact of ocean acidification on the commercial harvest of marine species from Maine's ocean waters, we must consider them in the context of other anthropogenic perturbations. For example, like much of the ocean, the Gulf of Maine is warming. Although there is some debate about the actual rate of temperature increase in the Gulf of Maine (at least one study suggesting that it is warming approximately 8 times faster than the rest of the world ocean (A. Pershing, Gulf of Maine Research Institute, unpublished data)), it is warming at least as fast as the rest of the Earth with increases equivalent to ~0.13 °F per decade (EPA 2014). This warming must be considered in the broader context of ocean acidification research on Maine's coastal marine species so that their combined effect can be evaluated.

The Northeastern United States has some of the highest external loading of nutrients anywhere on Earth (Howarth 2008). For example, even in the small city of Portland, the Portland Water Districts Waste Water Treatment Plant releases on average over 3,000 pounds of total nitrogen per day into Portland Harbor. This nitrogen promotes growth of algae and during some times of the year will lower dissolved oxygen when this algae decays away. In addition to lowering oxygen, carbon dioxide will also be produced and is an extremely important source of acid in coastal waters impacted by large inputs of external nutrient loads. Work by Friends of Casco Bay shows the clear relationship between dissolved oxygen concentration and pH in Casco Bay in seawater samples taken from 1993-2008 (Figure 14). Dissolved oxygen concentrations and pH are generally strongly correlated in coastal ecosystems (Frieder et al. 2012; Cai et al. 2011, Wallace et al. 2014) and the effect on acidification can be striking. For example, in the Chesapeake Bay, CO_2 produced from excess nutrient loading has resulted in the progressive lowering of pH at a rate nearly 3 times faster than the open ocean (Waldbusser et al. 2011b).

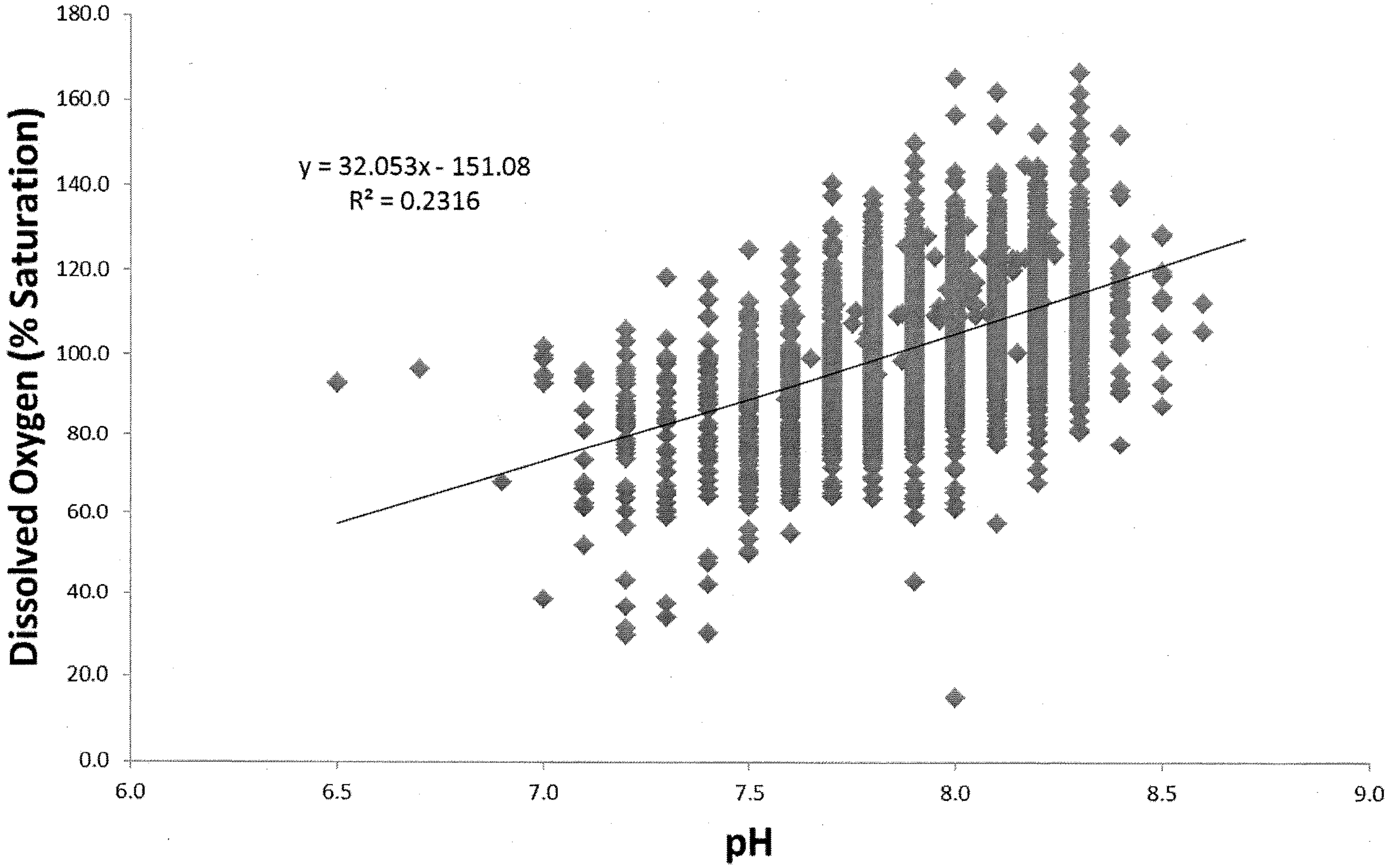

Figure 14. Friends of Casco Bay surface water quality data (1993-2008) show the positive relationship between dissolved oxygen and pH. (Friends of Casco Bay, unpublished)

Like the potential for additional stress from a warming ocean, the co-occurrence of chronic low oxygen with low pH exemplifies why ocean acidification research of marine species shoreward of the shelf-break needs to consider the interactive effect of each.

The effects of other stressors coinciding with an acidifying ocean on marine organisms are still poorly understood (Pörtner 2008; Przeslawski et al. 2008). However, most current ongoing ocean acidification research is factorial in nature, considering the combined impact of an acidifying ocean with other anthropogenic threats, in particular increasing water temperature and chronic low oxygen. The combined interaction of stressors can have simple additive effects (both are significant, but there is no significant interaction) or complex interactive effects where they have either synergistic (increased stress) or antagonistic (decreased stress) responses on biological processes (Folt et al. 1999).

Research on larval and juvenile stages of hard clams (*M. mercenaria*) and bay scallops (*A. irradians*) to past, present and future temperatures (24 and 28 °C) and CO_2 concentrations (~250, 390, and 750 ppm) demonstrated that increases in temperature and CO_2 each significantly depressed survival, development, growth and lipid synthesis of *both species* and that the effects were additive (Talmage & Gobler 2011). The combined effect of elevated temperature and CO_2 also works additively to increase metabolic rate in pteropods (Comeau et al. 2010b) and brittlestars (Wood et al. 2010). Effects greater than the simple additive effects of elevated temperature and CO_2 have also been reported in oysters (Lanning et al. 2010). Elevated CO_2 likely narrows the range of tolerance for temperature of marine species such as sea urchin larvae and crab (Metzger et al. 2007; O'Donnell et al. 2009). At high $p\text{CO}_2$ (1000 ppm), metabolism in the squid, *Dosidicus gigas*, is reduced at high temperature (Rosa & Seibel 2010); as mentioned earlier in this report, this is likely due to reduced oxygen carrying capacity of oxygen-carrying proteins.

4.5. Ecosystem Effects of Ocean Acidification

To date, most experiments have focused on single species responses to ocean acidification. But how ocean acidification affects the structure of marine ecosystems as a whole is unknown. Without an analog in Earth's history (no past event has occurred at the current rate) to help us predict what ecosystem changes can be expected, research efforts must move beyond the single species approach to consider how OA will impact the structure and function of ecosystems and apply new tools to investigate the indirect impacts. Ecological theory provides insights and it can be inferred that as the metabolic expense to calcify increases, other functions and or behavior will suffer (Cohen & Holcomb 2009). Reallocation of energy can result in altered predator-prey dynamics (Kroeker et al. 2014), compromised immune systems, disrupted reproduction, growth and competition. Observations of marine communities' responses to naturally occurring undersea CO_2 vents also provide insights into impacts of life in low pH conditions. Species diversity decreases near CO_2 vents and calcifying species are absent (Connell et al. 2013). In highly calcified ecosystems, like coral reefs, healthy coral communities shift to coral-free areas dominated by algae adjacent to the vents (Hall-Spencer et al. 2008).

While multispecies mesocosm experiments (Leu et al. 2013) and food web models designed to investigate indirect effects (Busch et al. 2013) are rare, these are the research efforts that are needed to shed light on the realistic scenarios facing marine communities. To investigate ecosystem impacts of OA in Puget Sound, researchers in Washington State developed a scenario-based food web model that decreased productivity of calcifiers (Busch et al. 2013). The most pronounced effects were seen in response to changes in copepod productivity. For example, forced declines in copepods resulted in a decrease in herring harvest (whose main food source is copepods), but also in declines in biomass of non-commercially important species including migratory diving birds and gulls, who eat herring. This model highlights the importance of considering the direct and indirect responses in the context of the entire food web.

Given that Maine has lower marine biodiversity with less functional redundancy than Puget Sound, there are fewer species performing the same ecological function, so if one species in a trophic level is removed or compromised, there may not be another to take its place. A similar modeling exercise in the Gulf of Maine could provide managers with a tool for incorporating ocean acidification into resource management.

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APPENDIX D

Proposed Legislation

An Act to Create the Ocean Acidification Council

December 5, 2014

Be it enacted by the People of Maine as follows:

Sec. 1. 5 MRSA §24004-I, sub-§57-H, is enacted to read:

57-H.

Marine Resource	Ocean Acidification Council	Expenses/Legislative per diem	38 MRSA c. 32

This subsection is repealed December 31, 2018.

Sec. 2. 38 MSRA, chapter 32, is enacted to read:

§3020. The Ocean Acidification Council

1. Establishment and purpose. The Ocean Acidification Council, referred in this section as the "council," established by Title 5, section 12004-I, sub-§57-H is created to identify, study, mitigate and prevent the direct and indirect effects of coastal and ocean acidification on species that are commercially harvested and grown in the state's coastal and ocean environments.

2. Membership. The council consists of the following 16 members:

A. Two members of the Senate appointed by the President of the Senate, including one member from each of the 2 parties holding the largest number of seats in the Legislature;

B. Three members of the House of Representatives appointed by the Speaker of the House, including at least one member from each of the 2 parties holding the largest number of seats in the Legislature;

C. Eight members appointed by the Commissioner of Marine Resources, including:

(1) Two representatives of an environmental or community group or one from each type of organization;

(2) Three persons who fish commercially, including at least one aquaculturist; and

(3) Three scientists who have studied coastal or ocean acidification.

D. Three members as follows:

(1) The Commissioner of Marine Resources or the commissioner's designee;

(2) The Commissioner of Environmental Protection or the commissioner's designee; and

(3) The Commissioner of Agriculture, Conservation and Forestry or the commissioner's designee.

3. Chairs. The first-named Senate member is the Senate chair and ther firt-named House of Representatives member is the House chair of the council.

4. Staff assistance. Within the limits of its budget, the council is authorized to contract and employ staff members to assist the council in carrying out its duties. In the event funding does not permit adequate staff support, the Department of Marine Resources and the Department of Environmental Protection shall provide staff support within the departments' existing resources.

5. Quorum. For purposes of holding a meeting, a quorum is 7 members. A quorum must be present to start a meeting or to vote but not to continue or adjourn a meeting.

6. Terms; vacancies. Members of the council shall serve for a term of 2 years and may be reappointed. A vacancy must be appointed by the same appointing authority that made the original appointment. Members may continue to serve until their replacements are designated. A member may designate an alternate to serve on a temporary basis.

7. Consultation. Whenever the council deems it appropriate, the council may seek the advice of experts in fields related to its duties.

8. Powers and duties. The council:

A. Shall meet at least twice annually;

B. Shall review, study and analyze existing scientific literature and data on coastal and ocean acidification and how it has directly or indirectly affected or may potentially affect commercially harvested and grown species along the coast of the State;

C. Shall identify critical scientific data and knowledge gaps pertaining to coastal and ocean acidification as well as critical scientific data and knowledge gaps pertaining to the effects of coastal and ocean acidification on species that are commercially harvested and grown along the coast of the State;

D. Shall include in its review of the relevant scientific literature and data the results of studies presented at conferences or workshops related to coastal and ocean acidification;

E. Shall identify and monitor the factors contributing to coastal and ocean acidification;

F. Shall work to strengthen existing scientific monitoring, research and analysis regarding the causes of and trends in coastal and ocean acidification;

G. Shall identify methods and protocols to mitigate coastal and ocean acidification;

H. Shall work to increase public awareness of coastal and ocean acidification;

I. Shall work to implement the r recommendations contained in the December 2014 report of the Commission To Study the Effects of Coastal and Ocean Acidification and Its Existing and Potential Effects on Species That Are Commercially Harvested and Grown Along the Maine Coast authorized by Resolve 2013, chapter 110;

J. When appropriate, may consult and advise State agencies, the Legislature, Maine's congressional delegation, the Governor and federal entities on matters regarding coastal and ocean acidification;

K. May assist the Legislature and the Governor on pending legislation related to coastal and ocean acidification, including, but not limited to, testimony at a public hearing on legislation before a joint standing committee of the Legislature;

L. May examine existing laws pertaining to coastal and ocean acidification;

M. Shall identify and promote economic development opportunities afforded by ocean acidification through development and commercialization of new technologies and businesses; and

N. May recommend or submit to the Legislature legislation relating to coastal and ocean acidification matters; and

O. May hold public hearings to receive testimony and recommendations from members of the public and qualified experts on matters related to coastal and ocean acidification.

9. Report. The council shall submit an annual report of its activities to the Governor, the joint standing committee of the legislature having jurisdiction over marine resources and the joint standing committee having jurisdiction over environmental protection. The council shall post the report on a publicly accessible site, maintained by the State on the Internet.

10. Reimbursement of expenses. The members of the council shall be compensated according to the provisions of Title 5, section 12004-I, subsection 57-H.

11. Accounting; outside funding. All funds appropriated, allocated or otherwise provided to the council must be deposited in an account separate from all other funds of the Legislature and are nonlapsing. Funds in the account may be used only for the purposes of the council. The council may seek and accept outside funding and is authorized on behalf of the State to accept federal funds to fulfill council duties. Prompt notice of solicitation and acceptance of funds must be sent to the Legislative Council. All funds accepted must be forwarded to the Executive Director of the Legislative Council, along with an accounting that includes the amount received, the date that amount was received, from whom that amount was received, the purpose of the donation and any limitation on use of the funds. The executive director shall administer all funds

<u>received in accordance with this section. At the beginning of each fiscal year, and at any other time at the request of the cochairs of the council, the executive director shall provide to the council an accounting of all funds available to the council, including funds available for staff support.</u>

Sec. 3. Repeal. This chapter is repealed on December 31, 2018.

SUMMARY

The bill establishes the Ocean Acidification Council to identify, study, mitigate and prevent the direct and indirect effects of coastal and ocean acidification on species that are commercially harvested and grown in the State's coastal and ocean environments.

It provides for 16 council members, including two members of the Senators, 3 members of the House of Representative, 2 representatives of an environmental or community groupo, 3 persons who fish commercially, including at least one aquaculturist, 3 scientists and the Commissioner of Marine Resources, the Commissioner of Environmental Protection and the Commissioner of Agriculture, Conservation and Forestry.

The duties of the council include, but are not limited to, the following:

1. The review and study of the existing scientific literature and data on coastal and ocean acidification and how it has directly or indirectly affected or potentially will affect commercially harvested and grown species along the coast of the State;

2. Identify and monitor the factors contributing to coastal and ocean acidification and methods to mitigate acidification:

3. Work to implement the r recommendations contained in the December 2014 report of the Commission to Study the Effects of Coastal and Ocean Acidification and Its Existing and Potential Effects on Species That Are Commercially Harvested and Grown Along the Maine Coast established by Resolve 2013, chapter 110;

4. Advise State agencies, the Legislature, Maine's Congressional Delegation, the Governor and federal entities on matters of coastal and ocean acidification;

5. Assist the Legislature and the Governor on pending legislation related to coastal and ocean acidification including giving testimony at a public hearing on legislation before a joint standing committee of the Legislature;

6. Identify and promote economic development opportunities afforded by ocean acidification through development and commercialization of new technologies and businesses;

7. Recommend or submit legislation to the Legislature relating to coastal and ocean acidification matters; and

8. Hold public hearings to receive testimony and recommendations from members of the public and qualified experts on matters related to coastal and ocean acidification.

This bill also requires the council to submit an annual report to the Legislature and authorizes the council to accept funding from outside sources and contains a provision repealing the laws establishing the council. This Act is repealed on December 31, 2018.

APPENDIX E

Synopsis of Goals and Recommendations

GOALS	RECOMMENDATIONS
1. Invest in Maine's Capacity to Monitor and Investigate the Effects of Ocean Acidification and Determine Impacts of Ocean Acidification on Commercially-Important Species and the Mechanisms Behind Those Impacts	*1.1. Enhance monitoring and create a database sufficient to support the development of regulatory and non-regulatory approaches to reduce and limit nutrients and organic carbon from sources that are contributing significantly to acidification of Maine's marine waters. Enhanced monitoring should begin in one or more pilot estuaries where impacts are presently occurring.*
	1.2. Expand monitoring of ocean acidification to establish its natural variability and to detect trends in water chemistry and related biological responses.
	1.3. Develop new tools with which to assess and understand acidification and its impacts in Maine waters.
	1.4. Determine the causes and relative importance of acidification in the waters and sediments of Maine.
	1.5. Identify the impacts of acidified waters and sediments on Maine's commercial species.
2. Reduce Emissions of Carbon Dioxide	*2.1. Strengthen coordination and continue participation with existing national, state, and regional initiatives regarding the reduction of atmospheric* CO_2 *levels.*
	2.2. Encourage key leaders and policymakers to synchronize in establishing a comprehensive and unified strategy to reduce carbon dioxide emissions.
	2.3. Expand actions at the state and local levels that may help in reducing CO_2 *emissions.*

GOALS	RECOMMENDATIONS
3. Identify and Reduce Local Land-Based Nutrient Loading and, Organic Carbon Contributions to Ocean Acidification and Freshwater Runoff by Strengthening and Augmenting Existing Pollution Reduction Efforts and Making Groundwater Recharge a Land Use Priority.	*3.1. Identify and reduce nutrient loading and organic carbon from point source and nonpoint discharges determined to cause or contribute to ocean acidification.*
	3.2. Assess the need for water quality criteria relevant to ocean acidification.
	3.3. Ensure that state staff and other practitioners are working with the best information and most effective technology.
	3.4. Investigate incentive programs for pollution and freshwater runoff reduction.
	3.5. Support and reinforce current planning efforts and programs that address the impacts of nutrients and organic carbon and freshwater runoff into coastal waters.
	3.6. Enhance education and outreach programs that provide landowners with information about best practices for reduction of nutrient pollution.
4. Increase Maine's Capacity to Mitigate, Remediate and Adapt to the Impacts of Ocean Acidification	*4.1. Preserve, enhance and manage a sustainable harvest of kelp, rockweed and native algae in bivalve areas and adjacent shoreline, and preserve and enhance eelgrass beds.*
	4.2. Encourage bivalve production to support healthy marine waters.
	4.3. Spread shells or other forms of calcium carbonate (CaCO$_3$)in bivalve areas to remediate impacts of local acidification.

GOALS	RECOMMENDATIONS
(Goal 4 continued)	*4.4. Increase the capacity of the fishing and aquaculture industries to adapt to ocean acidification.*
	4.5. Identify refuges and acidification hotspots to prioritize protection and remediation efforts.
	4.6. Encourage the enhancement and creation of research hatcheries.
5. Inform Stakeholders, the Public, and Decision-Makers about Ocean Acidification in Maine and Empower Them to Take	*5.1. In addition to providing the commission's report, its key findings should be communicated to the Governor, Maine's legislative leaders, Maine's Congressional delegation, the press and the general public in a series of briefings by commission members.*
	5.2. Continue efforts to increase the understanding of ocean acidification among key stakeholders, targeted audiences and local communities to help implement the commission's recommendations.
	5.3. Enhance the existing communication network of engaged stakeholders, state agency representatives and the research community.
	5.4. Develop, adapt and use curricula on ocean acidification in K-12 schools and institutes of higher education and increase interdisciplinary university programs to equip young leaders with the skills to find solutions to complex multidisciplinary problems such as ocean acidification.

GOALS	RECOMMENDATIONS
6. Maintain a Sustainable and Coordinated Focus on Ocean Acidification.	*6.1. Create an on-going ocean acidification council.*

APPENDIX F

Glossary of Terms

Glossary of Terms

Term	Definition
Acclimate	The process in which an individual organism adjusts to a gradual change in its environment (such as a change in temperature or pH), allowing it to maintain performance across a range of environmental conditions.
Acidification Budget	Acidification budget is a quantifiable expression that accounts for all net inputs and sinks of acid to a defined ecosystem.
Amorphous $CaCO_3$	Amorphous calcium carbonate is the amorphous (has no definitive form) and least stable form of calcium carbonate. It is so unstable under normal conditions that aside from several specialized organisms it is not found naturally.
Anthropogenic	Originating in human activity.
Aragonite	Aragonite is a carbonate mineral crystal form of calcium carbonate. It is formed by biological and physical processes, including precipitation from marine and freshwater environments. It is denser, considerably harder, but more soluble than calcite.
Benthos / Benthic	*Benthos* refers to the community of marine and aquatic organisms that live on or close to the bottom of a water body. *Benthic* refers to plants and animals inhabiting the ocean bottom.
Biogeochemical	Biogeochemistry is the study of the cycles of chemical elements, such as carbon and nitrogen, and their interactions with and incorporation into living things transported through earth scale biological systems in space through time.
Bivalve	Mollusks that have two shells e.g., clams, oysters, scallops and mussels are all bivalves.
Buffering	A buffer minimizes change in the acidity of a solution when an acid or base is added to the solution.
Calcite	A specific crystalline form of the mineral calcium carbonate, found in the shells of many marine organisms, including adult oysters, lobsters, and sea urchins; it dissolves less readily than aragonite.

Glossary of Terms

Term	Definition
Calcium Carbonate / Bicarbonate / Calcification / Ions	A mineral composed of calcium (Ca^{2+}) and carbonate ions (CO_3^{2-}). Marine calcifiers incorporate specific crystalline forms of $CaCO_3$ (e.g., calcite and aragonite) into their shells, skeletons, and other hard body parts.
Carapace	The upper shell or exoskeleton of several animal groups (e.g. lobster, shrimp, zooplankton) and serves as a protective cover for the animal. Because the carapace of different species contains varying degrees of calcium carbonate, ocean acidification may be a particularly acute stressor for these species.
Carbon Dioxide (CO_2)	A colorless, odorless, incombustible gas present in the atmosphere and formed during respiration.
Coccolithophores	A type of single-celled microalgae. Most species are marine, although some do live in freshwater. Coccolithophores are characterized by calcium carbonate plates, called coccoliths that surround the cell. As the only calcifying phytoplankton, they play an important role in inorganic carbon flux out of the uppermost layer of water.
Copepod	A group of small crustaceans that live in both the ocean and freshwater ecosystems. As the primary grazers of phytoplankton and generally the major food for organisms such as small fish and krill they represent an important ecological role on Earth.
Cyanobacteria	A photosynthetic nitrogen fixing bacteria that contains chlorophyll and a blue pigment. Cyanobacteria occur in wide variety of habitats including marine, freshwater, and soils.
Diatoms	Are one of the most common types of microalgae and are characterized by cell walls made of silica, known as a frustrule. Diatoms are unicellular, but frequently occur in colonial chains.
DIC (Dissolved Inorganic Carbon)	The total Dissolved Inorganic Carbon is the sum of carbon dioxide ($CO_2 \cdot H_2O$ or H_2CO_3), bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}) species.

Glossary of Terms

Term	Definition
Dinoflagellates	A group of flagellated marine protists that can propel itself with two slender threadlike structures. Some species of dinoflagellates can produce harmful algal blooms, such as red tide.
Emerging isotope techniques	Isotopes are different forms of an element that has the same chemical properties but different atomic weight. The different weights cause different isotopes of the same element to behave slightly differently, depending on many conditions such as temperature or other environmental conditions. Scientists are continually learning new controls on isotope behavior, as well as new ways of measuring tiny variations in their abundance.
Estuaries	A partially enclosed coastal body of water with one or more rivers or streams flowing into it, and with a free connection to the open sea.
Eutrophication	The process whereby excessive nutrients in a body of water (frequently due to land runoff) causes intense biological productivity followed by decomposition resulting in severe oxygen depletion and the release of carbon dioxide, both of which can be harmful to benthic ecosystems.
Extreme Precipitation Events	"Extreme precipitation events" are rain or snows events during which the amount of precipitation experienced in a location substantially exceeds what is normal as based on the historical record.
Fixed nitrogen	Nitrogen fixation is a process in which nitrogen (N_2) in the atmosphere is converted into ammonium (NH_4^+). Atmospheric nitrogen or molecular nitrogen (N_2) does not easily react with other chemicals to form new compounds. The fixation process frees up the nitrogen atoms to be used in other ways such as the production of organic matter.
Foraminifera	A class of single-celled organisms, known as protists. Foraminifera typically produce an external shell that is composed of either calcium carbonate ($CaCO_3$) or clumped sediment particles. The species composed of calcium carbonate are susceptible to dissolution from ocean acidification.

Glossary of Terms

Term	Definition
Gastropod	Mollusks that have one shell (univalves), e.g., conch, moon snails, and periwinkles.
Gelbstoff	The dissolved or colloidal organic matter that imparts a "tea" color to waters that have had sufficient contact time with decaying vegetation. This is also known as colored dissolved organic matter (CDOM).
Gene pool	The total number of genes of every individual in an interbreeding population.
Genome	The genetic material present in the cell of an organism.
Hypercapnia / Acidosis	A condition of abnormally elevated carbon dioxide levels in the blood.
Hypoxia	A deficiency in the amount of oxygen reaching body tissues.
Inshore	Refers to parts of the ocean close to land and with greater influence of freshwater. We imply no boundary between inshore and offshore; rather, we use the terms to indicate the relative influences of connection with land and freshwater. These relative influences change with water depth, freshwater inflow, stage of tide, etc.
Intracellular	Any material or process located or occurring inside a cell.
Macroalgae	Macroscopic, multicellular algae; commonly referred to as seaweeds. Common macroalgae in Maine include rockweed (brown algae) and sea lettuce (green algae).
Mesocosm experiments	A mesocosm is an experimental tool that brings ecologically relevant components of the natural environment under controlled conditions.
Metabolism	The chemical processes occurring within a living cell or organism that are necessary for the maintenance of life. In metabolism some substances are broken down to yield energy for vital processes while other substances, necessary for life, are synthesized.

Glossary of Terms

Term	Definition
Metal speciation	Dissolved metals, such as copper or lead, may form different molecules by associating with various atoms. This distribution of forms is termed speciation.
Microalgae	Microalgae are microscopic algae, typically found in freshwater and marine systems. They are unicellular species which exist individually, or in chains or groups.
Microcosm experiments	Small-scale experiments performed in artificial simplified ecosystems. They are used under controlled conditions to determine the effects of a perturbation (i.e. climate change or ocean acidification) on a key species or group of species.
Nauplius	The early larval stage of some crustaceans including barnacles and copepods. This life stage is characterized by the use of antennae for swimming and the formation of an eye.
Nearshore	See inshore
Neutralization	The process in which an acid and a base react quantitatively with each other. In water, neutralization results in there being no excess hydrogen or hydroxide ions present in the solution.
Nonpoint sources	Nonpoint source pollution, unlike pollution from industrial and sewage treatment plants, comes from many diffuse sources e.g. rainfall or snowmelt moving over and through the ground.
Nutrients	Any substance that nourishes an organism. The growth of most marine plants is limited by the availability of the nutrient nitrogen in the ocean.
Ocean acidification	Ocean acidification (OA) refers to the processes that lower the pH of ocean water.
Offshore	Referring to parts of the ocean away from land and with less influence of freshwater. We imply no boundary between inshore and offshore; rather, we use the terms to indicate the relative influences of connection with land and freshwater. These relative influences change with water depth, freshwater inflow, stage of tide, etc.
Olfactory	Relating to the sense of smell.

Glossary of Terms

Term	Definition
Organic vs. Inorganic	The primary difference between organic compounds and inorganic compounds is that organic compounds always contain carbon while most inorganic compounds do not contain carbon. Also, almost all organic compounds contain carbon-hydrogen or C-H bonds.
pCO_2	The partial pressure of carbon dioxide. The value of pCO2 depends on the amount of total carbon in the water, its buffering capacity and water temperature.
PETM (Paleocene-Eocene Thermal Maximum)	Refers to a climate event that began at the time of boundary between the Paleocene and Eocene ages (thought to be close to 55.8 million years ago) during which a huge amount of carbon dioxide was released into the atmosphere significantly reducing the calcification ability of organisms world-wide. The fossil record provides evidence of mass extinctions during the PETM.
pH/pH scale/Acidification	An **acid** is any substance that causes an increase in the concentration of hydrogen ions (H^+) when it dissolves in water. The **pH** of any solution is a measure of how acidic or basic it is. The pH scale runs from 0 to 14 with pH 7.0 being neutral. Pure water, for example, is neutral. Any pH value less than 7.0 means that the solution is acidic, and solutions with pH's greater than 7.0 are basic. Since pH is technically defined as the negative logarithm of the hydrogen ion concentration, each increase or decrease of one pH unit corresponds to a 10 fold increase or decrease in acidity.
Photosynthesis	The process used by plants and other organisms to capture the sun's energy to split water into hydrogen and oxygen. The hydrogen is combined with carbon dioxide (absorbed from air or water) to form sugar (glucose); oxygen is produced as a waste product.
Phytoplankton	Photosynthesizing microorganisms that inhabit the upper sunlit layer of the ocean. In terms of numbers, the most important groups of phytoplankton include the diatoms, cyanobacteria and dinoflagellates.
Primary Production	Refers to the creation of organic matter by photosynthesis.

Glossary of Terms

Term	Definition
Proxies	A way to indirectly measure aspects of climate. Biological or physical records from ice cores and tree rings are good examples of proxy data for historic climate conditions not directly measured.
Pteropods	Commonly called "sea butterflies," pteropods are animals about the size of a pea that swim using a wing –like appendage. Most have a calcified shell and are an important food source for many marine animals including whales and salmon.
Recharge	A hydrologic process where water moves downward from surface water to groundwater.
Respiration	The metabolic conversion by organisms of nutrients into biochemical energy. Respiration provides energy to cells, which is used to power all life processes and releases CO_2 and water as waste products.
Salinity	Salinity is the saltiness or dissolved salt content (such as sodium chloride, magnesium and calcium sulfates, and bicarbonates) of a body of water or in soil.
Saturation / Undersaturation / Supersaturation	Minerals can dissolve in water, or in some cases be precipitated out of water. We can predict which process should occur based on the dissolved concentrations of the ions that make up the crystalline solid. If the dissolved concentrations are higher than a specific value, we say that the solution is *supersaturated* with respect to that crystalline solid. On the other hand, if these concentrations are below this specific value, we call the solution *undersaturated*. We describe the condition of water with respect to this precipitation vs. dissolution with a term called the *saturation state*.
Spat	Refers to newly settled marine animals (e.g. clams, scallops, oysters) that have metamorphosed from planktonic larvae into benthic (bottom dwelling) juveniles. Metamorphosis is also called "setting." Oyster and clam seed are often referred to as spat or "post-set."

Glossary of Terms

Term	Definition
Stratification	Refers to the buoyant layering of water masses on top of one another, in a manner that inhibits mixing up and down. Stratification can prevent deeper waters from releasing respired carbon dioxide back to the atmosphere, or replacing used up oxygen.
TA	See total alkalinity.
Tipping Point	The point at which there is an abrupt change in an ecosystem quality, property or phenomenon, or where small changes in an environmental driver produce large responses in the ecosystem.
Total alkalinity	Alkalinity describes the amount of strong acid that a solution can absorb before it reaches a certain pH – usually around 4.5. It is thus similar to buffering but not exactly the same. *Total alkalinity* (abbreviated as *TA*) refers to this property applied to all of the dissolved ions in seawater.
Trophic	The trophic level of an organism is the position it occupies in a food chain.
Zooplankton	An animal that swim weakly or drift in the water. As with phytoplankton, their movement is in large part due to currents. Individual zooplankton are usually too small to be seen with the naked eye, but some, such as jellyfish, are large.

APPENDIX G

Island Institute 2014 report, Increasing Community Resilience to Ocean Acidification in Maine, Executive Summary

Increasing Community Resilience to Ocean Acidification in Maine:

Analyzing and Responding to the Economic, Cultural, and Social Impacts

A Workshop in the Island Institute's Climate of Change Series

October 7, 2014

Maine Maritime Museum
Bath, Maine

Organized and Hosted by: The Island Institute and The Natural Resources Defense Council
Facilitated by: Heather Deese, Island Institute & Laura Taylor Singer, SAMBAS Consulting

Full Workshop Report Found at: www.islandinstitute.org/OceanAcidification

ISLAND INSTITUTE

NRDC
THE EARTH'S BEST DEFENSE

Executive Summary

Ocean acidification (OA) can have profound impacts on marine ecosystems and human communities that depend on marine resources. The impact of ocean acidification has become a major focus for fishermen, scientists, and policy makers who are concerned about the threat to commercially important fisheries and the aquaculture industry. Unfortunately, the cold temperatures and relatively large freshwater inflows to the Gulf of Maine and high dependence on fisheries make Maine's coastal communities particularly susceptible to ocean acidification. In April 2014, the Maine legislature created a commission to study the effects of ocean and coastal acidification on species that are commercially harvested and grown along the Maine coast and provide policies and tools to respond to OA.

Recent collaborations among researchers, nonprofit organizations, government agencies, industry members, and private citizens have made progress in better understanding the potential environmental impacts of OA. However, less work has been done to assess the social and economic vulnerability of communities to OA. *Increasing Community Resilience to Ocean Acidification in Maine: Analyzing and Responding to the Economic, Cultural, and Social Impacts* was held as part of the Island Institute's *Climate of Change Series* to raise awareness in Maine about the various tools and data being used in vulnerability assessments. Co-hosted by the Natural Resources Defense Council (NRDC), the workshop featured the work of Drs. Lisa Suatoni and Julie Ekstrom (NRDC) who recently completed a national assessment of communities' vulnerability to ocean acidification. Maine exhibited high sensitivity to OA because of dependence on shellfish and aquaculture, and high social vulnerability in Downeast areas.

Workshop participants were asked to prioritize valued *environmental or socioeconomic qualities* of a healthy coastal ecosystem or coastal community and to develop a list of indicators that Maine may want to use to assess the ecosystem or community's vulnerability to OA. They then identified data that is available and data that is needed to track these indicators.

Environmental Qualities Valued:

- water quality
- species diversity
- ecosystem health and services
- habitat diversity
- sustainable fisheries

Socioeconomic Qualities Valued:

- cultural identity
- economic and social sustainability of communities
- controlled growth
- thriving working waterfront
- sustainable fishing industry

Participants came up with numerous Maine-specific indicators to measure these qualities. Some of the data needs identified in order to complete a vulnerability assessment included environmental data such as: carbonate chemistry time series data at more locations (co-located with commercially important species and adjacent to point sources- in estuaries, mud, open ocean, surface, sea floor), more comprehensive data on species (specifically lobster); and socioeconomic data such as: the breakdown of licenses/landings by community, sector, activity and time of year, margin between costs and income, number of fishermen holding second jobs, new entrants into fisheries, etc.

The workshop also explored mitigation, remediation, and adaptation options and demonstrated how the results of a vulnerability analysis can be used to focus these efforts. While the primary cause of OA is carbon emissions being absorbed by the ocean, there are local actions we can take to mitigate coastal acidification, such as reducing polluted runoff from farms, lawns, and septic systems that are causing coastal waters to acidify more rapidly, and preserving marine photosynthesizers, like eel grass, that may reduce local acidification.

Workshop participants made a series of recommendations to address OA. Although not refined or prioritized, they can serve as a starting point for further conversations about OA in Maine.

Mitigation

- ➔ CO_2 reduction- reduce energy waste and consumption
- ➔ Reduce nutrient input to coastal waters
- ➔ Establish and update criteria and standards

Remediation

- ➔ Increase pH in mudflats
- ➔ Increase CO_2 and nutrient uptake in coastal waters and estuaries

Adaptation

- ➔ Diversify local economies

Research & Monitoring

- ➔ Work closely with the Northeast Coastal Acidification Network (NECAN)
- ➔ Monitor pH levels
- ➔ Identify location and extent of nitrogen input
- ➔ Develop technological solutions
- ➔ Document impacts of OA

Policy & Planning Initiatives

- ➔ Increase state planning efforts
- ➔ Expand local planning and use of model ordinances

Public Education & Dialogue

- ➔ Expand communication networks and planning forums
- ➔ Increase outreach and communication to the public
- ➔ Actively engage the fishing industry

A full, detailed report from the meeting including the agenda, presentation notes, and participant list can be found at: www.islandinstitute.org/OceanAcidification