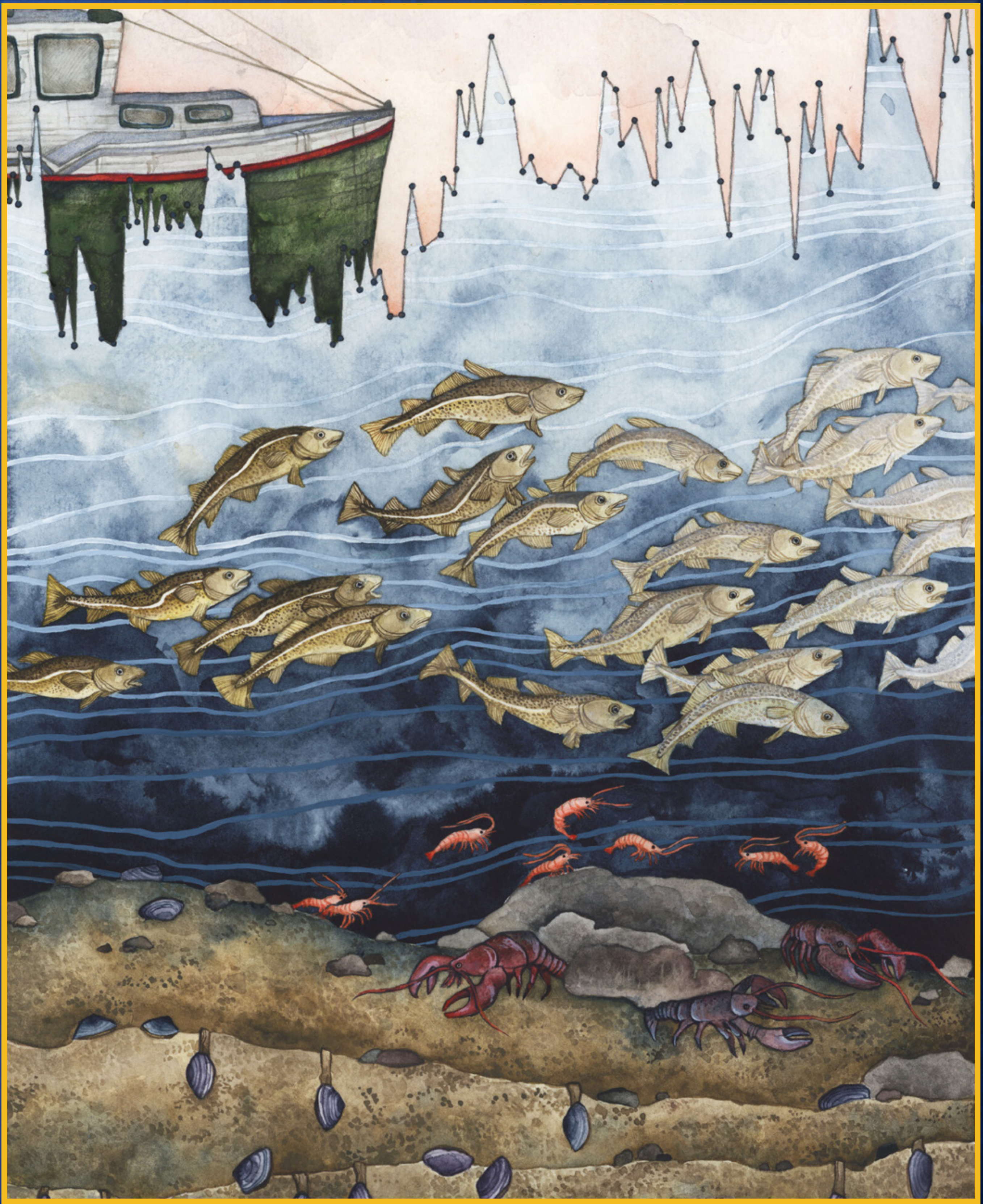
Scientific Assessment of Climate Change and Its Effects in Maine



MAINE CLIMATE COUNCIL
SCIENTIFIC AND TECHNICAL SUBCOMMITTEE

COVER IMAGE

Gulf of Maine Temperature Variability tells the story of increasing temperature fluctuations in Maine's coastal marine environment. The watercolor uses ocean temperature data from the past 15 years to highlight how greater variability affects various species including ourselves. The piece also highlights the inattention to the coupled relationship between human action and environmental responses that has contributed to depleted fish stocks and increased ocean acidification. This Gulf of Maine story spans the water column: from the burrowing clams and bottom-dwelling lobster and shrimp, to the overfished cod which disappear across the painting as they struggle to return to a changing habitat, and finally up to the surface where fishers and managers may adopt sustainable practices or continue the practices that have resulted in overfishing and by-catch. Each species has a complex interaction with the environment, and if the imbalance of our give-and-take relationship with the ocean persists, we will continue to see new stresses that irreversibly change ocean conditions within the intertidal mudflats and into the yet unexplored ocean depths.

Source: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5051723/

Artist: Jill Pelto is an Artist and Scientist who grew up in Worcester, MA, lived in Orono, ME from 2011 to 2018, then traveled and now resides back on the east coast. She completed her Masters of Science degree in 2018, and prior to that she completed her Bachelors of Arts degree in Studio Art and Earth Science, both at the University of Maine. Her graduate research focused on studying the sensitivity of the Antarctic Ice Sheet to changes in Earth's climate system. She has conducted research on mountain glaciers in Washington and British Columbia, the Dry Valleys and Transantarctic Mountains of Antarctica, the Falkland Islands and in the mountains of New Zealand. Most recently, TIME magazine commissioned Jill for the cover of the July 2020 Climate issue.

Scientific Assessment of Climate Change and Its Effects in Maine

A REPORT BY THE SCIENTIFIC AND TECHNICAL SUBCOMMITTEE OF THE MAINE CLIMATE COUNCIL

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EXECUTIVE SUMMARY

Climate change has already made its presence known in Maine, from shorter winters and warmer summers with ocean heat waves, to stronger storms, new species showing up in our backyards and the Gulf of Maine, aquatic algal blooms, acidic ocean waters that affect shellfish, and new pests and diseases that harm our iconic forests and fisheries.

The health of Maine people is also being affected by climate change, from high heat index days driving increased emergency room visits to the ravages of Lyme and other vector-borne diseases. And our economy is feeling the effects, too -with farmers trying to adapt to longer growing seasons but dealing with severe storms and late frosts, aquaculturists already adapting to a more acidic ocean, and winter sports like skiing and snowmobiling being impacted by our shrinking winter season.

This is the first report from the Maine Climate Council's Scientific and Technical Subcommittee, produced by more than 50 scientists from around the State representing Scientific and Technical Subcommittee members, other co-authors, and contributors. This report is part of the 2020 Maine Climate Action Plan. The report summarizes how climate change has already impacted Maine and how it might continue affecting our State in the future.

The findings from this report inform the ongoing deliberations of the Maine Climate Council and have aided the Maine Climate Council's six working groups in the development of draft strategies to address climate change by reducing Maine's greenhouse gas emissions. In addition, the Scientific and Technical Subcommittee identified critical scientific information gaps and needs to better understand and forecast potential future climate change impacts in the State. Key take-aways from this report are listed below, with the full details appearing in each of the twelve chapters.

Key deliverables from the Scientific and Technical Subcommittee in this report include:

- A summary of climate change's impacts across the State and to Maine's human and animal health, economy, and forest and agriculture systems,
- Sea level rise projections to 2100,
- An initial estimate of the contribution of Maine's forests to the state's annual carbon budget,
- Identification of priority information and data gaps about conditions in or for Maine, and
- Identification of methods to build resilience to direct and indirect effects of climate change for the State's species.

Climate

Maine's statewide annual temperature has increased by 3.2 °F (≈1.8 °C) since 1895, with rising overnight low temperatures driving more of this increase than daytime highs. Climate models project that Maine could warm an additional 2 to 4°F by 2050 and up to 10 °F (≈1-6 °C) by 2100 depending on the scenario of greenhouse gas emissions and societal development. Maine's winters are warming faster than any other season, and coastal areas have warmed more than the interior of the State.

The warming climate has been associated with a trend towards longer summers and shorter winters, where the change in duration in each of these seasons is about two weeks over the past century. Most of the increase in the length of the warm season has occurred during early fall. There has likewise been a net increase in the length of the growing season. These trends are expected to continue over the next century.

While the growing season has lengthened overall, some years have seen killing frosts in late spring/early fall. It is uncertain whether such events will become more or less frequent in the future.

Maine's statewide annual precipitation (rainfall and snowfall) has increased by 6 inches (152 mm) since 1895, with the unusually wet interval 2005-2014 significantly influencing this increase. Annual precipitation surpluses are mostly due to increased rainfall in summer and early fall. Most climate models project that Maine will continue to get wetter over the next century as increased heating intensifies the hydrologic cycle.

Maine has experienced an increase in the average number of heavy precipitation events per year, particularly since the mid-2000s. Likewise, studies of U.S. Northeast region precipitation show that heavy precipitation events have increased each season of the year, with the largest percentage increases in winter and spring. These trends are expected to continue over the next century as increased heating intensifies the hydrologic cycle.

An increase in storm frequency and intensity has been observed across the Northern Hemisphere since the 1950s, mostly during the cold season. A recent study of mid-autumn wind storms impacting New England also found a statistically significant positive trend in the frequency of bomb cyclones (low pressure systems that rapidly intensify) and in total storm precipitation for that time of year. It remains uncertain to what extent storms will change in frequency and intensity over the northeastern U.S.

There has not been an observed increase in meteorological drought occurrence across Maine over the past century, with precipitation showing an overall upward trend. However, model projections indicate that as the climate warms it is likely that increased evaporation will dry surface soil layers, particularly in the warm season. It is less clear how the frequency of drought in Maine may change in the future as a result of increasing greenhouse gas concentrations.

While it is uncertain whether drought conditions will become more or less likely in Maine as the climate warms, when drought conditions do develop, they are likely to be exacerbated by increasing temperatures and an overall enhancement of the hydrologic cycle, meaning more extreme precipitation events as well as increased evaporative loss of water.

Hydrology

Annual floods have increased in volume in Maine's rivers and streams during the last century. Patterns in larger less-frequent floods, such as the 100-year flow (1% chance of occurrence annually) are uncertain but may decrease with declines in winter snowpack.

In the last 50-100 years, snowpack depths have decreased, and snowpack densities have increased in late winter. Snowmelt-related runoff and lake and river ice out dates have occurred earlier. While these trends are likely to continue with ongoing warming, the future effects on low streamflows during summer are less clear.

Groundwater levels and low streamflows have increased or not changed significantly in recent years. However, there may be an increase in the length of the summer and fall low-flow season in the future for high greenhouse gas emission scenarios. Competing water demands in select watersheds during times of low flow have the potential to become exacerbated during future droughts.

Up-to-date accessible digital statewide floodplain maps that incorporate climate related changes and the use of Lidar are key to responding to current and future impacts of flooding related to climate change.

An expanded statewide snowpack monitoring network is critical for providing more comprehensive coverage over space and time. This would allow better prediction of snowmelt runoff each year and provide better baseline data for future snowpack and snowmelt changes.

A better understanding of the impact of climate change on summer low streamflows is needed. An expanded riverine streamgaging network that includes more small headwater streams would provide baseline data for potential future changes that may impact aquatic habitat. Studies that help us understand the impact of changing summer precipitation on summer/fall low flows are also needed.

Freshwater Quality

Much like Maine's air temperatures, the water temperatures of rivers, streams and lakes have been increasing over the last several decades. Because Maine's stream and lake temperatures have increased, winter ice thickness and duration have correspondingly decreased over time. Warming temperatures in rivers, streams, lakes and wetlands can alter which species thrive in those environments and eliminate cold-water adapted species.

Surface temperatures of lakes in northern New England increased 1.4°F (0.8°C) per decade from 1984-2014 – faster than the worldwide average – with smaller lakes warming more rapidly than larger lakes. Maine lake surface temperatures have warmed on average by nearly 5.5°F (3°C).

Increases in precipitation (rain and snow) and runoff over the last century in Maine, in combination with a reduction in acidic deposition and longer growing seasons, have resulted in a rise of dissolved organic carbon (DOC) in Maine's rivers, streams and lakes, and thus export of DOC to the Gulf of Maine. The concentration of DOC can alter aquatic species and influence water temperature and stratification patterns, thus altering plankton dynamics in aquatic systems.

The water quality of a significant number of rivers, streams and lakes has improved as a result of the numerous laws and regulations that were put in place to mitigate the effects of development, agriculture, and forestry practices on water quality in Maine. However, recent increases in the volume of stormwater runoff have resulted in transport of tons of soil and pollutants into our waters thus laws and regulations may need adjusting.

If Maine continues to receive more intense rainfall, stormwater transport of nutrients and other pollutants to our fresh waters will increase. Increasing nutrients will shift biota in rivers, streams and lakes to less-desirable species including nutrient-loving invasive species, cyanobacteria and possibly toxin-producing harmful algal bloom species. This will cause receiving waters to be less likely to meet their classification standards and be designated as impaired. The restoration of these waters will be expensive; in one example, restoration of East Pond in the Belgrade Lakes region cost over $1 million.

Multiple studies on Maine lakes have shown that shoreline property values decrease when water clarity is reduced due to the deterioration of lake trophic state. This causes a domino effect with respect to property taxes by shifting the tax burden from shoreland properties to upland properties. These studies estimated that our lakes generate annual revenue of approximately $4 billion (amount adjusted for inflation).

Ocean Temperature

The temperature of Gulf of Maine has exhibited considerable decadal variability, with a notable warm period in the mid-20th Century and a strong warming trend over the last 15 years, particularly in the late summer and fall. Recent warming has been punctuated by strong "marine heatwaves" in 2012 and 2016. Under all climate scenarios the climate (30-year average) of the Gulf of Maine will continue to warm through at least 2050.

Beyond 2050, the warming rate depends strongly on the emissions pathways. Under a low-emission scenario, temperatures stabilize around 2.7 °F (1.5° C) above the 1976-2005 baseline. This would cause the southern coast of Maine to have an ocean climate similar to that of Massachusetts or Rhode Island.

Under the high-emission scenario, temperatures continue to rise and exceed 5.4°F (3°C) above the baseline by the end of the century. This would cause even the eastern coast of Maine to feel like Rhode Island.

The recent temperature changes are causing the Gulf of Maine ecosystem to begin losing its subarctic characteristics. This includes reductions in *Calanus finmarchicus*, a large zooplankton species at the heart of North Atlantic food webs, herring, and cod.

Maine has led the development of ocean observing technology, and the NERACOOS buoys operated by the University of Maine are a cornerstone of the observing network in the region. Maintaining and modernizing this network and expanding observing capabilities inshore would help fishing, aquaculture, and other marine industries detect and anticipate changes in temperature such as marine heatwaves.

Sea Level Rise and Storm Surge

The Scientific and Technical Subcommittee (STS) recommends adopting a scenario-based approach which considers a range of potential future Maine sea levels. The STS recommends that the Maine Climate Council consider an approach of committing to manage for a certain higher probability / lower risk scenario, but also preparing to manage for a lower probability / higher risk scenario. This approach is one that has been adopted by several New England states and municipalities. In the context of this concept should be the consideration for the *risk tolerance of different kinds of infrastructure.* Using this approach, the **STS recommends that the Climate Council consider** committing to manage **for 1.5 feet of relative sea level rise by 2050, and 3.9 feet of sea level rise by the year 2100. Additionally, the STS recommends that the Climate Council consider** preparing to manage **for 3.0 feet of relative sea level rise by 2050, and 8.8 feet of sea level rise by the year 2100.**

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Over about the last century, sea levels along the Maine coast have been rising at about 0.6 to 0.7 feet/century (1.8 to 2 mm/year) or two times faster than during the past 5,000 years. Over the past few decades, the rate has accelerated to about 1 foot/century (3 to 4 mm/year) or three times the millennial rate. These local changes have been following short- and long-term global averages.

About half of the last century's sea level rise in Maine has occurred since the early 1990s and it is likely that sea level in Maine will rise between 3 and 5 feet by the year 2100 based on an intermediate sea level rise scenario, although scenarios of higher rise are physically plausible. Sea level is expected to rise along the Maine coastline well beyond 2100.

Abrupt sea level change on the order of months, rather than years, can also occur on top of the long-term rise. Several months between 2009 and 2011 saw higher than normal sea levels, with a peak in 2010 of nearly a foot above the level in previous winters. Along the East Coast of the United States, this abrupt change was most pronounced in the Gulf of Maine.

A 1-foot increase in sea level in the future will lead to a 15-fold increase in the frequency of "nuisance" flooding. Nuisance flooding in Portland in the last decade was about 4 times more frequent than the 100-year average. A 1-foot increase in sea level, which could occur by 2050, would cause a "100-year storm" flood level to have a probability of occurring once in every 10 years. Not accounting for changes in storm intensity or frequency, this would result in a 10-fold increase in coastal flooding in Maine in the next 30 years.

Sea level rise will cause high tides to regularly inundate coastal lowlands with salt water and may cause limited salt contamination of groundwater aquifers. Coastal beaches, dunes, salt marshes, and bluffs are likely to experience increased erosion, landward movement, land loss and sediment redistribution due to long-term sea level rise. A 1.6-foot sea level rise will submerge two thirds or 67% of Maine's coastal sand dunes and reduce the dry beach area by 43%, which may happen by 2050 or earlier depending on the amount of sea level rise and available natural sand supply.

Rules that govern activities in Maine's Coastal Sand Dune System (NRPA 38 M.R.S. §480, Ch. 355), are the only ecosystem-focused policy that currently anticipates higher sea level. Maine's other regulatory authorities governing management of salt marshes and bluffs do not anticipate sea level rise. Maine's Coastal Management Policies (38 M.R.S. §1801) do discourage development in hazard areas affected by sea level rise in concept but not in practice.

Ocean Acidification

Scientific data indicate that the rate of ocean 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.

Since the beginning of the 19th century, the world's surface ocean pH has decreased from 8.2 to 8.1, a 30% increase in the average acidity of ocean surface waters, most of which has occurred in the last 70 years. Ocean acidification is a relatively recent area of scientific research and regular measurements in the Gulf of Maine only started within the last decade.

Further reductions in ocean pH are expected, ranging from 0.05-0.33 pH units by 2100, depending upon emissions scenarios. It is not yet clear how conditions in the Gulf of Maine will deviate from these global estimates.

Ocean acidification in the Gulf of Maine is considerably different than acidification in its nearshore coastal estuaries. In addition to atmospheric CO2, other drivers contribute to inshore acidification and are potentially very important to Maine's marine resources. Coastal acidification is often fueled by nutrients carried into the ocean by more acidic river discharge, stimulating phytoplankton blooms that subsequently decompose on or near the seabed. Because of variability in regional circulation, discharge and productivity patterns, long-term trends in coastal acidification may be more difficult to predict in the Gulf of Maine as compared to the adjacent Atlantic Ocean.

Other climate-induced impacts, like increasing amounts of fresh water supplied through Arctic outflow to the north and increases in average annual rainfall and the frequency of extreme precipitation and runoff events, will exacerbate the Gulf of Maine region's sensitivity to acidification. In fact, the combination of global and local drivers of acidification in the Northeast make New England's shellfisheries – including both its wild harvest fisheries and aquaculture production, and the communities that rely on them – potentially among the most vulnerable to ocean acidification in the United States.

Ocean and coastal acidification will most heavily impact those marine organisms that produce calcium carbonate to build shells such as scallops, clams, mussels, and sea urchins. The impacts on crustaceans such as lobsters and crabs are less clear, with some studies showing negative impacts and others showing that processes like warming are more likely the dominant factor to influence populations.

One of the most important and urgent challenges facing Maine as we try to understand and prepare for the impacts of ocean and coastal acidification is to determine how and where inshore causes of acidification contribute to Maine's "acidification budget" and what actions we can take at the local scale to reduce acidification, in addition to reducing atmospheric CO2 levels.

Marine Ecosystems

Large areas of the Gulf of Maine are changing rapidly with respect to the assemblage of species. The trend appears to be going in a direction of more temperate and fewer subarctic species, which presents challenges and opportunities for marine resource management and ecosystem function.

Ocean warming has played a key role in distributions of commercial and noncommercial species shifting northwards along the Maine coast, as well as contributing to an ever-increasing suite of non-native species invading from the south that exacerbate losses of native marine organisms through predation, competition and other biotic factors.

Maine people depend on marine resources, ecotourism, and maritime industries, so changes cascade well beyond the limits of the high tide mark. Market analyses for the developing shellfish and seaweed aquaculture industries point to potential for market growth, with groups like FOCUS Maine predicting 5,800–17,400 new jobs and $230–$800M in additional net exports from the aquaculture sector alone by 2025. Besides an economic dependence, Maine's very identity is inexorably linked to its living shoreline.

Most climate impact studies have considered warming, ocean acidification, or sea level rise in isolation. The interactive effects of these processes on coastal ecosystems is not known and it is possible that they may interact in unexpected ways.

Climate-driven thermogeographic changes create challenges for traditional place-based and population equilibrium-based management of marine ecosystems, fisheries and aquaculture. Amid such rapidly changing conditions, marine species populations are unlikely to achieve equilibrium with the environment's carrying capacity, challenging the concept of maximum sustainable yield so central to fishery management.

Reducing greenhouse gas emissions associated with marine resource use and quantifying and enhancing "blue carbon" potential (from submerged aquatic vegetation like coastal wetlands, marshes, and seaweed beds and farms) and related volunteer carbon and nitrogen markets offer opportunities to reach carbon neutrality while maintaining social and economic resilience.

Biodiversity

Maine is a biodiverse ecological transition area, where temperate ecosystems characteristic of southern New England give way to northern boreal systems often associated with southern Canada. Climate change is already having dramatic effects on this biodiversity, and those impacts will likely escalate in the future.

What We Already Know

- Approximately one-third of the 442 plants and animals, 21 habitats, and Species of Greatest Conservation Need found in the state are affected by climate-change related threats, including habitat shifts and alterations, droughts, temperature extremes, and storms and flooding, and are therefore highly vulnerable to climate change. Another one-third are moderately vulnerable.

- Iconic Maine species such as furbish lousewort, moose, Canada lynx, loons, boreal chickadees, eastern brook trout, and Atlantic puffins are experiencing multiple threats as a result of climate change, including shifting winter ice cover and scouring regimes; shorter winters with less deep snow cover (resulting in mismatch of fur color and ground cover); a rapid expansion of pests (e.g., winter ticks); parasites previously only seen further south; heat stress; lack of cold water refugia; more frequent and higher flooding of tidal marshes; and changes in available prey species. Many other lesser known species face additional threats.

- Some species have already started shifting ranges north in Maine, including for example, red-bellied woodpeckers, tufted titmice, opossum, gray fox, and arctic fritillary.

What The Future Holds

- Scientists predict that 34%–58% of species will go extinct given current climate change scenarios if they are unable to disperse to new locations, while 11–33% will still go extinct even if they can disperse to future areas that are within their current climatic niche.

- The best way to maintain biodiversity is to ensure a network of biologically and geographically diverse lands that are well connected so that plants and animals can move across the landscape to find the places they need for breeding, feeding, resting, and raising their young. The specific species and habitats will change over time, with some adapting and moving more quickly than others.

- In fragmented landscapes and for species with limited mobility (for example, many lichens, wildflowers, salamanders, turtles, fish, and invertebrates), additional conservation measures may be needed to maintain species viability in a changing climate.

Forestry and Forest Ecosystems

Forests currently cover nearly 89% of Maine's area and sequester over 60% of the state's annual carbon emissions, while the forest industry sector is statewide, multi-faceted, and provides between $8-10B in direct economic impact. However, both the natural forest and industry expect significant challenges in the decades to come. For example, the state has some of the highest densities of non-native forest pests in the US, linked to changes in both climate and human behavior, which are expected to continue to increase in the coming decade.

In addition, Maine's forest is a transitional ecotone with a broad mixture of species, which means that changing climatic conditions create significant stress as most species are either at their northern or southern limit. This stress has become even more evident as precipitation events have become more extreme and snowpack has become less continuous as well as more variable, which has significant implications for trees, the broader forest ecosystem, and forest management.

All of these factors create high uncertainty for the forest industry as they could influence wood supply, harvesting, and transportation as well as the future composition and structure of Maine's forest. In addition, exotic pests like Emerald ash borer threaten key cultural aspects.

- Forest productivity will likely be more variable with some portions of the state seeing greater growth due to a longer growing season and more favorable climate, while other areas will decline due to the increased occurrence of drought. In short, the forest response to climate change will be complex and difficult to predict given the range of conditions and species present in Maine's current forest as well as variation in future management practices.

- The spruce-fir forest type will likely decline as a result of less snow and warmer winter temperatures, but some supplementary suitable habitat along the southern edge of species' ranges will generally persist. Hardwoods, particularly paper/yellow birch, red maple, and red oak are expected to displace spruce-fir with a much greater fraction of the landscape considered as a mixed forest type.

- Policy recommendations based on Maine's forest carbon cycle require adequate measurements and monitoring of all carbon pools and fluxes. While some of those pools and fluxes are regularly measured in Maine, many are not, leaving considerations of offsets a challenge. A recent analysis estimated that ≈50-60% of Maine's greenhouse gas emissions are offset by forest growth, and ≈75% are offset by forest growth and durable products. Note that this estimate is also intended as a first approximation that both provides insights on Maine's dynamic carbon cycle, but also highlights the challenge and complexity of the task that will require research and monitoring to improve carbon cycling calculations and tracking over time.

- Primary recommendations include: (1) improved monitoring of key forest attributes like species composition, health, growth, and carbon; (2) revised projection models that cover a broader array of potential future scenarios; (3) improved tools to help with decision-support and forest management planning; (4) a greater number of studies that evaluate and assess the human behavior component of forest management; and (5) increased linkages between forest researchers, land managers, and policymakers to ensure long-term sustainability.

Agriculture and Food Systems

Maine agriculture is diverse and generates over $660 million of direct value into the Maine economy, not counting multiplier effects from support industries. Opportunities exist to reduce greenhouse gas emissions from Maine agriculture while simultaneously promoting soil heath and farm sustainability.

Too much *and* too little precipitation are the most extensive climate change impacts on Maine agriculture. Relative to most other states, Maine has a favorable outlook for overall continued soil moisture availability. Capabilities for locally specific, real-time, weather-based decision support offer large return on investment for government and private sector services to assist farmers in maximizing climatic opportunities and minimizing short-term weather risks.

Warming temperatures bring both potential benefits from longer growing seasons and lower heating costs, but also potential damages from heat stress to workers, crops and livestock, as well as greater cooling costs.

Approximately 90% of Maine food is imported from out of state. Despite enough food to prevent hunger in Maine, food insecurity exists because of uneven distribution due to socioeconomic and other factors.

Human and Animal Health

Climate change impacts human and animal health in a wide variety of ways. The following areas are of highest priority for further research and development of adaptation strategies, based on a high risk of adverse health outcomes for Mainers:

Temperature extremes

- Although Maine has generally enjoyed a relatively cool climate, extreme heat in Maine has increased in recent decades, and is projected to increase further in a changing climate, with the number of "extreme" heat days increasing from current levels by two- to four-fold by the 2050s.

- Mainers experience heat-related illnesses every summer, and recent research has found that there are approximately 10% more all-cause emergency department visits and all-cause deaths on extremely hot days (95°F/35°C), as compared to moderate days (75°F/24°C).

- Mainers are vulnerable to the health effects of exposure to extreme heat because of a lack of physiological adaptation to heat; low rates of home air conditioning rates; older demographics; high rates of some chronic diseases; high rates of outdoor occupations; and a high proportion of the population living in rural areas.

- As Maine's climate warms, we will experience more heat-related illnesses and deaths.

- Mainers currently experience more cold-related than heat-related illnesses and deaths, but this is expected to change over the coming decades, as winters warm more quickly than summers.

Extreme weather

- Extreme weather events, primarily extreme precipitation events, coastal storms, and nor'easters, are likely to increase in frequency and intensity as Maine's climate warms, which may lead to increases in storm-related injuries and deaths; outbreaks of waterborne diseases; carbon monoxide poisonings and foodborne illnesses following power outages; and mental health impacts.

- Droughts and distant wildfires may impact Maine as well, with implications for reduced water quality and quantity, and effects on respiratory health.

- Certain categories of storms, such as ice storms and severe wind storms, are complex and difficult to predict, but may become more frequent and/or intense under warming conditions, leading to adverse health impacts such as injuries, deaths, and effects of power outages among Mainers.

Tick-borne diseases

- Tick-borne diseases (TBDs) transmitted by the deer tick (*Ixodes scapularis*) in Maine include Lyme disease, anaplasmosis, babesiosis, and Powassan encephalitis virus.

- Case numbers and geographic extent of TBDs have been increasing in Maine since the late 1980s.

- Through warmer, shorter winters and earlier degree-day accumulation, climate change has played a role in this expansion and will continue to do so unless mitigated through landscape-scale policies.

- The lone star tick (*Amblyomma americanum*), a vector of erlichiosis and capable of causing red meat allergy, may soon begin to establish in Maine as well.

The following areas are of medium priority for further research and development of adaptation strategies, based on a lower risk of adverse health outcomes for Mainers, or more limited availability of data and information:

Food- and water-borne infections:

- Vibrios are a type of highly pathogenic bacteria particularly responsive to sea surface temperature and salinity, which can cause a range of adverse health effects, from gastroenteritis and skin infections to septicemia and death following contact with contaminated seawater or ingestion of contaminated seafood. Warming sea surface temperatures, coupled with climate-driven changes in salinity and turbidity in coastal waters, can lead to increased growth, abundance, seasonal growth windows, and range of vibrio bacteria, which is expected to lead to increasing risk of human exposure and subsequent illness.

- Climate change is likely to change the distribution, range, frequency, and severity of some harmful algal blooms (HABs) and associated illnesses, with increases expected. This assessment is based on inference and not data. Data on environmental hazards of HABs are more robust compared to data on exposures. Data associating HAB exposures with climate change are sparse to non-existent. However, it would be prudent to assume climate change will increase exposure to HABs.

Pollen:

- Earlier spring arrival, warmer temperatures, changes in precipitation, and higher carbon dioxide concentrations can influence plant-based allergens, hay fever, and asthma by increasing the duration of the pollen season and increasing the amount of pollen produced by plants.

- The frequency and severity of allergic illnesses, including asthma and hay fever, are likely to increase as a result of a changing climate.

- Reliable pollen monitoring and forecasts are needed for allergy pretreatment. Despite having had as many as three pollen-counting stations historically, Maine has no publicly available, statewide mechanism for reporting pollen data.

Mosquito-borne diseases (MBDs):

- MBDs in Maine include West Nile virus (WNV), Eastern Equine Encephalitis (EEE), and Jamestown Canyon virus (JCV).

- Through increased growing season precipitation and earlier degree-day accumulation in spring, it is likely climate change will increase the size of vector mosquito populations and increase viral amplification within mosquitoes during spring and summer. Thus, we anticipate greater incidence of MBDs.

Mental Health

- Exposure to climate-related events and disasters, such as extreme storms, flooding, drought, and extreme heat, can cause mental as well as physical health effects.

- Anxiety, depression, post-traumatic stress disorder, and suicidality have been documented in communities that have been displaced or severely impacted by storms or flooding.

- Exposure to extreme heat has been associated with decreased well-being, reduced cognitive performance, aggression, violence, and suicide.

- Those with existing mental illness are often disproportionately vulnerable to other effects of exposure to extreme weather or other climate-related exposures; and especially to the effects of exposure to extreme heat.

Maine's Economy and Climate Change

Climate change will affect all sectors of Maine's economy from tourism, agriculture and forestry to transportation. The state has, and will likely experience more, economic losses in some sectors that *may* be offset in others. Warmer temperatures, more rain, and sea-level rise will increase the incidence of flooding, and damage to coastal property and infrastructure. The responses that we make to mitigate and adapt to climate change will determine, in part, the economic and social costs to Maine's economy. The extent of the costs to Maine are also dependent on how climate change will impact people and businesses, net population flows, tourism and our imports and exports.

Economic opportunities from the response to climate change include the growing renewable energy industry including land and ocean-based wind power, solar, and biofuels. Growing renewable energy production and use also means fewer imports of fossil-based energy supplies of which Maine has none.

Of particular concern are changes that impact traditional industries such as lobsters and shellfish harvesting, other commercial fishing and the forest products industry. The share of Maine's gross domestic product (GDP) coming from forestry and paper product manufacturing has shrunk considerably in the last decade. Today, Maine's economy is dominated by service industries such as finance, insurance, and real estate (EIA, 2019).

Warmer temperatures may extend seasons for tourism activities such as cruise ships and boating while reducing the seasons for skiing and snowmobiling. Longer growing seasons will permit farmers to expand the range of crops and animals in Maine agriculture. The forest products industry, which has been adapting to changing species mix and market demand, will experience more variable impacts due to a longer growing season but increased occurrence of drought. The agricultural sector will also likely have a longer and warmer growing season. In addition, while some recreational experiences (e.g., snowmobiling) may be degraded by increasing temperatures, parts of Maine tourism industry may still benefit if Maine's climate remains superior to the climate in competing regions.

INTRODUCTION

On June 26, 2019 Governor Janet Mills signed into law LD 1679 *An Act To Promote Clean Energy Jobs and To Establish the Maine Climate Council*. The law established ambitious goals for greenhouse gas reductions and cost-effective adaptation and resilience in Maine, and charged the newly created 39 member Maine Climate Council with developing an integrated Maine Climate Action Plan by December 1, 2020, to be updated every four years thereafter. In support of the work of the Maine Climate Council, the law also established six Working Groups: (1) Transportation, (2) Coastal and Marine, (3) Buildings, Infrastructure and Housing, (4) Natural and Working Lands, (5) Energy, and (6) Community Resilience, Public Health, and Emergency Management. The working groups were charged with developing draft strategy recommendations to the Maine Climate Council early in the summer of 2020 to form the basis for Maine Climate Council deliberations in the development of the - Maine Climate Action Plan by the end of 2020.

In addition, the law established the Scientific and Technical Subcommittee (STS) in support of the work of the Maine Climate Council and the working groups. The STS was *established to identify, monitor, study and report out relevant data related to climate change in the State and its effects on the State's climate, species, marine and coastal environments and natural landscape and on the oceans and other bodies of water.* The STS was comprised of scientists with a broad array of expertise on climate change in Maine, and began regular meetings in the fall of 2019. In January of 2020 the STS provided the Maine Climate Council and working groups with a 329-page *Phase I Working Document* which was a draft compilation of climate change effects in Maine to support the deliberations around working group strategy development. As the STS continued its work in the spring of 2020, it provided ongoing technical support to working groups and affiliated consultants, while further refining the documentation of our current state-of-knowledge on climate change effects in Maine.

It is of historical relevance that during the spring of 2020, the world experienced the onset of the COVID-19 pandemic. While this had a dramatic effect on people's lives in Maine and how the work of the Maine Climate Council, the STS, and the working groups could conduct their business, this work rapidly transitioned to conform with the challenges of the pandemic. Indeed, the deliberations continued at an almost accelerating pace given the importance of the work being done to prepare Maine for the developing realities of climate change and the need to assure a sustainable and thriving future for Maine people.

This document represents the 2020 final report to the Maine Climate Council and working groups by the STS entitled Scientific Assessment of Climate Change and Its Effects in Maine. While much of the science presented in the Phase I report remains the same, improvements, additions, and refinements have been incorporated in the intervening months to provide the latest information for the ongoing deliberations of the Maine Climate Council. Authorship of this report includes members of the STS and additional contributors noted in the title page, as well as others who were valuable resources recognized in the Acknowledgements.

We would add a final word on the issues of *extent* and *uncertainty*. The *extent* of the subject matter in this report focused on the priority charge of the STS, and the STS membership and its deliberations do not pretend to have adequately addressed all possible subject matter to the fullest extent possible. The STS members are highly regarded scientists with an expertise and passion about Maine across many key sectors of our state, drawn from academic institutions, non-governmental organizations, and state and federal agencies. In addition, the timeline to provide this stage of our scientific assessment was short by necessity, which shaped the nature of our process. The other issue of importance for readers of this document is how science deals with *uncertainty*. To that end, we have provided several terms in the insert here to guide the reader on how these concepts are used in these sciences. Readers are encouraged to visit the Maine Climate Council web site (https://www.maine.gov/future/initiatives/climate/climate-council) for additional information on the work of the Maine Climate Council, and access to existing and emerging scientific information on climate change in Maine.

Uncertainty, Likelihood, Variability, and Confidence

Scientists describe varying degrees of 'certainty' in our ability to predict climate-related changes. There are common terms used throughout this report that have different connotations of certainty, and we briefly describe them here:

- **Uncertainty:** A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, or uncertain projections of human behavior. Uncertainty can therefore be represented by quantitative measures (e.g., a probability density function) or by qualitative statements (e.g., reflecting the judgment of a team of experts)[1].

- **Likelihood**, or probability, is a calculable statistic. But the word 'likely' is also used to convey a higher level of certainty. Generally speaking, scientists are more comfortable using this term when at least one well-regarded citation from the primary literature (and often more) can support the statement. Scientists use this term when there is sufficient probability that a change will have a specific directionality and that the mean magnitude of change is measurable and impactful. This is the state of much of our knowledge about select highly studied trends in the face of climate change.

- However, even if a directional, measurable gradual average change is likely to occur, it will almost always follow a fluctuating path. **Variability**, in a statistical sense, doesn't preclude a pattern – it is just the measurable amount of noise around that temporal or spatial pattern. For more easily measured parameters, like temperature and rainfall, we have large data sets from which to calculate annual, seasonal, or geographic variability. But for others, like ocean acidification, we are still hard-pressed to constrain the range of variation in seawater pH along the state's shorelines. Climate change not only can influence general trends, but it can also expand the range of variation. Extreme events outside this range of variation can emerge that further constrain our sense of certainty.

- The range of variation can be very strictly defined using probabilities, or likelihoods, that the mean trend will persist, despite the noise around it. Scientists often define **confidence** in the conclusions they draw as a percentage of certainty (e.g. 95%) that a trend is occurring and will continue in future projections. For rates of temperature increase and sea level rise, we can estimate with higher confidence what those changes will be in the coming decades based on robust and comprehensive historical data sets.

[1] IPCC, 2013: Annex III: Glossary [Planton, S. (ed.)]. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

CLIMATE

HIGHLIGHTS

- Maine's statewide annual temperature has increased by 3.2 °F (≈1.8 °C) since 1895, with rising overnight low temperatures driving more of this increase than daytime highs. Climate models project that Maine could warm an additional 2 to 4°F by 2050 and up to 10 °F (≈1-6 °C) by 2100 depending on the scenario of greenhouse gas emissions and societal development. Maine's winters are warming faster than other season, and coastal areas have warmed more than the interior of the State.

- The warming climate has been associated with a trend towards longer summers and shorter winters, where the change in duration in each of these seasons is about two weeks over the past century. Most of the increase in the length of the warm season has occurred during early fall. There has likewise been a net increase in the length of the growing season. These trends are expected to continue over the next century.

- While the growing season has lengthened overall, some years have seen killing frosts in late spring/ early fall. It is uncertain whether such events will become more or less frequent in the future.

- Maine's statewide annual precipitation (rainfall and snowfall) has increased by 6 inches (152 mm) since 1895, with the unusually wet interval 2005-2014 significantly influencing this increase. Annual precipitation surpluses are mostly due to increased rainfall in summer and early fall. Most climate models project that Maine will continue to get wetter over the next century as increased heating intensifies the hydrologic cycle.

- Maine has experienced an increase in the average number of heavy precipitation events per year, particularly since the mid-2000s. Likewise, studies of U.S. Northeast region precipitation show that heavy precipitation events have increased each season of the year, with the largest percentage increases in winter and spring. These trends are expected to continue over the next century as increased heating intensifies the hydrologic cycle.

- An increase in storm frequency and intensity has been observed across the Northern Hemisphere since the 1950s, mostly during the cold season. A recent study of mid-autumn wind storms impacting New England also found a statistically significant positive trend in the frequency of bomb cyclones (low pressure systems that rapidly intensify) and in total storm precipitation for that time of year. It remains uncertain to what extent storms will change in frequency and intensity over the northeastern U.S.

- There has not been an observed increase in meteorological drought occurrence across Maine over the past century, with precipitation showing an overall upward trend. However, model projections indicate that as the climate warms it is likely that increased evaporation will dry surface soil layers, particularly in the warm season. It is less clear how the frequency of drought in Maine may change in the future as a result of increasing greenhouse gas concentrations.

- While it is uncertain whether drought conditions will become more or less likely in Maine as the climate warms, when drought conditions do develop, they are likely to be exacerbated by increasing temperatures and an overall enhancement of the hydrologic cycle, meaning more extreme precipitation events as well as increased evaporative loss of water.

DISCUSSION

Temperature and Precipitation

Maine's statewide mean annual temperature has increased by 3.2 °F (≈1.8 °C) since 1895 (Fig. 1). Minimum temperatures (overnight lows) have increased more than maximum temperatures (daytime highs) throughout the year. Coastal climate areas have warmed slightly more (0.2 °F [≈0.1 °C]) than the interior of the State, and winter (December-February) has seen the most warming of the four seasons (Fernandez et al. 2020). The six warmest years on record have all occurred since 1998.

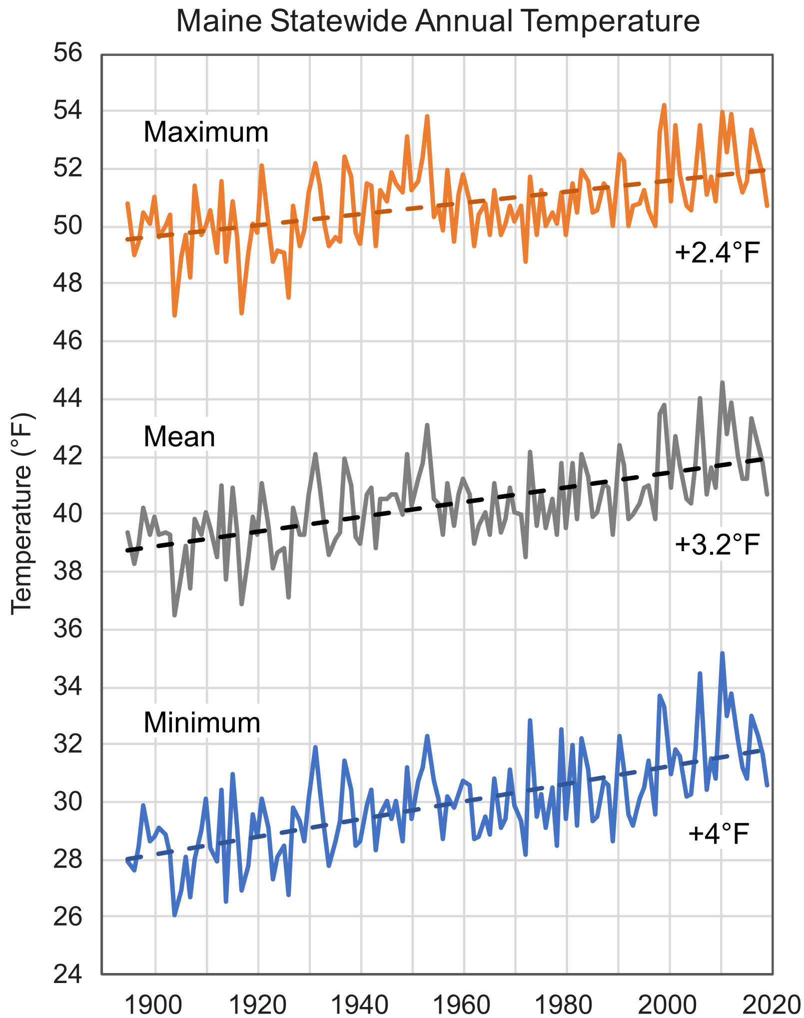

Figure 1. Maine statewide annual temperature, 1895-2019, based on maximum (top), mean (middle), and minimum (bottom) daily temperature observations. The values at right below each curve show the amount of temperature increase since 1895 based on a linear trend. These values indicate that overnight lows (minimum daily temperatures) have warmed more than daytime highs over this period. Data from the NOAA U.S. Climate Divisional Database.

A warming climate brings changes in season length. In comparison to a century ago, winters are now shorter and summers are longer by about two weeks (Birkel and Mayewski, 2018; Fernandez et al. 2015). Likewise, the growing season is estimated to have lengthened by 16 days on average statewide since 1950, where most of the expanded growing season can be attributed to warming temperatures in September and October (Fernandez et al. 2020).

Statewide, total annual precipitation (rainfall and snowfall) has increased by about 6.1 inches (155 mm), with more rain and less snow falling since 1895 (Fig. 2). Across the northeastern U.S., the most pronounced increase has occurred over the past 20 years, with total annual surpluses driven by more frequent and intense extreme precipitation events occurring primarily in summer and fall (Collow et al. 2016; Frie et al. 2015; Hoerling et al. 2016; Howarth et al. 2019; Huang et al. 2017). With the exception of 2016-17, wet conditions have persisted in Maine since the mid-2000s. During this wet interval, high-pressure blocking patterns have developed more frequently over Greenland in conjunction with changes in atmospheric features elsewhere across the Northern Hemisphere (Fang 2004; Woollings and Blackburn 2010; Hanna et al. 2013). Maine's precipitation trend stems in part from these large-scale linkages, or climate "teleconnections" (Birkel and Mayewski 2018; Simonson 2020).

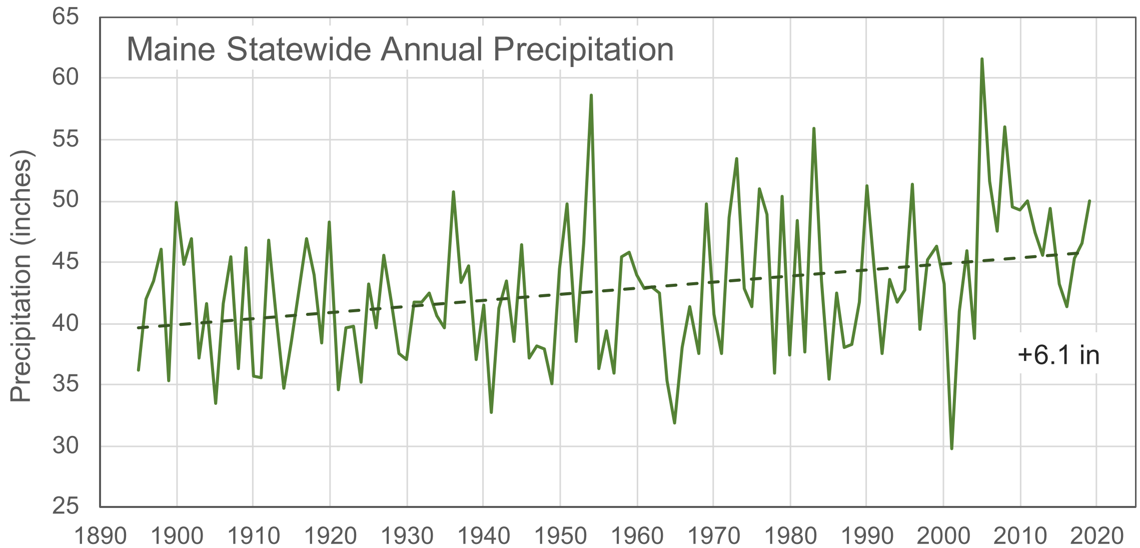

Figure 2. Total annual precipitation, 1895–2019, averaged across Maine based on monthly data from the NOAA U.S. Climate Divisional Database. The linear trend shows an overall increase of 6.1 inches for the record period.

Extreme Weather

As highlighted in the Fourth National Climate Assessment (USGCRP 2017), extreme weather events – heat waves, cold waves, intense rainfall, and impactful storms – are becoming more common across the northeastern U.S. and elsewhere in the world. Heavy precipitation in the northeastern U.S. has increased at a higher rate than any other region in the U.S. (Kunkel et al. 2013; Easterling et al. 2017). This is also true in Maine, where precipitation has become both heavier and more frequent; nine of eleven long-term weather records located around the state show that most extreme precipitation events (≥ 2 inches/day) have occurred in the past two decades (Fernandez et al. 2015). An analysis of daily precipitation data from Farmington shows most of the increase in precipitation has come from 1" and 2" events, though extreme events of 3" and 4" have also become more frequent (Fig. 3) (Fernandez et al. 2020). In addition, the Farmington record shows an increase in the overall frequency of extreme precipitation events since 2000, with 10-15 more events occurring per year compared to the previous century.

There is evidence that intense low-pressure storms have become more frequent across the Northern Hemisphere since 1950, particularly during the cold season (Vose et al. 2014). Recent major wind storms, such as those that occurred on 30 October 2017, 15-16 October 2019, and 1 November 2019, brought damaging gusts (over 70 mph in some places during the 2017 storm) that caused well over 200,000 power outages across Maine. A recent Ph.D. dissertation at the University of Maine (Simonson 2020) investigated the historical occurrence of fall storms in the did find, however, a significant positive trend in the frequency of bomb cyclones (low pressure systems that rapidly intensify) and in total precipitation from storms developing during the middle of fall.

One of the ways in which storms can intensify in a warming climate is through increased heat and moisture supplied from warmer-than-normal ocean water. It has also been suggested that Arctic warming and diminished sea ice may result in a slower, wavier jet stream by weakening the poleward temperature gradient (Francis and Vavrus 2015). A relatively slow jet stream can increase the likelihood of heat or cold waves developing from so-called "blocking" patterns. When these features begin to break down, the steep temperature differences on either side of the wave can drive a powerful storm front with heavy precipitation and strong winds. However, whether Arctic amplification (the relatively greater warming in the Arctic compared to lower latitudes) has shown a significant impact on upper-level wave patterns remains a topic of debate and continued research (e.g., Meleshko et al. 2016; Cohen et al. 2020).

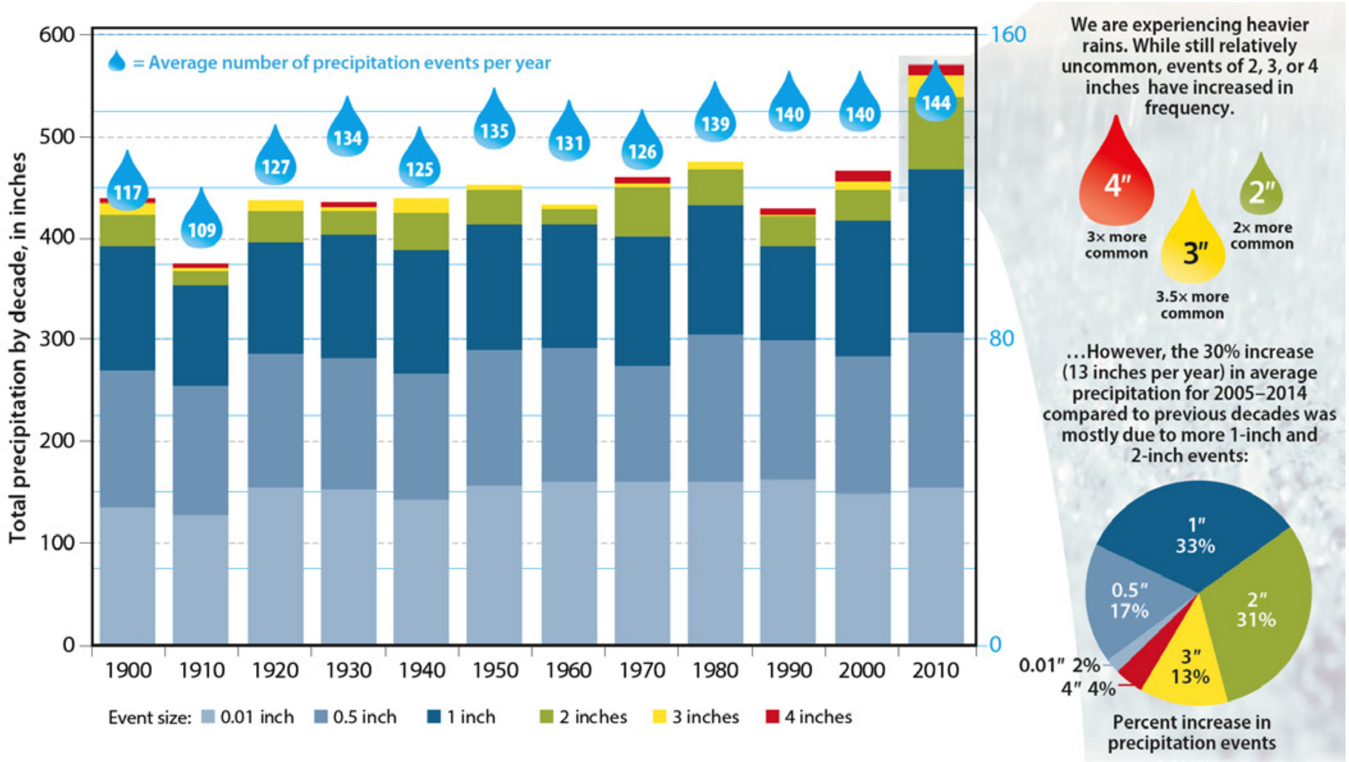

Figure 3. Total decadal precipitation and mean annual number of precipitation events for Farmington, Maine calculated from daily precipitation values. Precipitation events are defined as days with measurable (>0.01 in) rain or water equivalent of snow. Data from the NOAA Global Historical Climatology Network. Figure and caption from Maine's Climate Future 2020 Update (Fernandez et al. 2020).

Changing Winters

As highlighted by Fernandez et al. (2020), winter is both a defining season in Maine and also the fastest changing due to climate change. Winter temperatures have warmed 5.1 °F (≈2.8 °C) on average since 1895 (**Fig. 4**), and winter rainfall events have generally increased. An analysis of winter in the northeastern U.S. and Canada reported similar patterns over the past century (Contosta et al. 2019). The study found 20 fewer days of snow cover and of minimum air temperatures below freezing and equivalent increases in the number of days when air temperatures were above freezing and snow cover was absent (Contosta et al. 2019). Similarly, ice-out is occurring on Maine lakes 1-2 weeks earlier on average compared to around 1960 (Fernandez et al. 2020).

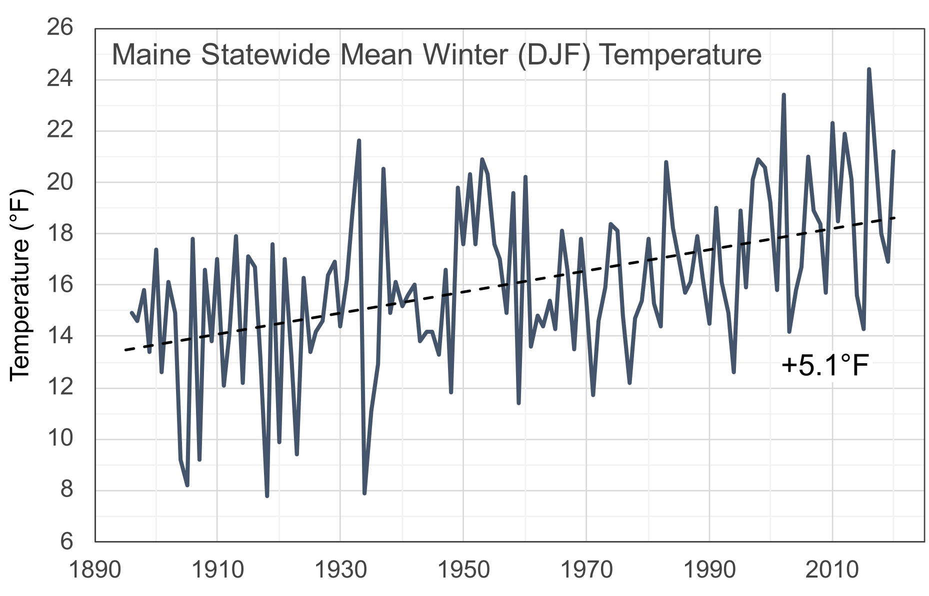

Figure 4. Maine statewide mean winter (December-February) temperature, 1895-2020. Data from the NOAA U.S. Climate Divisional Database.

Despite these clear trends, the warming winters manifest differently across Maine owing to the steep climatological temperature gradient from south to north. For example, long-term observations of snowfall in Portland show an overall decline of about 7 inches since 1940, whereas observations in Caribou show an increase of about 11 inches (**Fig. 5**). This dichotomy arises as the northern climate division continues to see daytime high temperatures near or below freezing even during a "warm" winter, whereas the central and coastal climate divisions are more likely to see temperatures above freezing. Thus, for a given winter storm, the northern climate division can see snowfall while the other climate divisions might see rain or mixed precipitation.

For additional discussion on winter indicators, refer to the *Winter and Spring Snowpack, Snow Melt, and Lake Ice* subsection of the *Hydrology* chapter in this report.

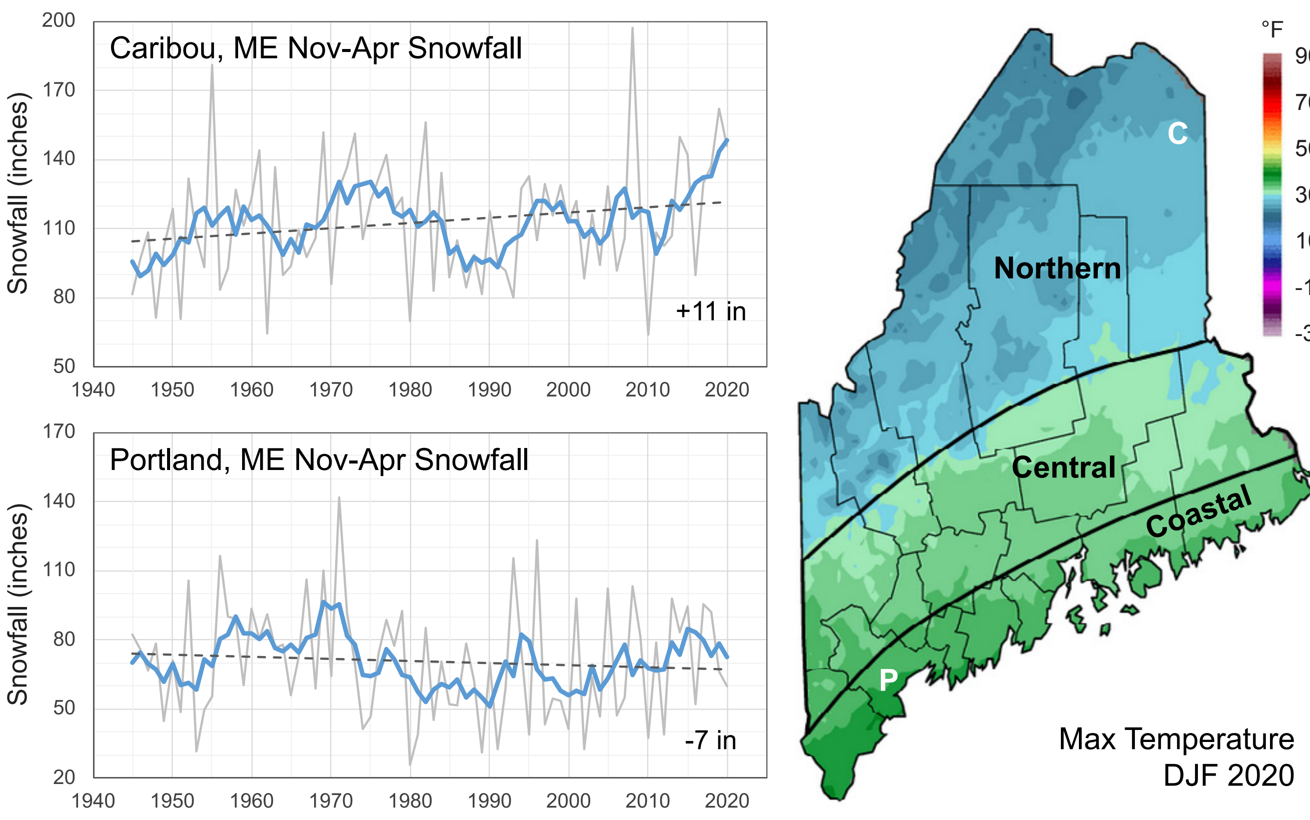

Figure 5. November-April snowall, 1940-2020, for Caribou (top-left) and Portland (bottom-left) from station observations, and Maine statewide average maximum temperature for the 2020 winter (right). Portland and Caribou are labeled P and C on the map, respectively. Snowfall data from NOAA ACIS; gridded temperature data from the PRISM Climate Group and the Maine Climate Office.

Drought

To date there has been only limited research investigating historical droughts in Maine (Lombard 2004, Gupta et al. 2011). While drought is primarily driven by a prolonged period (several months to multiple years) of low precipitation relative to normal conditions, its impacts are associated with water deficiencies across the hydrological spectrum. Drought is thus often described as falling into three categories: **meteorological drought** (associated with reduced precipitation), **agricultural drought** (reduced soil moisture) and **hydrologic drought** (reduced runoff, streamflow and groundwater levels).

From a meteorological drought perspective, the protracted drought of the 1960s stands as the drought of record in Maine (and the northeastern U.S. generally) in terms of its overall duration and accumulated precipitation deficits (Seager et al. 2012; Lyon et al. 2005; Leathers et al. 2000) (**Fig. 6**). Other notable droughts include the short-lived but high impact drought of 2016, the protracted drought from 1999-2002, which brought major impacts to the agriculture, water resources and forestry (Kasson and Livingston 2012) sectors and the 1940s drought, which was the main contributor to wildfires in 1947 that burned over 250,000 acres of forest and destroyed over 850 homes across 9 Maine communities (Maine Historical Society). In addition to deficient precipitation, drought severity is also influenced by above-average temperatures. Higher temperatures can 1) increase water loss due to evaporation in plants and soils (particularly during the warm season; e.g., Sherwood and Fu (2014)); 2) reduce snowpack in winter; 3) increase the rain to snow ratio of precipitation events during winter; and 4) lead to earlier runoff in the spring (Hodgkins et al. 2003; Hodgkins and Dudley 2006; Dudley et al. 2017). For example, above-average temperatures played a role in the development and severity of the recent 2016 drought in Maine, when across the Northeast winter snowpack was reduced, spring runoff peaked earlier than average and high summer temperatures likely contributed to increased evaporative water loss (Sweet et al. 2017). In Maine and the northeastern U.S. generally, elevated air temperatures during drought typically result from large-scale atmospheric circulation features (e.g., a heatwave), rather than in response to the drought itself (e.g. Koster et al. 2006). From a hydrologic perspective, there is also often a lag between the timing of the precipitation deficits and subsequent reductions in streamflow and groundwater, the latter two also being sensitive to timing of the drought during the year (e.g., Lombard 2004).

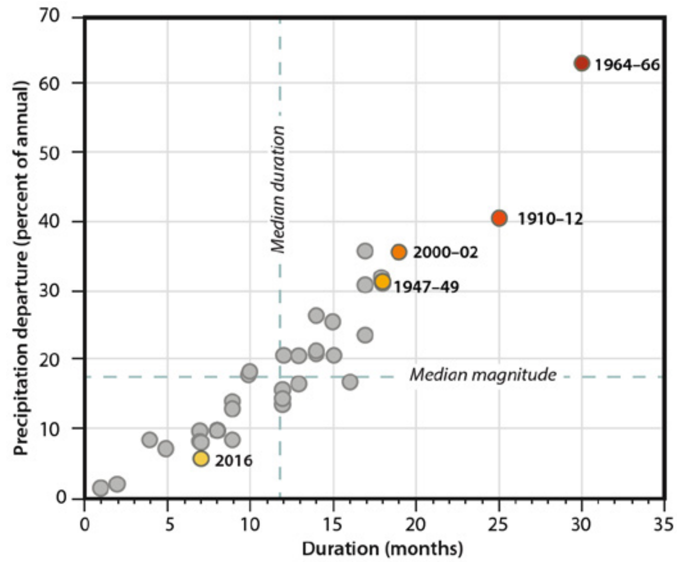

Figure 6. Statewide droughts based on the six-month Standardized Precipitation Index (SPI6), computed from monthly precipitation values averaged across the state of Maine (using NOAA climate division data). From Maine's Climate Future 2020 (Fernandez et al. 2020).

Historical Trends

As the climate warms it is expected that the water cycle ("hydrologic cycle") will intensify (e.g., Kundzewicz 2008), meaning both an increase in extreme precipitation events and greater evaporative loss. Extreme rainfall will likely result in greater runoff rather than an attendant increase in soil moisture and groundwater recharge. As noted above, the northeastern U.S. is already experiencing an increase in extreme rainfall events (e.g., Easterling et al., 2017), which is consistent with general expectations. At the same time, on the interannual time scale, meteorological (precipitation) drought indicators show a statistically significant increase in variability based on an analysis of climate division data from the National Oceanographic and Atmospheric Administration (NOAA) by the University of Maine and a recent study by Krakauer et al. (2019). These analyses imply that we are already experiencing both the increase in precipitation and increased evaporation, or a more extreme hydrological cycle, that are expected as the climate becomes warmer.

The influence of higher temperatures on drought in Maine can be manifest in ways other than evaporative loss or rainfall intensity. For example, changes in hydrology are already being observed in New England, with streamflow tending to peak earlier in the year (Hodgkins et al. 2003) and the ratio of rain to snow events in winter generally increasing (Huntington et al. 2004). While a quantitative analysis has not been conducted in Maine, the combination of higher temperatures and attendant increase in the growing season may be associated with an increase in the evaporative loss of soil moisture as evaporation increases and plants green up faster in the spring and stay green longer into the fall (Creed et al. 2015).

It is important to note that analyses of drought trends and variability can be sensitive to the specific drought index used (an undesirable result). A particularly important example is the use of the Palmer Drought Severity Index (PDSI) which, in addition to being prone to regional calibration issues (Alley 1984), can have an unrealistic sensitivity of evaporative loss to temperature (e.g., Dai et al. 2004; Dai 2011) depending on the specific formulation of evaporative loss used (Sheffield et al. 2012). The PDSI is mentioned since Maine state code (Chapter 587) uses a threshold of this index to identify "natural drought" conditions, when water withdrawals from surface water supplies are allowed to exceed other regulatory standards. Care should be used in examining temporal trends in the PDSI and the future occurrence of natural drought.

Natural Variability and Human Attribution

While Maine's century-long temperature and precipitation trends are increasing, both signals show considerable variability over year-to-year (interannual), multi-year, and multi-decadal timescales. In general:

- Interannual and shorter timescale variability are the largest contributors to overall climate fluctuations in Maine associated with large-scale weather patterns that can develop and persist for days or even several weeks. Perhaps the most prominent pattern of variability (or "teleconnection") impacting our region over these timescales is the North Atlantic Oscillation (NAO), which refers to changes in atmospheric sea level pressure differences between the subtropical and subpolar North Atlantic (Hurrel and Deser 2009). Changes in the "phase" of the NAO, and also of the related Arctic Oscillation (AO) (changes in strength of atmospheric circulation over the Arctic), can drive significant changes in temperature, wind, and precipitation across the Northern Hemisphere, especially during winter.

- Variability on 3-5 year timescales has some limited association with the El Niño Southern Oscillation (ENSO), which is a large-scale phenomenon driven by coupled changes in sea surface temperature (SST), wind, and pressure across the equatorial Pacific Ocean. Regional responses vary greatly owing to the type and intensity of a given ENSO event and complex downstream teleconnections (e.g., Yu et al. 2012). There is some evidence for a tendency for warmer-than-normal conditions to develop across Maine during El Niño years (and the opposite for La Niña years) (Birkel and Mayewski, 2018), but these connections are not statistically significant. Precipitation tendencies associated with ENSO are even less clear.

- Multi-decadal shifts in Maine's annual temperature record relate in part to a mode of variability commonly referred to as either the Atlantic Multidecadal Oscillation (AMO) or Atlantic Multidecadal Variability (AMV) (Schlesinger and Ramankutty, 1994; Enfield et al. 2001; Booth et al. 2012). The AMO/AMV are generally understood to represent the atmosphere-ocean response to natural climate forcings (namely, volcanic aerosols and solar activity), and perhaps to industrial aerosol emissions (Booth et al. 2012; Birkel et al. 2018).

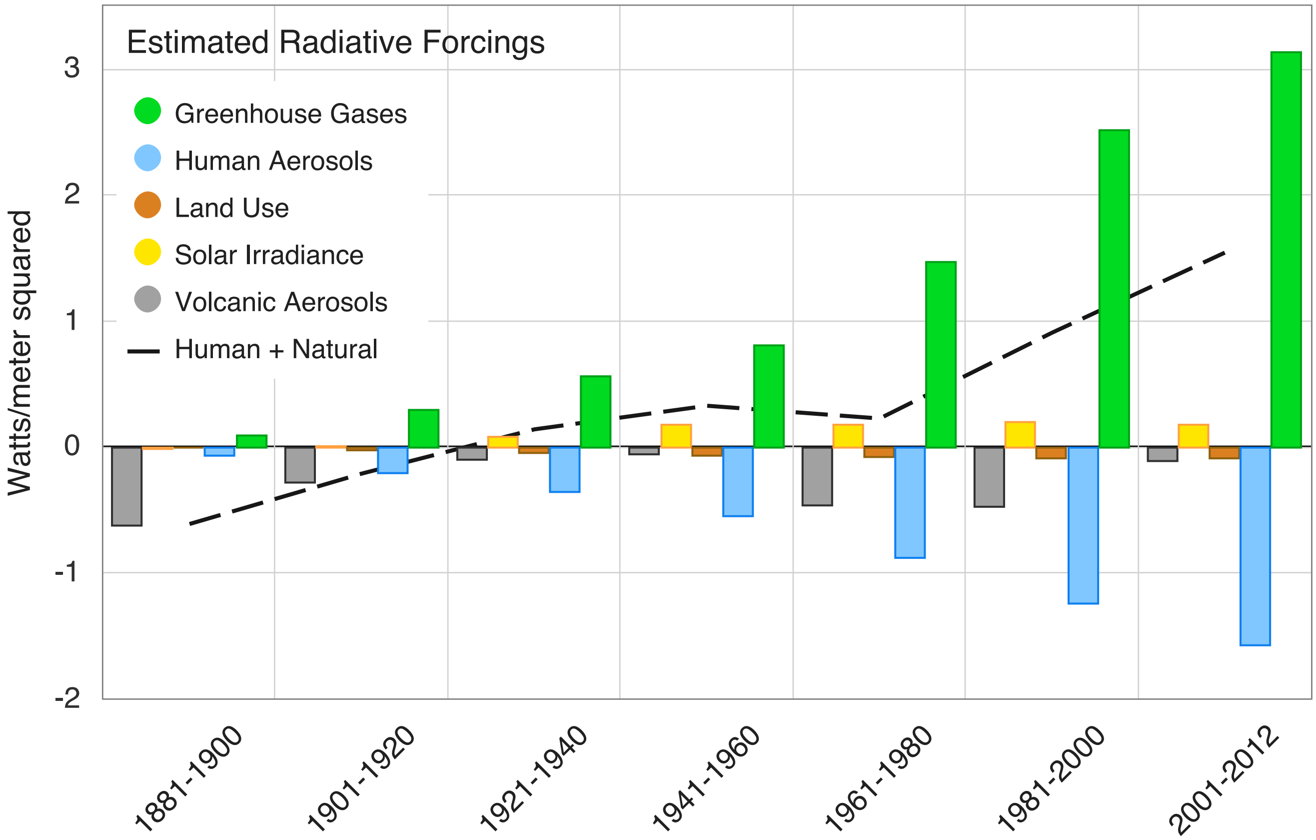

Figure 7. Estimates of the predominant natural and anthropogenic radiative forcings that have impacted global climate since the late 1800s. The black dashed line represents the sum of all forcings, and shows a steep upward rise onward from the 1960s due to increased human-sourced greenhouse-gas forcing. Values represent 20-year means. Data from Hansen et al. 2011.

The work of fleshing out "what-drives-what" lies in the realm of attribution studies, which typically rely on physically-based numerical modeling. Since 1995, model development and experimentation for past, recent, and future climates has been led by an international consortium called the Coupled Model Intercomparison Project (CMIP) (e.g., Taylor et al. 2012). These models, which are foundational to assessment reports from the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2014), simulate the climate-sys-

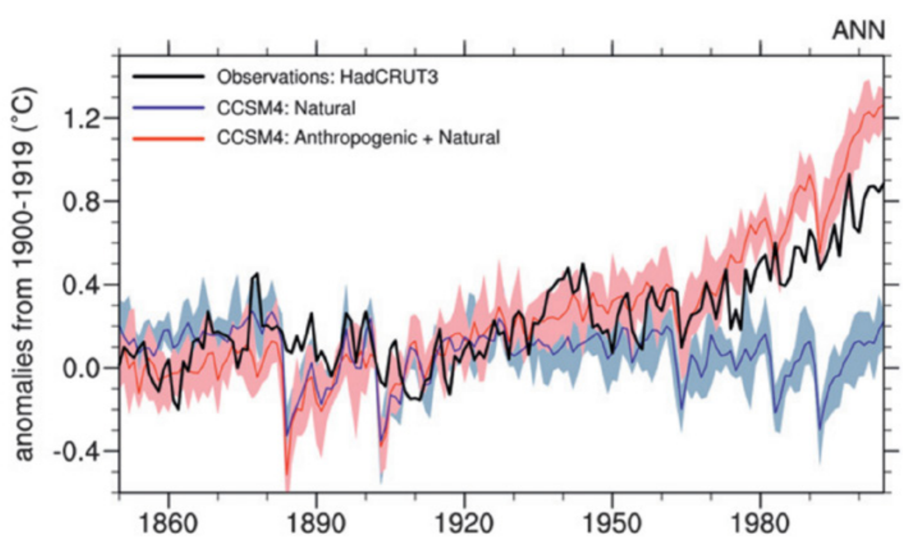

Figure 8. Observed mean global temperature (black) since 1850 compared to ensemble simulation results from the NCAR Community Climate System Model version 4 (CCSM4) (colored lines for mean values and shading for the ensemble range). The simulation timeseries in blue represents "natural-forcing only", whereas the red represents "natural + anthropogenic forcing". Image from Meehl et al. 2012.

tem response to changes in observed and prescribed radiative forcings from natural (e.g., volcanic aerosols and solar irradiance) and anthropogenic (e.g., greenhouse-gas emissions, aerosol emissions, and land-use changes) sources. Estimates of the latter show that anthropogenic greenhouse-gas emissions have become the dominant radiative perturbation to climate since at least the 1960s (Hansen et al. 2011) (**Fig.**7).

Climate models are tested and calibrated against historical observations onward from the mid 1800s. Historical climate simulations driven separately by "natural" and "natural + anthropogenic" forcings also suggest that by the 1960s measurable climate warming attributable to human activity emerged from the noise of natural variability (Meehl et al. 2012) (**Fig. 8**). While changes in climate over the first half of the 20th century were likely dominated by natural processes, the observed warming of global mean climate since at least the 1960s cannot be explained without accounting for the overwhelming radiative impact of human-sourced greenhouse gas emissions (IPCC 2014).

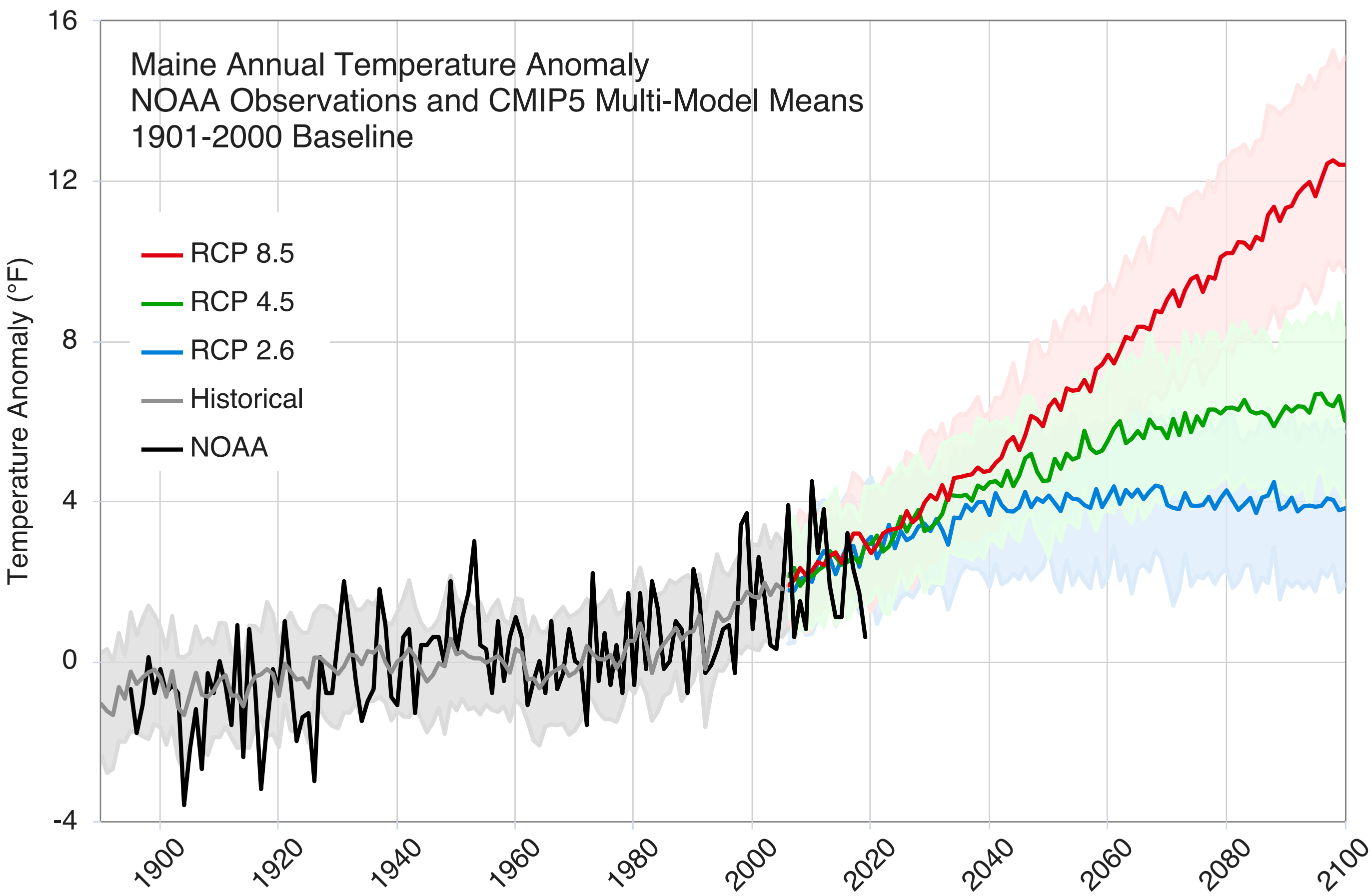

Figure 9. Timeseries of observed (black line) and model-projected (gray and colored lines) annual temperature anomalies for Maine under different socio-economic/emissions scenarios (RCPs – Representative Concentration Pathways) from the Coupled Model Intercomparison Project version 5 (CMIP5) (Taylor et al. 2012). RCP numbers indicate the projected radiative forcing (W/m^2) on the climate system from greenhouse gas emissions by the year 2100. Colored lines represent multi-model means (one ensemble member per model) for each RCP, whereas the corresponding shading denotes one standard deviation from the mean as calculated from all utilized model outputs. The number of available models is different for each RCP: 32 (RCP 2.6), 42 (RCP 4.5), and 39 (RCP 8.5). The gray line and shaded area represent the mean and standard deviation of the multi-model CMIP5 historical simulation (38 models). Observational values shown in black are from the NOAA U.S. Climate Divisional Database. CMIP5 multi-model temperature timeseries were obtained using the KNMI Climate Explorer for land-only grid cells spanning Maine. Adapted from Fernandez et al. 2020.

Future Projections

Climate model projections indicate that Maine's mean annual temperature will likely warm between 1 and 4 °F (0.6-2.2 °C) by 2050 and up to 10 °F (5.6 °C) by 2100 relative to a 2001-2018 climate baseline (**Fig. 9**). The precise temperature trajectory to emerge depends on greenhouse-gas emissions that will result from global socio-economic and public policy choices made now and in coming decades – i.e., Representative Concentration Pathway (RCP). It should be noted that RCP 8.5, often referred to as the "business as usual" scenario, may overpredict future climate warming because of what may be an unrealistic assumption of heavy reliance on coal, given recent market trends towards other means of energy production (Ritchie and Dowlatabadi, 2017). RCP 8.5 is nevertheless included in **Fig. 9**, because it is part of the CMIP5 study suite and remains a somewhat plausible outcome.

There is high confidence that annual precipitation will increase in Maine in response to increasing greenhouse gas concentrations, particularly during winter and spring (Easterling et al. 2017). Climate model projections for changes in summer and fall precipitation are less certain. There is high confidence that extreme precipitation events will continue to increase in frequency. Projected changes in drought frequency (as identified using modeled precipitation and soil moisture deficits) are less certain, although increased evaporative demand is expected to reduce near-surface soil moisture and at least partially offset any projected increases in precipitation during the warm season (e.g., Wehner et al. 2017; Hayhoe et al. 2007). What the result will be for deeper soil moisture levels or groundwater is less certain.

Recent work has also narrowed the range of estimates for earth's equilibrium climate sensitivity to a hypothetical doubling of atmospheric CO2. These sensitivity estimates have, for decades, been constrained between 2.7 and 8.1 °F (1.5 and 4.5 °C) from historical, paleoclimate, systems feedback, and model analyses. An exhaustive re-examination of available studies identifies consistent information suggesting a tighter range of possible climate sensitivities between 4.7 and 8.1 °F (2.6 and 7 °C) (Sherman et al. 2020). While this new work does not necessarily change the interpretation of the projections in Fig. 9 (the mean climate sensitivity for CMIP5 matches that of the Sherwood et al. estimated range), it does suggest that the possibility of much lower rates of future warming than expected are unlikely, and policy discussions must account for the likelihood of the higher rates of planetary warming.

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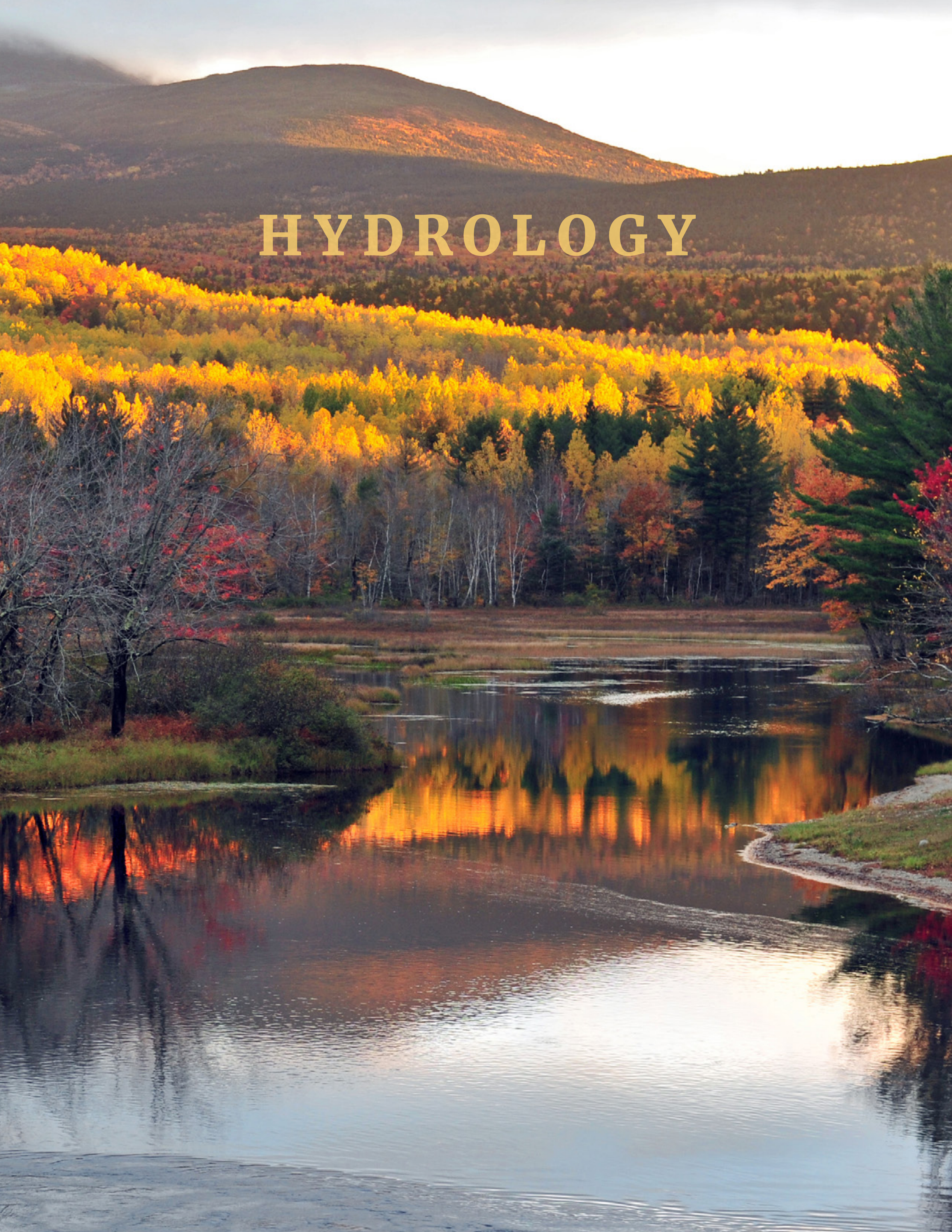
HYDROLOGY



SUMMARY HIGHLIGHTS

Annual floods have increased in volume in Maine's rivers and streams during the last century. Patterns in larger less-frequent floods, such as the 100-year flow (1% chance of occurrence annually) are uncertain but may decrease with declines in winter snowpack.

In the last 50-100 years, snowpack depths have decreased, and snowpack densities have increased in late winter. Snowmelt-related runoff and lake and river ice out dates have occurred earlier. While these trends are likely to continue with ongoing warming, the future effects on low streamflows during summer are less clear.

Groundwater levels and low streamflows have increased or not changed significantly in recent years. However, there may be an increase in the length of the summer and fall low-flow season in the future for high greenhouse gas emission scenarios. Competing water demands in select watersheds during times of low flow have the potential to become exacerbated during future droughts.

Up-to-date accessible digital statewide floodplain maps that incorporate climate related changes and the use of Lidar are key to responding to current and future impacts of flooding related to climate change.

An expanded statewide snowpack monitoring network is critical for providing more comprehensive coverage over space and time. This would allow better prediction of snowmelt runoff each year and provide better baseline data for future snowpack and snowmelt changes.

A better understanding of the impact of climate change on summer low streamflows is needed. An expanded riverine streamgaging network that includes more small headwater streams would provide baseline data for potential future changes that may impact aquatic habitat. Studies that help us understand the impact of changing summer precipitation on summer/fall low flows are also needed.

DISCUSSION

Peak Streamflows

Historical Trends

The amount of water flowing in rivers and streams (streamflow), varies naturally throughout the year depending on precipitation, snowmelt, evaporation, and other factors. Maine receives precipitation fairly evenly throughout the year, but our maximum annual streamflows tend to occur in the spring during snowmelt season. These annual floods have increased in volume and become more frequent for relatively natural watersheds in Maine, ones with minimal human influence such as reservoir regulation and urbanization (Hodgkins and Dudley, 2005; Collins, 2009; Hodgkins, 2010; Armstrong et al., 2011; Archfield et al., 2016; Hodgkins et al., 2019; Ryberg et al., 2019). Many watersheds in Maine are not pristine, with flows that are affected by human development in some way. Annual floods in Maine generally increased by an average of 19% from 1966-2015 (Dudley et al., 2018). A step increase in average flood size occurred around 1970 that may be related to multidecadal variability from large scale atmospheric patterns (Collins, 2009; Armstrong et al., 2011; Armstrong et al., 2014). By contrast, patterns in peak streamflows that occur infrequently, such as the 100-yr peak flow, are difficult to assess because analyses depend on very high peak flows that occur a few times per century or less.

While the heaviest rain events have increased by 55% in the Northeast during the last 50 years, the magnitude of annual maximum/peak streamflows has increased by a smaller amount (Easterling et al., 2017; Hodgkins et al., 2019). Changes in the frequency and magnitude of peak streamflows in Maine do not always track those in heavy precipitation for several reasons. Although heavy precipitation events are often thought of as a proxy for high streamflows, the biggest precipitation events in a year only result in correspondingly large streamflow 36% of the time in the United States (Ivancic and Shaw, 2015). In the Northeast, much of the increase in precipitation has occurred in seasons outside of the primary flood season, when streamflow tends to be lower (Small et al., 2006; Frei et al., 2015). In addition, the impact of heavy precipitation on streamflows depends on current soil moisture conditions, snowpack conditions, urbanization, and streamflow regulation (Sharma et al., 2018; Hodgkins et al., 2019), all of which may also be changing due to climate change and other factors.

Future Flood Projections

Small (annual and other regularly occurring high streamflows) have been increasing in Maine with increases in precipitation. It is unclear whether future annual floods will increase with increased precipitation or decrease with increased temperatures and decreased snowpacks. Large floods (defined in scientific literature as 3-day high 100-year peaks) are projected to decrease during the next century in Maine, despite a projected intensification in precipitation (Demaria et al., 2016a). Projected decreases may be linked to projected decreases in snowpack (Demaria et al., 2016a; Hodgkins and Dudley, 2013). Global flood risk models project mixed increases and decreases for the 100-year flood in Maine, depending on which general circulation model is used, making it difficult to project the future of these larger floods based on currently available research (Arnell and Gosling, 2016; Hirabayashi et al., 2013).

Impacts and Risks

The increasing frequency and size of some types of flooding events will still impact human safety, riverside infrastructure, water quality, erosion, and stormwater runoff (Demaria et al., 2016a). Outdated and inaccurate flood maps put community planners at a disadvantage and put communities at risk. Ninety-four percent of river miles in Maine have 100-year flood maps used to determine flood insurance rates that are out of date (FEMA, written communication, 2019).

Priority Needs

- Develop detailed flood models and flood inundation maps for areas of recurring riverine flooding in order to develop mitigation actions. Create up-to-date accessible digital floodplain maps statewide based on Lidar.
- Build targeted watershed models to better understand and manage water contributed to winter and spring floods by snowmelt runoff.

Winter and Spring Snowpack, Snow Melt, and Lake Ice

Historical Trends

Late winter snowpack has changed significantly in northern New England over the last century, with both the density and depth of snowpack decreasing over time based on long-term snow measurement monitoring sites (Hodgkins and Dudley, 2006). Supporting this finding, observations of the amount of snow versus rainfall in winter have revealed that less snow fell between December and March in northern New England from 1949 to 2000 (Huntington et al., 2004). The year-to-year ratio of snowfall versus precipitation correlated with total snowfall over that time.

Snowmelt-related runoff in the springtime advanced by 1-2 weeks at rivers in Northern New England in the last century (Hodgkins et al., 2003; Hodgkins and Dudley, 2006; Dudley et al., 2017) (**Fig. 1**). These changes in timing are linked to higher March-April air temperatures and increased winter rain. While average streamflows in March increased significantly over time in Maine, May streamflows decreased (Hodgkins and Dudley, 2005).

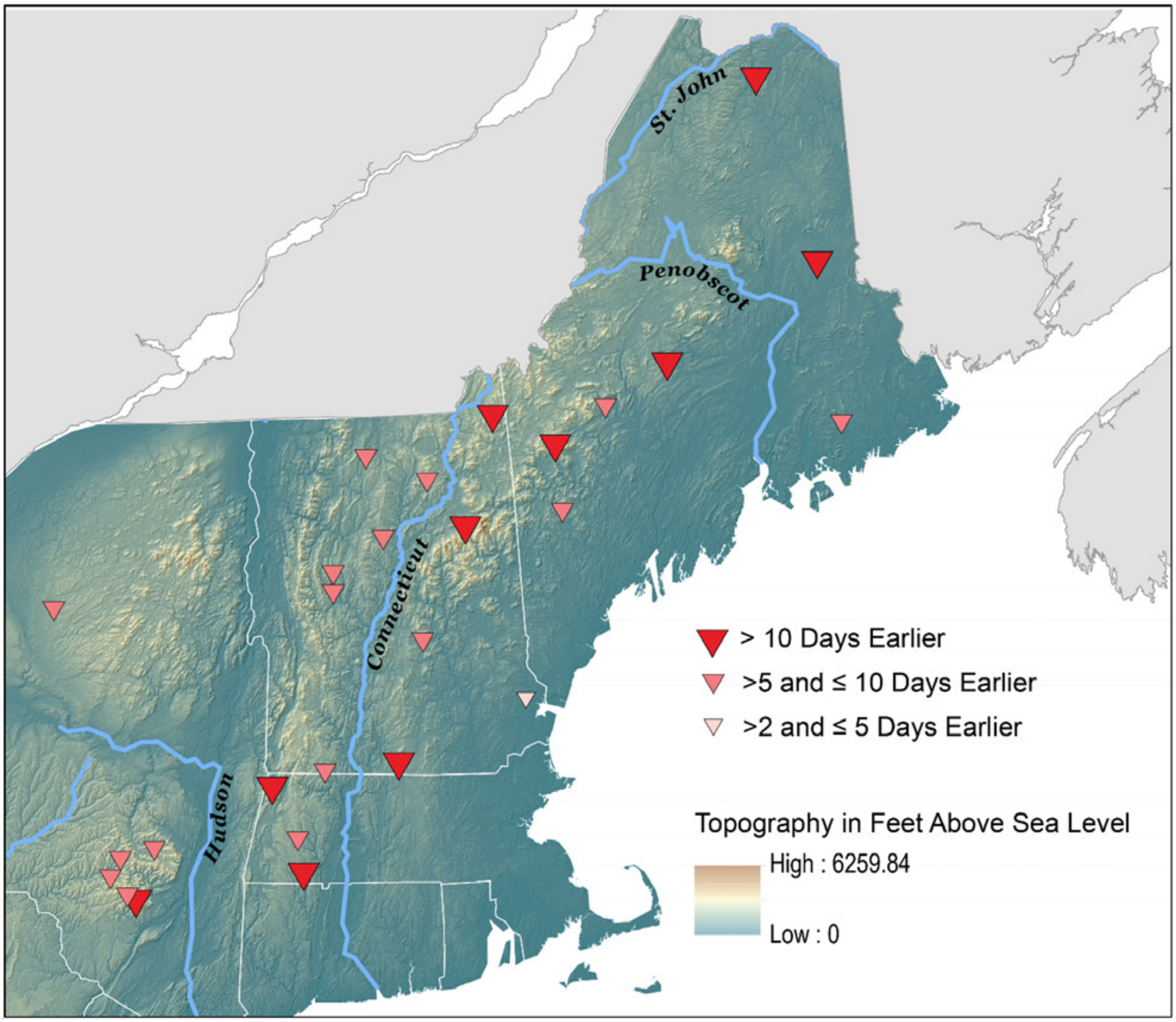


Figure 1. Map depicting historical changes in the timing of snowmelt-related streamflow for sites across the northeastern U.S. from 1960 to 2014 [Figure from Dupigny-Giroux et al., 2018, based on Dudley et al., 2017].

Lake ice-out dates advanced by an average of 4.5 days during the last 75 years. Changes were greater in southern Maine than in northern and mountainous areas (Hodgkins et al., 2002; Hodgkins, 2013). The variability of annual lake ice-out dates is strongly related to late winter/early spring air temperatures (Hodgkins et al., 2002; Beyene et al., 2018).

For nine rivers in northern New England, the total number of winter days with ice-affected flow decreased significantly; and river-ice breakup dates became significantly earlier, from 1936 to 2000 (Hodgkins et al., 2005a). Most of the 20-day change in the total days of ice occurred from the 1960s to 2000. Average ice thickness around February 28 decreased by about 9 inches on the Piscataquis River in central Maine from 1912 to 2001 (Huntington et al., 2003).

Projections

Snowmelt-related runoff is projected to continue to become earlier in the next century, by more than 10 days for some river basins in Maine (Hayhoe et al., 2007; Demaria et al., 2016b).

Related Impacts and Risks

Earlier lake-ice thaw dates may lead to decreased summer dissolved oxygen levels in deep lakes, which could lead to enhanced nutrient release from lake sediments , excessive growth of algae, and lower coldwater fish survival (Hodgkins, 2013). Snow and ice cover are important for regional economies and ecosystem resources in Maine. Projected increases in winter temperatures and associated changes in regional snowpack may reduce the viability of winter recreation tourism as an economic resource. Warmer winters will shorten the average snowmobile, ice fishing, ski, and snowboard seasons, increase snowmaking requirements, and drive up operating costs. Fewer winter sports tourists will affect restaurants, lodging, gas stations, grocery stores, and bars (Frumhoff et al., 2007; Wobus et al., 2017; Burakowski and Magnusson, 2012).

Priority Needs

- Expand statewide snowpack monitoring network for better temporal and spatial coverage in order to better predict runoff
- Further research on how changes in snowpack, snowmelt-runoff timing, and lake and river ice impact related ecosystems will help Maine predict and better adapt to future impacts with warming.
- Updated comprehensive historical and projected trends in lake ice, snowmelt timing, and snowfall versus other types of precipitation
- Evaluation of the economic impacts of reduced snow and ice cover specific to Maine.

Groundwater, Low Stream Flows, and Water Availability

Historical Trends

Groundwater levels have increased or not changed significantly at USGS wells in Maine in recent years, consistent with relatively high precipitation in recent decades (Weider and Boutt, 2010; Dudley and Hodgkins, 2013; Hodgkins et al., 2017).

Dudley et al. (2019) found little significant change in summer low streamflow periods in Maine from 1966-2015 in relatively natural watersheds. The timing and magnitude of late summer and early fall low streamflows are correlated much more with summer precipitation than with air temperature during any month of the year (Hodgkins et al., 2005b).

Projections

Projections of changes in 7-day low streamflows and baseflows in Maine by mid-century are generally mixed and statistically insignificant (Demaria et al., 2016a). However, there may be an increase in the length of the low-flow season under high-emissions scenarios, meaning that Maine's summer and fall low streamflow period may become longer.

To try to determine the impacts of human water use on groundwater in different low streamflow scenarios, a U.S. Geological Survey study used groundwater and streamflow simulations to look at three watersheds in southern Maine. The results determined that water withdrawals from groundwater pumping have the potential to conflict with Maine's in-stream flow requirements concerning water withdrawals that are designed to protect natural aquatic life and other designated uses in Maine's waters (Chapter 587 of Maine DEP's Water Rules) , especially in later summer and during periods of drought (Nielsen and Locke, 2015).

Impacts and Risks

- If the length of the low-flow season increases in Maine, there is a greater chance for conflict with human water use, particularly if water use increases. Competing water demands at key times of the year and in select watersheds have the potential to become exacerbated during future periods of hydrologic drought.

Priority Needs

- Initiate studies to understand the changing impact of summer precipitation on both historical and projected summer/fall low streamflows.

- Expand riverine stream-gaging network to include streamflow on more small headwater streams.

- Watershed modeling for watersheds that have experienced water-use conflicts or competing water-use demands during times of low flow or drought.

- An expanded groundwater well data network throughout Maine.

Priority need for climate and hydrology (applies to all hydrology sections)

- The additional data needed to address the priorities outlined in this assessment could be captured in a hydrologic climate-response network for Maine similar to the one outlined for New England by Lent et al. (2015). The framework identified specific inland hydrologic variables that are sensitive to climatic changes; identified geographic regions with similar hydrologic responses; proposed a fixed-station monitoring network composed of existing streamflow, groundwater, lake ice, snowpack, and meteorological data-collection stations for evaluation of hydrologic response to climate variation and change; and identified streamflow basins for intensive, process-based studies and for estimates of future hydrologic conditions.

- The additional data, if collected, would allow water managers and Maine towns and residents to better prepare for the impacts of climate change on our snow, streams, rivers, lakes, and water-dependent species. Changes in Maine's water balance also have very important impacts on agriculture and farms, as further detailed in the Agriculture and Food System chapter of this report.

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FRESHWATER QUALITY

HIGHLIGHTS

- Much like Maine's air temperatures, the water temperatures of rivers, streams and lakes have been increasing over the last several decades. Because Maine's stream and lake temperatures have increased, winter ice thickness and duration have correspondingly decreased over time. Warming temperatures in rivers, streams, lakes and wetlands can alter which species thrive in those environments and eliminate cold-water adapted species.

- Surface temperatures of lakes in northern New England increased 1.4°F (0.8°C) per decade from 1984-2014 – faster than the worldwide average – with smaller lakes warming more rapidly than larger lakes. Maine lake surface temperatures have warmed on average by nearly 5.5°F (3°C).

- Increases in precipitation (rain and snow) and runoff over the last century in Maine, in combination with a reduction in acidic deposition and longer growing seasons, have resulted in a rise of dissolved organic carbon (DOC) in Maine's rivers, streams and lakes, and thus export of DOC to the Gulf of Maine. The concentration of DOC can alter aquatic species and influence water temperature and stratification patterns, thus altering plankton dynamics in aquatic systems.

- The water quality of a significant number of rivers, streams and lakes has improved as a result of the numerous laws and regulations that were put in place to mitigate the effects of development, agriculture, and forestry practices on water quality in Maine. However, recent increases in the volume of stormwater runoff have resulted in transport of tons of soil and pollutants into our waters thus laws and regulations may need adjusting.

- If Maine continues to receive more intense rainfall (see the Climate chapter of this report), stormwater transport of nutrients and other pollutants to our fresh waters will increase. Increasing nutrients will shift biota in rivers, streams and lakes to less-desirable species including nutrient-loving invasive species, cyanobacteria and possibly toxin-producing harmful algal bloom species. This will cause receiving waters to be less likely to meet their classification standards and be designated as impaired. The restoration of these waters will be expensive; in one example, restoration of East Pond in the Belgrade Lakes region cost over $1 million.

- Multiple studies on Maine lakes have shown that shoreline property values decrease when water clarity is reduced due to the deterioration of lake trophic state. This causes a domino effect with respect to property taxes by shifting the tax burden from Shoreland properties to upland properties. These studies estimated that our lakes generate annual revenue of approximately $4 billion (amount adjusted for inflation).

Introduction

This chapter seeks to review some of the largest influences on water quality in Maine's streams, lakes, rivers, and wetlands in the context of climate change to date and in the future. Clean water benefits not only humans but natural ecosystems and species. Clean lakes, ponds, rivers, and streams maintain waterfront property values, contribute to the economic status of entire communities, provide lower-cost drinking water, and offer intrinsic, aesthetic value for recreation.

Water quality is influenced by many types of physical, chemical, and biological factors, all of which may be altered by the effects of climate change. These factors include: water temperature; dissolved organic carbon; nutrients and stormwater runoff; trophic changes in lakes; and freshwater harmful algal blooms.

Temperature. Lake temperatures provide a stable measure of long-term variation in climate change due to the high heat capacity in lake water, which reduces short-term temperature variability (Schneider and Hook, 2010; Torbick et al., 2016). As such they are considered regional sentinels of climate change (Williamson et al, 2009). Increased water temperatures influence trophic status and have the potential to promote cyanobacterial harmful algal blooms on lakes in Maine. River, stream and wetland temperatures likely vary more than in lakes and are more dependent on landscape position and shading effects. Extreme temperatures will determine the survival of plant and animal species therein. Thus, the collection and analysis of lake and river, stream and wetland temperature datasets are a critical component of the climate-response network in Maine.

Dissolved Organic Carbon. The concentration of DOC can alter plankton biota promoting mixotrophic species, and influence water temperature and stratification patterns, thus altering plankton dynamics in aquatic systems. Systematic tracking of DOC in all freshwaters is needed. Although wetlands are a contributor of DOC to other freshwaters, they can be a source or sink for carbon and little is known about the relative values of different wetland types for carbon sequestration in Maine (Nahlik and Fennessy, 2016).

Nutrients and Stormwater Runoff. While water temperature and DOC greatly influence the biota of rivers, streams, lakes and wetlands spatially and temporally due to their physical influence on thermal structure, characteristics of the watershed draining to these waters largely determine nutrient concentrations. Watershed land use contributes to nutrient loading yet the effectiveness of many state regulations, local ordinances and construction BMPs to adequately protect freshwater resources is questionable. Many were established 30-50 years ago and were based on previous climate conditions. Culvert sizing for replacements and new road construction may be adequate to handle the volume of rainfall from intense storms, but many older culverts are now undersized. The changing climate necessitates that land use regulations, enforcement practices and road construction priorities be reevaluated to protect Maine's waters from being in violation of statutory classification standards.

Trophic Changes in Lakes and Freshwater Harmful Algal Blooms. Maine statute mandates that lake trophic state be stable or improving. Trophic state is directly related to the quantity of algae and cyanobacteria in lakes. Climate change influences trophic condition via air and water temperatures, ice duration, DOC additions, nutrient additions via stormwater runoff due to increased storm intensity and frequency, and, effects of high winds. Thus, climate change has the potential to cause increases in temperature and phosphorus, deterioration of trophic state, thus increases in lake impairments and harmful algal blooms, which are known to produce cyanotoxins (dermatoxins, hepatotoxins and neurotoxins). In response, better assessment tools and approaches are needed along with expanded monitoring in lakes, rivers and streams.

HAB at Sabattus Pond, 2019
Photo by DEP Lake Assessment Staff

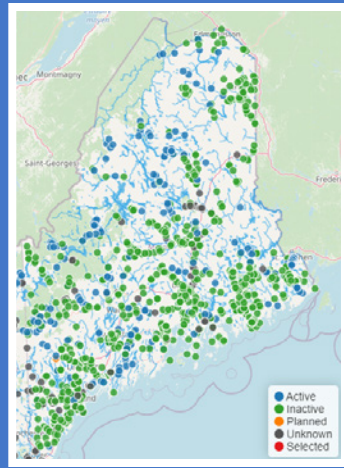
Temperature

Historical Trends

Much like Maine's air temperatures (see the Climate chapter in this report), the water temperatures of rivers, streams and lakes have been increasing over the last several decades. Temperature controls the duration and thickness of ice cover in both streams and lakes during Maine's winter and early spring (Piscataquis River, Maine: Huntington et al, 2003; New England lakes: Hodgkins et al, 2002). Because Maine's stream and lake temperatures have increased, ice thickness and duration have correspondingly decreased over time, thus expanding the growing season for these waterbodies. Water temperature, coupled with length of the growing season, exerts a profound influence on the biological communities in these waters.

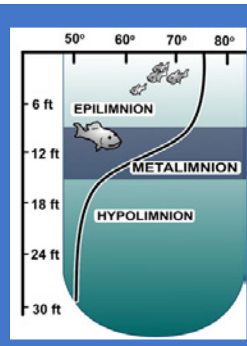
How do we measure stream temperatures?

The U.S. Fish and Wildlife Service coordinates the Maine Stream Temperature Workgroup, which includes representatives from state agencies, federal agencies, academia, and watershed associations in Maine. Temperature loggers deployed in streams across the state collect data, which is uploaded to the Spatial Hydro-Ecological Decision System (SHEDS; http://db.ecosheds.org/). SHEDS provides a portal for viewing and managing stream temperature data collected across the northeastern U.S. This database is used to calibrate a regional stream temperature model, which predicts daily mean water temperature at the catchment scale, based on geospatial attributes (*e.g.* land use) and climate data (*e.g.*, air temperature and precipitation). As of May 2020, 370 sites are actively being monitored in Maine.



Rivers and Streams. Mean May water temperature in the Wild River near Gilead, Maine increased 5.7°F (3.15°C) from 1966-2001 (Huntington et al., 2003). Stream temperature increased in the Penobscot River from 1978-2002 (Juanes et al., 2004).

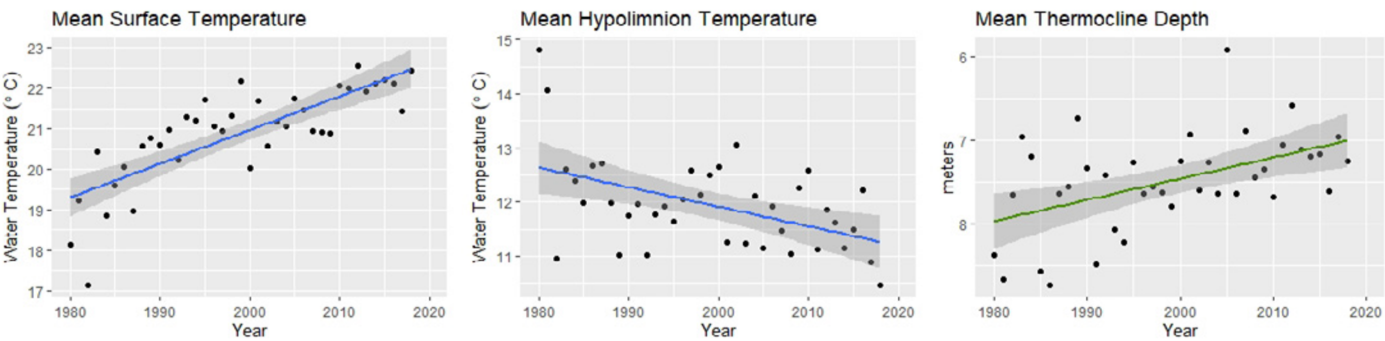
Lakes. Surface temperature of lakes in northern New England has increased 0.8 degrees C per decade from 1984-2014 based on satellite remote sensing data, with smaller lakes warming more rapidly than larger lakes (Torbick et al., 2016). This warming rate is faster than the worldwide average (Oreilly et al, 2015), yet it corresponds with other observations in the northern tier of the North Temperate Zone. NASA studies indicate that the Earth's largest lakes are warming and at a faster rate than oceans (NASA, 2010; 2015). Maine DEP is currently participating in a regional long-term lake monitoring network (4 lakes), which will allow future trend analysis on reference lakes and includes continuous temperature measurements that are important for capturing daily and seasonal variation.



A lake "thermocline" is a layer of water below the surface where the lake temperature drops rapidly across a small change in water depth. This layer affects both oxygen levels and nutrients in the deep parts of lakes.

Image: Lakes of Missouri Volunteer Program

Maine DEP maintains a lake water quality dataset spanning 50 years that includes temperature data collected from the surface to bottom of many lakes. Maine DEP's preliminary analysis of annual mean temperature data collected from 92 Maine lakes reveals that water temperatures, both at the surface and in the warmer top layer, have warmed significantly since 1980. Surface temperatures have warmed on average by nearly 5.5°F (3°C). The opposite has occurred in the deeper layer, which has become significantly cooler during this time period – by about 2.7°F (1.5°C) on average. Significant changes in the temperature gradients from shallow to deeper lake waters, or "stratification patterns," have also emerged, with a shift to shallower mean thermoclines by more than 3 feet (1 meter). Warmer surface temperatures will promote harmful algal blooms and stress aquatic animal species including fish, insects and bivalves. In 2020, Maine Department of Inland Fisheries and Wildlife received more reports of such kills than in previous years, and earlier in the season. Thermocline changes could narrow the cool water refuge for cold-water fish species during low oxygen conditions in the deep water and promote internal recycling of the nutrient phosphorus from sediments.



Local freshwater beach closures have increased during prolonged hot, breezeless, dry stretches during the summer due to bacterial contamination of the water. Bacteria and other pathogens persist longer in warmer water. Poor hygiene practices and over-use of small water access areas by people and pets is responsible for these closures.

At present, wetland temperature data are collected when wetlands are visited for research purposes, but little if any long-term temperature data are being collected in Maine's wetlands. However, shifting patterns in temperatures, growing season and precipitation with climate change may alter wetland hydroperiod (depth and duration of saturation and/or inundation), which will greatly influence ecosystem health.

Projections

Data analyzed thus far reveal significant warming trends in Maine rivers, streams and lakes; warming is likely occurring in wetlands as well. The continued monitoring of ice duration and temperature will provide more reliable projections for future decades in Maine's waterways. Aquatic species are already shifting their home ranges, particularly game fish. The kinds of fish found in Maine rivers, streams, and lakes will also likely change from fish species that tend to eat other fish ("piscivorous") to species that tend to eat free-floating and sediment-dwelling prey ("planktic-benthivorous") due to increased nutrient concentrations (Jeppesen et al, 2009; Linlokken, 2019; Jacobson et al, 2017). Hot summers will continue to result in over-use of freshwater swimming areas and occurrence of harmful algal blooms.

Impacts and Risks

Human Health. Prolonged warm stretches of weather during the summer promote the use of local freshwater swimming holes and beaches. Poor hygiene practices and overuse of these areas can result in bacterial and pathogen contamination. Warmer river and stream temperatures can promote growth of toxic benthic or bottom-dwelling algae. Increased lake temperatures can alter chemical and biological conditions ("trophic status") and have the potential to stimulate cyanobacterial toxin-producing harmful algal blooms in Maine lakes (Torbick et al., 2016; Moore et al., 2008). See the section on harmful algal blooms in the Human Health chapter of this report for more information about how they can affect human and animal health.

Ecological Health. Warming temperatures in rivers, streams, lakes and wetlands can alter which species thrive in those environments and eliminate cold-water adapted species. Hydroperiod alterations in wetlands may impact species composition (vegetation and other aquatic life) and result in greater potential for opportunistic/invasive species to become established. Altered lake stratification timing and depth patterns, in conjunction with lake morphometry (Kraemer et al, 2015), can have a profound effect on lake-dwelling species. Preliminary analyses of Maine lake temperature data indicate that both temperature and stratification patterns have already changed. Based on current lake trends and projections for future warming, Maine's lakes, streams, rivers, and wetlands and the species living within them will not look the same in the future.

Dissolved Organic Carbon

Historical Trends

Historical changes in precipitation and runoff over the last 70 years have resulted in increases in the transportation of dissolved organic carbon (DOC) from land to the Gulf of Maine (Huntington et al, 2016; 2018). DOC plays an important role in spurring biological activity in the lakes and oceans, so changes in the average amount of DOC being delivered there from the land can have profound impacts on freshwater and marine species. Increases in DOC to freshwater lakes over the last 30 years due to a decrease in atmospheric sulfate deposition (Gavin et al; 2018; Strock et al, 2016; Sanclements, 2012), warmer temperatures, and longer growing and decay seasons likely contributes to the observed increase in DOC "export" from the land to the ocean.

Projections

Climate projections for the northeastern U.S. (Hayhoe et al., 2007) indicate likely increases in runoff and DOC transport from the land into aquatic systems in winter and decreases in export during the summer (Huntington et al., 2016). The increase of DOC in Maine's freshwater resources will likely stabilize at a concentration higher than in the past. With the new normal, will come an additional increase in temperature as browner waters warm more than clear water, alterations to lake stratification patterns, and shifts in the aquatic species composition. The timing of stabilization and thus the extent of DOC increase will be based on the speed of recovery from acid deposition, as well as duration of growing and decay seasons.

Impacts and Risks

Changes in the timing and amount of DOC exported to the near-shore coastal ocean may influence the development of nuisance and harmful marine algal blooms (Hayes et al., 2001; Huntington et al., 2016) and carbon sequestration (Schlünz and Schneider, 2000). An increase in DOC export to fresh waters may alter the biological productivity of inland waters and impact which species can thrive there. Additionally, DOC tends to be a great vehicle to "carry along" elements such as mercury and aluminum and nutrients such as phosphorus and iron, which ultimately end up in the water column of lakes. Maine already has a fish consumption advisory in effect; additional mercury contamination is of concern. The availability of phosphorus in lakes is controlled by critical ratios of aluminum to iron, and aluminum to phosphorus. The algal bloom and fish kill in Lake Auburn in 2012 has been attributed to an increase of iron in the water column carried by DOC from upstream wetlands (Doolittle et al, 2018).

Fish kill due to an algal bloom in Lake Auburn in 2012.

Nutrients and Stormwater Runoff

Historical Trends

Maine's water classification system was initiated in the 1950s, largely completed by the mid-1960s and has undergone revisions since. Over this period, classification standards have been upgraded as wastewater treatment technology has advanced, discharges have been removed, and water quality has improved (Schaffner et al,2018). Stormwater runoff is responsible for the transport of many pollutants from the land to the water including pesticides, fertilizers, petroleum products, and soil. All land uses contribute nutrients to Maine's freshwater resources.

The water quality of a significant number of rivers, streams and lakes has improved as a result of the numerous laws and regulations that were put in place to mitigate the effects of development, agriculture, and forestry practices on water quality in Maine. However, recent increases in the volume of stormwater runoff have resulted in transport of tons of soil and pollutants into our waters. An early June 2012 storm that dumped between 6-8 inches of rain in the Auburn area caused the washout of a culvert and adjacent land such that the gully was larger than a tractor trailer truck. A 3-inch storm that passed through the Augusta area in 2014 washed out several roads including Town House Road in Chelsea. All the eroded soil ended up in our freshwater resources along with polluting nutrients.

Projections

If Maine continues to receive more intense rainfall (see the Climate chapter of this report), stormwater transport of nutrients and other pollutants to our fresh waters will increase. This increase in nutrient status will shift the biota from species that prefer clean, clear water to pollution insensitive species.

Impacts and Risks

Increasing nutrients will shift biota in rivers, streams and lakes to less-desirable species including nutrient-loving invasive species, cyanobacteria and possibly toxin-producing harmful algal bloom species. This will cause receiving waters to be less likely to meet their classification standards and be designated as impaired. The restoration of these waters will be expensive; in one example, restoration of East Pond in the Belgrade Lakes region cost over $1 million.

This picture shows ME-129 in South Bristol where intense rainfall in July 2020 caused undermining of the road and washing-out of the ditch. National Weather Service reported as much as 5 inches of rain in the belt between Waldoboro and Waterville and a gage near US-1 in Newcastle reported nearly 3 inches in 24 hours between July 14th and 15th, 2020. Climate scientists generally agree that we can expect more frequent, more intense storms under future elevated greenhouse gas scenarios.

Trophic Changes in Lakes and Freshwater Harmful Algal Blooms

Historical Trends

Maine Statute states that Maine Lakes and Ponds must have a stable or decreasing *(improving)* trophic state, subject only to natural fluctuations, and must be free of culturally induced algal blooms that impair their use and enjoyment (Maine Revised Statutes, Title 38, Chapter 3, Subchapter 1, Article 4-A, §465-A). Limnological (lake) research indicates that cyanobacterial harmful algal blooms will increase in frequency due to climate change (Jeppesen et al, 2009; Markensten et al, 2010; Wagner & Adrian, 2009; Havens & Jeppesen, 2018; Wheeling, 2019). Maine DEP has been tracking bloom conditions in lakes for the last 5 decades and posts a list of lakes that have at least one bloom of record on their website (Maine DEP, 2018). Nearly all these blooms were driven by increased phosphorus levels. Lakes that have exhibited trophic deterioration and (or) algal blooms in Maine in recent years include:

- Lake Auburn, the water supply for Lewiston and Auburn, exhibited trophic deterioration as evidenced by extreme dissolved oxygen loss in 2011/12 following severe localized storms, erosion in the watershed, and flushing of upstream wetlands. This resulted in the death of an estimated 500 Togue (lake trout, *Salvelinus namaycush*) in September of 2012. Historically, this lake exhibited excellent water quality. It has since been necessary to treat the lake with an algaecide and alum to restore its trophic state to meet requirements of the EPA drinking water filtration waiver.

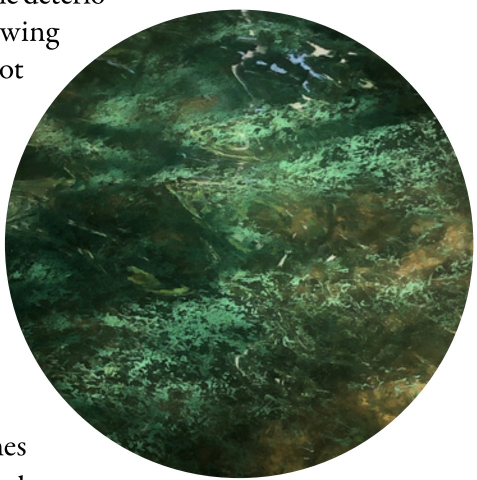
- Georges Pond (Franklin) experienced its first nuisance bloom in 2012 and a severe bloom in 2017 which persisted through 2018. This has been attributed to a longer ice-free period, earlier deep-water oxygen depletion ("anoxia), and resulting phosphorus release from lake sediments. Georges was treated with alum in spring of 2020; a second treatment is planned for 2021.

- Long Pond (Parsonsfield) experienced a severe bloom in 2017 which persisted through 2018. Again, the longer ice-free period, earlier anoxia and sediment phosphorus release are likely the cause. It is anticipated that an alum treatment will be pursued.

- Intermittent release of sediment phosphorus is thought to be responsible for the worst bloom in the history of North Pond (Smithfield) in 2018. Two years of drought (concentrating nutrients through evaporation) followed by a severe storm in 2017 that uprooted many trees in the Shoreland zone and released nutrients likely contributed to the intermittent low oxygen conditions/anoxia and subsequent bloom in this shallow system.

- Highland Lake (Windham) and Basin Pond (Fayette) have exhibited trophic deterioration. Highland Lake's deterioration may be due to a trophic cascade following manipulation of the fishery. Changes in Basin Pond's trophic status have not yet been attributed to a specific event.

- Damariscotta Lake (Damariscotta), a lake that is typically very clear, produced an unusual amount of algae in August of 2020 which raised concerns of residents and local conservation organizations. Investigation by DEP is ongoing.



Algal bloom in Damariscotta Lake in August 2020

Preliminary research conducted nearly a decade ago by DEP indicated that blooming lakes in Maine were most likely to produce the toxin microcystin, a hepatotoxin, on which subsequent DEP research has focused. Two approaches have been taken: a probabilistic approach to determine geographic extent, and a targeted approach to examine how concentrations vary during blooms. Open water, near shore and scum samples have been collected over the past 6 years. In September of 2019, DEP brought the ELISA analytical method for microcystin online and the analysis of samples obtained through November of 2019 is complete. Microcystin was detected in many samples taken from blooming lakes. Open water concentrations were below the EPA criteria for recreation, but some exceeded drinking water criteria. Microcystin concentrations in algal scums that accumulated along the shore were often well above both criteria. BMAA, another cyanotoxin of concern in the Northeast, can now be tested using the ELISA approach and should be evaluated on lakes known to produce harmful algal blooms.

Climate-induced changes in timing and extent of stratification, in addition to excess nutrients, have been shown to cause shifts in plankton dynamics that can lead to an increase in cyanobacteria blooms (Cantin et al, 2011; Adrian et al, 2006; Berger et al, 2009; Berger et al, 2007; Dupuis, 2009; Markensten et al., 2010; Wagner & Adrian, 2009; Havens & Jeppesen, 2018; Wheeling, 2019). Stratification is also influenced by dissolved organic carbon, which has been increasing in Maine lakes (See section on dissolved organic carbon above). Water clarity, closely associated with trophic state in Maine lakes, appears to be more susceptible to summer precipitation than lakes in the upper Mid-west regions of the country (McCullough et al, 2019).

Projections

Lakes are susceptible to climate change-related events. Because lakes and their watersheds are often somewhat unique, it is difficult to predict which lakes will experience a shift in trophic state. Lake response to perturbation(s) can include a significant time lag related to morphometric attributes (depth, size, volume, flushing rate). If all other variables are held constant, increases in flushing rate will result in deterioration of trophic state due to less settling and retention of nutrients in sediments (Vollenweider, 1968). Large, deep lakes may take decades to respond to climate-related forcing and consequently will take decades to restore. Small shallow lakes will respond more quickly. Intermediate-size lakes (size, depth, flushing) are likely to vary considerably in their responses. As the number of blooming lakes increases in Maine, an increase in harmful algal blooms can be expected.

Related Impacts and Risks

Health. Diverse impacts are anticipated as a result of climate change-induced shifts in lake trophic state. Establishment of regular nuisance algal blooms will transition into harmful algal blooms as the cyanobacterial species become established in lakes. Some of these species produce cyanotoxins which can have effects that range from skin rashes to liver damage and/or nervous system damage in humans, pets, livestock and wildlife. Maine DEP has been conducting research to determine the extent and magnitude of microcystin production in Maine lakes over the past decade and will continue coordinating with the Maine Center for Disease Control, providing data on which advisory decisions will be based.

Over the last few years, cyanotoxins have been blamed for dog deaths in areas outside of Maine, including New Brunswick. Anatoxin, a neurotoxin, produced by benthic cyanobacteria mostly in flowing waters, is thought to be responsible for these deaths. Little if any work has been done to date in Maine to evaluate potential for anatoxin production in flowing waters.

Freshwater harmful algal blooms are characterized by numerous species of cyanobacteria that are genetically capable of producing cyanotoxins. US EPA has issued health advisories for two cyanotoxins, microcystin and cylindrospermopsin in drinking water (USEPA, 2015) and for recreation (USEPA, 2019). Other freshwater cyanotoxins have been identified, but national advisories have yet to be established. Nevertheless, concentrations of the cyanotoxin

BMAA should be evaluated in Maine lakes. Maine CDC will consider establishing an advisory for freshwater Harmful algal blooms pending receipt of results specific to Maine.

Ecosystem. An emerging research avenue is quantifying the extent to which cyanotoxins are passed through the food chain, which could ultimately impact human health. A deteriorating trophic state leading to lake eutrophication will shift biota to nutrient-tolerant species, displacing existing aquatic species. Community evaluations using environmental DNA (eDNA) may help track these species assemblage changes. Lake waters with high biodiversity, generally an attribute contributing to resilience, should have additional protection in the context of climate change.

Economics. Numerous economic challenges are expected. Multiple studies on Maine lakes have shown that shoreline property values decrease when water clarity is reduced due to the deterioration of lake trophic state (Boyle and Bouchard, 2003; Michael et al, 1996; Schuertz, 1998; Schuertz et al, 2001). This causes a domino effect with respect to property taxes by shifting the tax burden from Shoreland properties to upland properties. These studies estimated that our lakes generate annual revenue of approximately 4 billion dollars (amount adjusted for inflation).

Priority Needs - Temperature

Basic and Applied Research

- Continued analysis of the long-term USGS stream temperature dataset, the Maine Stream Temperature dataset, and the Maine lakes dataset to determine magnitude of trends in lake and stream temperatures in Maine and model future conditions.

Monitoring/Surveillance

- Enhanced support for river, stream, lake and wetland temperature and core parameter monitoring in Maine.
- Establish a statewide freshwater beach closure tracking system including an education component.

Priority Needs Dissolved Organic Carbon

Basic and Applied Research

- Aggregation and analysis of dissolved organic carbon data from various agencies and research institutions.
- Development of an inexpensive analytic method for dissolved organic carbon.
- Investigate the role of different wetland types in carbon sequestration to prioritize Maine wetlands for protection (e.g., peatlands).

Monitoring and Surveillance

- Systematic long-term tracking of dissolved organic carbon in all freshwaters.

Priority Needs – Trophic Changes
Basic and Applied Research

- Improved evaluations of rivers, streams and lakes to determine vulnerability to developing harmful algal blooms, including use of eDNA and passive sampling approaches.

- Improved methods to evaluate algal toxin concentrations (microcystin, anatoxin, cylindrospermopsin, others) including a simple, rapid detection method to evaluate lake water for microcystin using EPA advisory levels.

- Evaluation of algal toxin movement through freshwater food chain.

- Evaluate lake communities using eDNA to identify lakes with the highest biodiversity and establish a new lake class to better protect these waters (Class GPAA) similar to the river and stream Class AA defined as waters "which are outstanding natural resources, and which should be preserved because of their ecological, social, scenic, or recreational importance."

Priority Needs - Runoff
Basic and Applied Research

- Evaluate the effectiveness of land use regulations (development, forestry and agriculture), enforcement practices, and road construction priorities to protect our waters from transport of nutrients and pollutants from the land.

- Ecosystem modelling of freshwater species' ranges and temperature tolerances, and, eDNA characterization of current species assemblages.

Monitoring and Surveillance

- Establish permanent monitoring stations on a range of each water type (size, depth relief) across the state.

- Implement regular use of satellite imagery and areal imagery to evaluate siltation events following intense storms.

Monitoring/Surveillance

- Expanded monitoring (including resources) of lakes by state agencies, Lake Stewards of Maine and other regional lake monitoring entities (Lakes Environmental Association, Cobbossee Watershed District, 7 Lakes Alliance, 30-Mile River Watershed, Mid-Coast Conservancy, Rangeley Lakes Heritage Trust, Passamaquoddy Tribe at Indian Township, Portland Water District, Auburn Water District, and many others).

- Evaluation of sediment geochemistry and redox potential from more lakes to determine susceptibility to internal recycling of phosphorus from sediments.

- Evaluation of flowing waters for presence of benthic cyanobacterial species associated with anatoxin production.

- Adopt Federal criteria or establish Maine criteria and establish guidelines for the public to evaluate risk including maps.

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OCEAN TEMPERATURE

HIGHLIGHTS

- The temperature of Gulf of Maine has exhibited considerable decadal variability, with a notable warm period in the mid-20th Century and a strong warming trend over the last 15 years, particularly in the late summer and fall. Recent warming has been punctuated by strong "marine heatwaves" in 2012 and 2016. Under all climate scenarios the climate (30-year average) of the Gulf of Maine will continue to warm through at least 2050.

- Beyond 2050, the warming rate depends strongly on the emissions pathways. Under a low-emission scenario, temperatures stabilize around 2.7 ºF (1.5° C) above the 1976-2005 baseline. This would cause the southern coast of Maine to have an ocean climate similar to that of Massachusetts or Rhode Island.

- Under the high-emission scenario, temperatures continue to rise and exceed 5.4°F (3°C) above the baseline by the end of the century. This would cause even the eastern coast of Maine to feel like Rhode Island.

- The recent temperature changes are causing the Gulf of Maine ecosystem to begin losing its subarctic characteristics. This includes reductions in Calanus finmarchicus, a large zooplankton species at the heart of North Atlantic food webs, herring, and cod.

- Maine has led the development of ocean observing technology, and the NERACOOS buoys operated by the University of Maine are a cornerstone of the observing network in the region. Maintaining and modernizing this network and expanding observing capabilities inshore would help fishing, aquaculture, and other marine industries detect and anticipate changes in temperature such as marine heatwaves.

DISCUSSION

General Setting

Maine's coastline forms the northern edge of the Gulf of Maine (Figure 1). The oceanography of our coast is highly dynamic. We have some of the largest tides in the world, an intense annual cycle of heating and cooling, and significant inputs of freshwater from the State's major rivers.

The Eastern Maine Coastal Current brings relatively cool and fresh water from Canada (Figure 1). The current is driven by the contrast in density between the fresher coastal water and the saltier water offshore (Pettigrew et al., 2005). A portion of the Eastern Maine Coastal Current turns offshore at the western edge of Penobscot Bay, though the amount of water flowing offshore changes seasonally and from year-to-year. Temperatures in the eastern region are relatively homogenous, both from east to west and, owing to strong tides, from surface to bottom (Figure 2). On average, there is a sudden increase (0.5° C in winter, 1.5° C in summer) in temperature at the western edge of Penobscot Bay (red line in Figure 1). The western coast of the state is warmer and the contrast in temperature from surface to bottom is stronger, especially in the summer (Figure 2).

The ocean conditions along the Maine Coast reflect the dynamics within the coastal region and the connections with the larger Gulf of Maine. Temperatures along the coast respond to heating and cooling, but significant amounts of heat are exchanged laterally with the Gulf of Maine.

The temperature in the Gulf of Maine is also driven by both local and remote factors. The strong annual cycle of heating, cooling, and wind mixing creates a correspondingly large annual cycle in water temperature. During the winter, cold, dry air masses traveling from the land draw heat out of the ocean, and the water can mix to depths of more than 650 feet (200 meters) in some years. Heating in the spring and summer stratifies the water column, creating a warm surface layer above the very cold water (Maine Intermediate Water) that is leftover from the winter.

There are three main sources of water into the Gulf of Maine, and each of these connects the Gulf of Maine to the broader North Atlantic. Cold, relatively fresh water comes into the Gulf of Maine via the Scotian Shelf. When this current is strong as it was in the 1990s, the Gulf of Maine is typically cooler and fresher (Greene & Pershing, 2007). Water also enters the Gulf of Maine through the deep Northeast Channel (Figure 1). This is an important pathway for bringing in the water that makes up the bulk of the volume of the Gulf of Maine. This deep water is a mix of Labrador Subarctic Slope Water (LSSW) or Atlantic Temperate Slope Water (ATSW). These water masses are salty and therefore dense, and LSSW (alternatively Cold Slope Water) is colder than ATSW (alternatively Warm Slope Water). The proportion of LSSW vs. ATSW is determined by the circulation in the western Atlantic.

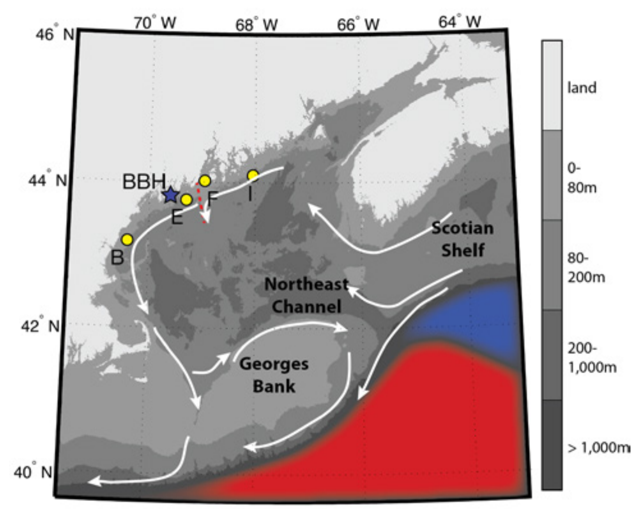

Figure 1. Map of the Gulf of Maine with arrows depicting the general circulation. The labeled yellow circles indicate the location of the four NERACOOS buoys off of the Maine coast, and the blue star is the Boothbay Harbor (BBH) site. The blue and red shaded regions represent the two main water masses that interact over the continental slope (see MERCINA 2001). The dashed red line marks the rough boundary between cooler eastern and warmer western waters.

Observed Changes

We have three main sources of information on temperature conditions in the Gulf of Maine and in Maine's coastal waters: Maine DMR's Boothbay Harbor time series (Figure 1, star), the NERACOOS buoys (yellow circles), and the NOAA Extended Reconstruction Sea Surface Temperature (ERSST) data covering the entire region. We created annual anomalies relative to a 1976-2005 baseline (see Supplementary Materials).

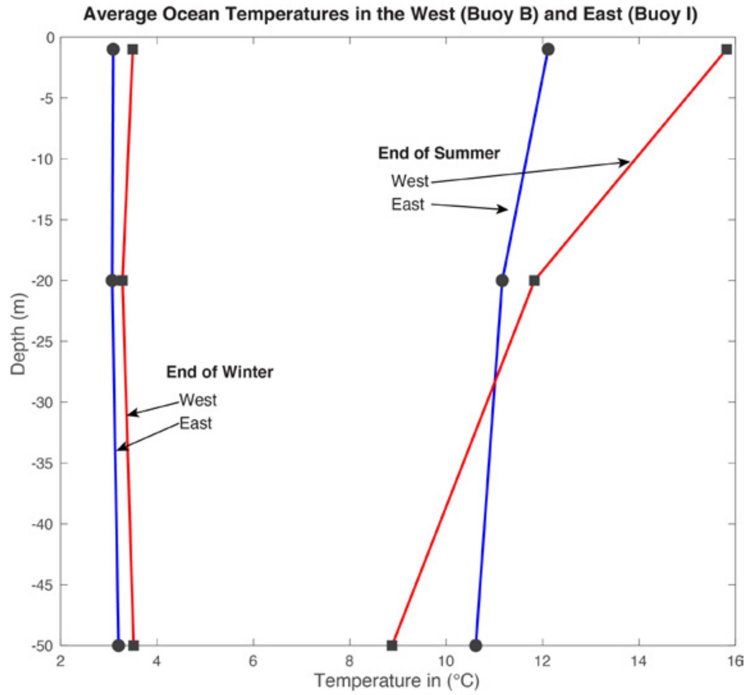

Figure 2. Winter and summer temperature profiles for the western coast (red line, NERACOOS Buoy B) and the eastern coast (blue line, Buoy I).

The dominant features in the century-scale ERSST and Boothbay Harbor time series are a warm period centered around 1950 and the recent warming trend that began in the late 1990s (Figure 3). The warm period in the mid 20th century is present (but less prominent) in the global temperature record and has been attributed to increased carbon dioxide concentrations and reduced volcanic activity (Hegerl et al. 2018). The subsequent cooling was due to increased sulphate emissions (Meehl et al., 2004). However, the mid 20th century warm period is much more prominent in data from the northwest Atlantic, and likely reflects changes in North Atlantic circulation that brought more ATSW into the Gulf of Maine.

The modern warming period is similar in the ERSST and NERACOOS buoys (Figure 3), and these time series are highly correlated (Table 1). The Boothbay Harbor time series has an unusual peak in temperature in 2006 that is not present in the other records. This peak and the adjacent years that are also warm reduces the correlation with the other data. Explaining the differences among the data is beyond the scope of this document, and we will henceforth focus on the ERSST data.

The recent decade is now the warmest in the record, warmer even than the mid-20th century warm period. Over this period, the ERSST time series has extreme values in 2012 and 2016 that correspond with major marine heatwaves (Mills et al., 2013; Pershing et al. 2018). The Gulf of Maine warming has been attributed to both increased inflow of ATSW (Record et al., 2019) and increased heat flux anomalies, especially during the heatwave years (Chen et al., 2014). Unlike the mid-20th century period when warming was strongest during the winter, the major feature of the recent warming is an intense trend during the summer and fall (Friedland & Hare, 2007). This leads to higher maximum temperatures and extends summer-like conditions deeper into the fall (Thomas et al., 2017).

	Gulf of Maine (1905-2018)	Gulf of Maine (2001-2018)	Buoys 1m (2001-2018)	Buoys 50m (2001-2018)
Boothbay	**0.29****	0.00	0.06	0.08
Gulf of Maine			**0.82****	**0.80****
Buoys 1m				**0.96****

Table 1. Relationships between the Boothbay Harbor, Gulf of Maine, and the NERACOOS buoys at 1 m and 50 m depth. The values in the tables are the r2 values from a correlation between the annual time series. Correlations that are significant ($p<0.05$) are indicated by ** and in bold. For the longer Boothbay and Gulf of Maine time series we computed the correlation for the entire common record (1905-2018) and for the shorter buoy period (2001-2018).

Impacts of Recent Warming

The Gulf of Maine has a classic subarctic ecosystem with an intense spring phytoplankton bloom and a large population of *Calanus finmarchicus,* a large copepod (a planktonic crustacean about the size of a grain of rice) that has many adaptations that allow it to take advantage of the spring bloom (Pershing & Stamieszkin, 2020). This supports a food web of iconic North Atlantic fish such as Atlantic herring and Atlantic cod, whales such as right and humpback whales, and seabirds such as Atlantic puffins and several species of terns.

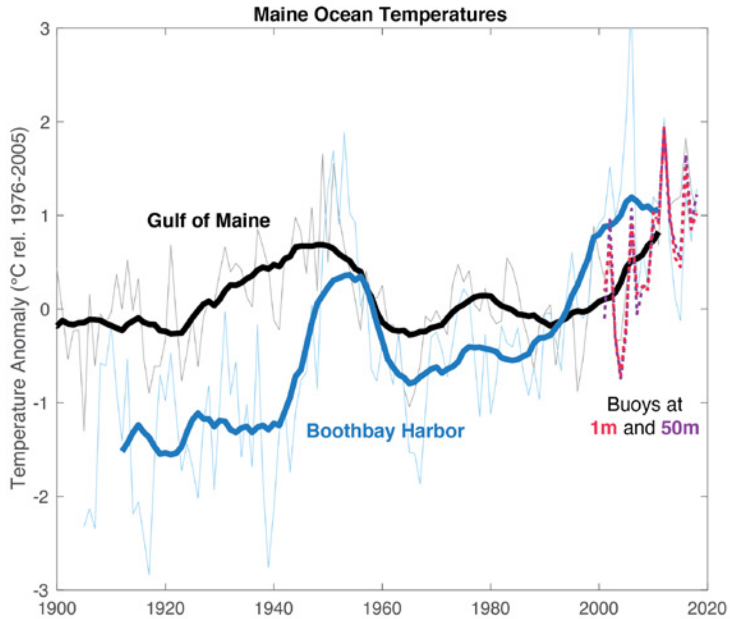

Figure 3. Temperature change along the coast of Maine and in the Gulf of Maine. The average temperature anomaly (relative to 1976-2005) from NOAA's Extended Reconstruction Sea Surface Temperature data set. This covers the Gulf of Maine, including Georges Bank, and is shown in black. The heavy line is a 15-year running mean, the light line shows the annual averages (means). The Boothbay Harbor surface temperature time series collected by Maine Department of Marine Resources is shown in blue. The dashed lines are the average temperatures at depths of 1m (red) and 50 m (purple) at the four buoys operated by the Northeast Regional Association of Coastal Ocean Observing Systems. The variability between buoys at the annual scale is small so the average of the four buoys is shown.

As the Gulf of Maine has warmed, the ecosystem has started to lose some of its subarctic character. The spring bloom is less intense but phytoplankton levels have been elevated in the winter. *Calanus finmarchicus* is more abundant in the winter, but its population during the summer has declined (Ji et al., 2017; Record et al., 2019). Right whales, which specialize on *C. finmarchicus* are producing fewer calves and have expanded their foraging areas to the north (Record et al., 2019). The abundance of Gulf of Maine cod is at record low levels (Pershing et al., 2015), and Atlantic herring recruitment has been below average for several years (NEFSC, 2018). We are also seeing more warm-water species such as black sea bass, longfin squid, and butterfish (Mills et al., 2013; Scopel et al., 2019). The recent warming has likely led to an expansion of lobster habitat (Steneck & Wahle, 2013) and contributed to the record harvests in recent years (Le Bris et al., 2018). However, there are signs that productivity has declined and that landings are likely to follow (Oppenheim et al. 2019).

Projected Temperature Conditions

Under both high emissions (i.e. RCP8.5) and low emissions (i.e. RCP2.6), the waters off Maine should continue to warm through the middle of the century (Figure 3). The scenarios diverge after 2050, with the high emissions scenario continuing to warm, eventually exceeding 5.4°F (3°C) above the 1976-2005 baseline. In contrast, the low-emissions scenario that is consistent with the State's goals to reduce carbon emissions shows Gulf of Maine temperatures leveling off at slightly more than 2.7°F (1.5°C) above baseline.

Projections using high resolution ocean models to downscale conditions for the Gulf of Maine region show a range of possible conditions for 2050 under high emissions. The difference in these projections likely reflects differences in the climate sensitivity of the different modeling approaches and potentially interannual variability. These scenarios range from a mean climate of 1.98°F (1.1°C) above the baseline to one where the mean climate is 4.3°F (2.4°C) above (Figure 4). Under 1.98°F climate, 2013 would be an average year and our recent heatwave years would seem like just mildly warm years. Very cold conditions like the 1990s or 2004 would be unlikely to occur in this climate, and conditions well above those in 2012 would be possible.

The 4.3°F climate is hard for us in 2020 to imagine based on our experience. The average conditions in this climate are 0.9°F (0.5°C) above the extreme experienced in 2012. Extremely warm years in this climate would produce conditions in Maine that we now associate with places like Rhode Island and New Jersey.

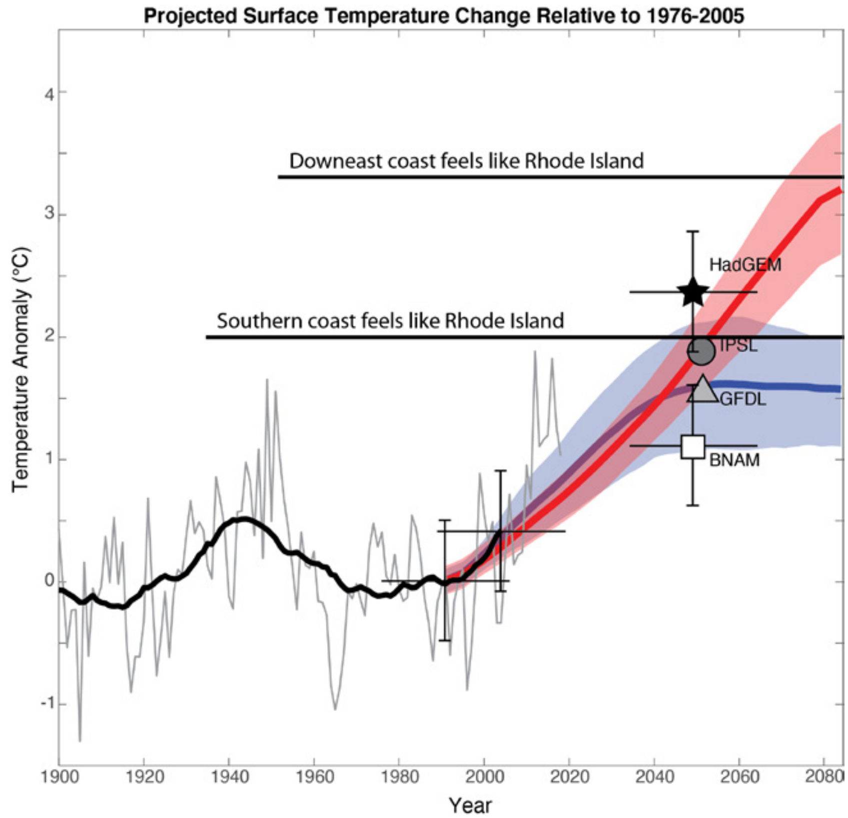

Figure 4. Observed and projected Gulf of Maine temperature anomalies relative to 1976-2005 baseline. Thin line = annual average temperature as in Figure 2. Thick line = 29 year running mean. Red line is the mean projected surface temperature anomaly for the Northeast US Shelf from the CMIP5 ensemble (data from www.esrl.noaa.gov/psd/ipcc/ocn/) using RCP8.5 forcing. The shaded region contains 50% of the CMIP5 ensemble members. Blue line and shading are the same but for RCP2.6. The shapes denote the mean projections from four downscaled climate projections for the Gulf of Maine. The projections represent the 30-year climate under RCP8.5 forcing centered on 2050. The crosses denote the 30 year period represented by the reference period, the most recent observations, and the projections with the least and most warming. The vertical extent of the crosses show variability of +/- 0.5°C consistent with the observations.

Projected Impacts

Under all of the projections depicted in Figure 3, the Gulf of Maine will continue to lose its subarctic character. In 2050, under modest warming, Calanus finmarchicus may continue to persist (e.g. Ji et al. 2017), but it could largely disappear under the more extreme warming (e.g. Grieve et al. 2017). Half of the commercial finfish and shellfish species in the Northeast have high or very high climate sensitivity and are expected to be negatively impacted by future warming (Hare et al., 2016). Cod recruitment in the Gulf of Maine declines with increasing temperature (Drinkwater, 2005; Fogarty et al., 2008; Pershing et al., 2015). With an increase of 5.4°F (3°C), the potential abundance of Gulf of Maine cod would decline but local extinction is not likely (Drinkwater, 2005).

Detailed population projections through 2050 suggest that lobster is likely to decline in abundance (Le Bris et al., 2018). This decline is in many ways indicative of the very high abundances in recent years, and even under the highest warming, lobster abundance was consistent with population levels in the late 1990s. If global carbon emissions are aggressively reduced, then these simulations suggest that Maine would hold on to a significant lobster fishery. However, under business as usual emissions, temperatures even in Downeast Maine would exceed those in Rhode Island (Figure 3), and Maine would likely lose its most valuable marine resource.

Projected Information Needs

Temperature in the waters off of Maine is notoriously variable, and we know that changes in temperature can have a large impact on marine ecosystems and fisheries. For example, the marine heatwaves in 2012 and 2016 led to an earlier peak in lobster landings (Mills et al 2013, Pershing et al 2018), and extremely warm conditions could potentially increase the prevalence of oyster diseases or harmful algal blooms. Nearly 20 years ago, the University of Maine deployed the buoys that now form the backbone of the NERACOOS system. Funding will be needed in the next few years to replace these buoys. There is also an opportunity to use newer, cheaper sensors to increase ocean monitoring along the coast. Expanded monitoring would help with the detection of unusual conditions and would support predictions that could help with short-term decisions and long-range planning.

While this review has focused on ocean temperature, warming and cooling does not occur in isolation. Changes in precipitation, especially the timing and intensity of spring runoff has a strong influence on salinity conditions along the coast. Understanding how the coastal circulation will be affected by forcing from the North Atlantic, local heating and cooling, and changes in river runoff is a challenging problem. Coastal circulation influences the supply of nutrients and phytoplankton into the estuaries as well as determining how the larvae of scallops, mussels, and lobsters spread along the coast. Downscaled climate models including those used in Figure 3 also have information on salinity and coastal currents. More detailed analysis of these models, as well as additional modeling studies, is essential for understanding how the coastal circulation will change.

Supplementary Material – Ocean Temperature

Temperature Data

We assembled three main sources of data on ocean temperature: a coastal station in Boothbay Harbor, the buoys operated by the Northeast Regional Association of Coastal Ocean Observing Systems (NERACOOS), and NOAA's Extended Reconstruction Sea Surface Temperature (ERSST) data.

Maine Department of Marine Resources began collecting daily temperature measurements from their dock in Boothbay Harbor in 1905. This is one of the longest continuous temperature records anywhere in the ocean and it provides a point record of changing conditions. We built a daily climatology for the period 1976-2005. We then calculated average temperature anomalies by subtracting the observed temperatures from the climatological average for that day. The anomalies were then averaged by year to form a yearly time series.

ERSST data provides a global spatial record of temperature from 1880 to present at a 2°-by-2° spatial and monthly temporal resolution. We used data from the grid cells covering the Gulf of Maine and Georges Bank region (Pershing et al., 2015). A monthly climatology for 1976-2005 was created for each grid cell. The climatology was subtracted and the anomalies were averaged in space and then by year.

The NERACOOS buoys labeled B, E, F, and I were installed and operated by the University of Maine in 2001 (Pettigrew et al., 2008). These record hourly temperature and salinity at depth of 1 m, 20 m, and 50 m. For each buoy and each depth, we created climatologies over the period 2002-2011 by partitioning the data into 180 bins evenly distributed throughout the year. We then computed anomalies relative to this period and then averaged anomalies in each year. Finally, we standardized the time series to the ERSST data by adding 0.3014°. This value is the average ERSST anomaly during the 2002-2011 period.

We explored the correlations among these different data sets. The two century-scale data sets, the Gulf of Maine ERSST and the Boothbay Harbor record are correlated over the entire record ($r^2=0.29$, $p<0.01$, Table 1). However, when these data are restricted to the recent period (2001-2018), the correlation becomes non-significant. This is due to the very high values around 2006 that are unique to the Boothbay Harbor time series. The annual mean anomaly averaged across all of the NERACOOS buoys is strongly correlated with the Gulf of Maine ERSST record at both 1 m (r^2=0.82, p<0.01, Table 1) and 50 m depth (r^2=0.80, p<0.01, Table 1). The temperature anomalies at the 1 m and 50 m buoy sensors are strongly correlated as well (r^2=0.96, p<0.01, Table 1). From this simple analysis, we conclude two things. First, the interannual variability and trends at the surface are a good indication of the variability and trend at depth along the Maine Coast. Second, the Gulf of Maine ERSST time series provides a reliable record of change along the coast.

Temperature Projections

Most climate projection studies begin from the Coupled Model Intercomparison Project (Taylor et al., 2012). This is an international effort to capture the uncertainty in projections of global climate by using a range of models all run using standard methods. Version 5 (CMIP5) is currently available.

For our study, we accessed CMIP5 sea surface temperatures from NOAA's Earth System Research Laboratory's Climate Change Portal (https://www.esrl.noaa.gov/psd/ipcc/). We downloaded the sea surface temperature anomalies for the Northeast US Large Marine Ecosystem (North Carolina to Maine) from RCP2.6 (low-emissions) and RCP8.5 (business as usual high-emissions) scenarios. The State's goal to achieve carbon neutrality by 2045 is consistent with RCP2.6. For each scenario, the website provides the full range, the 20th and 80th percentiles, and the mean temperatures across the models in the CMIP5 ensemble. Note that fewer models were run using RCP2.6 so the 20th and 80th percentile is also the min and max.

The advantage of the CMIP5 projections are that they have multiple models and the full range of emission scenarios. The disadvantage is that these models are run using coarse resolution and can not capture important details of the Gulf of Maine region like Georges Bank and the Northeast Channel. Two modeling groups have developed dynamically downscaled projections that include the Gulf of Maine. These efforts take output from the global CMIP5 models and drive high resolution models that can capture the details along the US and Canadian Shelves.

One effort used the Regional Ocean Modeling System configured to cover the entire US east coast to Newfoundland (Kang and Curchitser 2013). To estimate future conditions, Alexander et al. (2020) extracted surface fluxes and boundary values from three models in the CMIP5 database: the GFDL ESM2M, Institute Pierre Simon Laplace (IPSL) CM5A-MR, and the Hadley Center HadGEM2-CC (HadGEM). The forcings from 2070-2099 under RCP8.5 were delta-corrected and then used to force the ROMS model. The second effort used the BIO North Atlantic Model (BNAM). BNAM is a high resolution (1/12-deg) model of the North Atlantic Ocean. The surface forcing from six CMIP5 runs were averaged and then applied to the BNAM model (Brickman et al. 2016).

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SEA LEVEL RISE AND STORM SURGE

HIGHLIGHTS

The Scientific and Technical Subcommittee (STS) recommends adopting a scenario-based approach which considers a range of potential future Maine sea levels. The STS recommends that the Climate Council consider an approach of committing to manage for a certain higher probability / lower risk scenario, but also preparing to manage for a lower probability / higher risk scenario. This approach is one that has been adopted by several New England states and municipalities. In the context of this concept should be the consideration for the *risk tolerance of different kinds of infrastructure.* Using this approach, the **STS recommends that the Climate Council consider** committing to manage **for 1.5 feet of relative sea level rise by 2050, and 3.9 feet of sea level rise by the year 2100. Additionally, the STS recommends that the Climate Council consider** preparing to manage **for 3.0 feet of relative sea level rise by 2050, and 8.8 feet of sea level rise by the year 2100.**

Over about the last century, sea levels along the Maine coast have been rising at about 0.6 to 0.7 feet/century (1.8 to 2 mm/year) or two times faster than during the past 5,000 years. Over the past few decades, the rate has accelerated to about 1 foot/century (3 to 4 mm/year) or three times the millennial rate. These local changes have been following short- and long-term global averages.

About half of the last century's sea level rise in Maine has occurred since the early 1990s and it is likely that sea level in Maine will rise between 3 and 5 feet by the year 2100 based on an intermediate sea level rise scenario, although scenarios of higher rise are physically plausible. Sea level is expected to rise along the Maine coastline well beyond 2100.

Abrupt sea level change on the order of months, rather than years, can also occur on top of the long-term rise. Several months between 2009 and 2011 saw higher than normal sea levels, with a peak in 2010 of nearly a foot above the level in previous winters. Along the East Coast of the United States, this abrupt change was most pronounced in the Gulf of Maine.

A 1-foot increase in sea level in the future will lead to a 15-fold increase in the frequency of "nuisance" flooding. Nuisance flooding in Portland in the last decade was about 4 times more frequent than the 100-year average. A 1-foot increase in sea level, which could occur by 2050, would cause a "100-year storm" flood level to have a probability of occurring once in every 10 years. Not accounting for changes in storm intensity or frequency, this would result in a 10-fold increase in coastal flooding in Maine in the next 30 years.

Sea level rise will cause high tides to regularly inundate coastal lowlands with salt water and may cause limited salt contamination of groundwater aquifers. Coastal beaches, dunes, salt marshes, and bluffs are likely to experience increased erosion, landward movement, land loss and sediment redistribution due to long-term sea level rise. A 1.6-foot sea level rise will submerge two thirds or 67% of Maine's coastal sand dunes and reduce the dry beach area by 43%, which may happen by 2050 or earlier depending on the amount of sea level rise and available natural sand supply.

Rules that govern activities in Maine's Coastal Sand Dune System (NRPA 38 M.R.S. §480, Ch. 355), are the only ecosystem-focused policy that currently anticipates higher sea level. Maine's other regulatory authorities governing management of salt marshes and bluffs do not anticipate sea level rise. Maine's Coastal Management Policies (38 M.R.S. §1801) do discourage development in hazard areas affected by sea level rise in concept but not in practice.

DISCUSSION

Historical Sea Level Changes

Reconstructed curves of Maine's historical sea levels over the past 16,000 years indicate that changes were largely driven by vertical adjustment of the Earth's crust in response to deglaciation (Barnhardt et al., 1995). At the height of the last Ice Age, the weight of the glaciers depressed Maine's coast below ocean levels. As the glaciers receded, the ocean flooded a depressed coast and the shoreline was about 250 feet higher than present. Subsequently, the elevation of Maine's crust rapidly uplifted after the glacial weight was gone and relative sea level fell to over 200 feet below present. Sea level changes in the Gulf of Maine during this time were extremely rapid from a geological context and unlike that south of New York. It was glaciation and deglaciation – and the response of the Earth's crust – that historically dominated local sea level changes in Maine.

Over the past 5,000 years or so, relative sea level rise in Maine was comparatively slower than in the preceding 10,000 years and rose at rates of less than 0.3 feet/century (or 1 mm/year; Gehrels et al., 1996; Gehrels 2000; Kelley et al., 2010; 2013). During this much slower rate of sea level rise, most of Maine's current coastal landforms, including wetlands, bluffs, beaches, and dunes formed.

Modern Sea Level Rise

The instrumental record of measuring sea levels began in 1912 in Portland Harbor, 1929 in Eastport, and 1947 in Bar Harbor with the use of tide gauges. Physical measurements of sea level changes along the Maine coast by these National Oceanic and Atmospheric Administration (NOAA) gauges indicate that the long-term rate of sea level rise has been about 0.6 to 0.7 feet/century (1.8 to 2 mm/year, Figures 1 and 2). These changes in the Gulf of Maine are similar to observed global sea level rise trends.

These "modern" sea level changes are driven by two dominant factors that account for about 90% of the observed rise (Church et al., 2010). First is thermal expansion: as oceans warm, seawater physically expands. Second is an increase in the volume of ocean water caused by melting of land-based (terrestrial) ice sheets and mountain glaciers that release more water to the sea. Over the past several decades, volumetric increase has contributed more (44%) to sea level rise than thermal expansion (42%; Cazenave, 2018). Other factors such as ocean circulation patterns, vertical crustal movement in response to glaciation (now minor in Maine; Zervas et al., 2013), terrestrial water storage, and gravitational effects of glaciers account for the remaining 14% of modern sea level changes (Church et al., 2010). Modern sea level rise over the past century occurred at a rate that is about twice that of what it was when most of Maine's coastal landforms formed.

Recent Sea Level Rise

Since 1993, the advent and deployment of satellite altimetry provided a global perspective of sea level independent of tide gauges. Both altimetry data and Maine's three tide gauges (Portland, Bar Harbor and Eastport; Figure 2) show that in the last 25 years, the rate of sea level rise increased to just over 1 foot/century or just over 3 mm/year (Figures 1 and 2). This Gulf of Maine trend matches the global trend. About half of the observed sea level rise that has occurred over the past century has occurred since 1993 (Hayhoe et al., 2018).

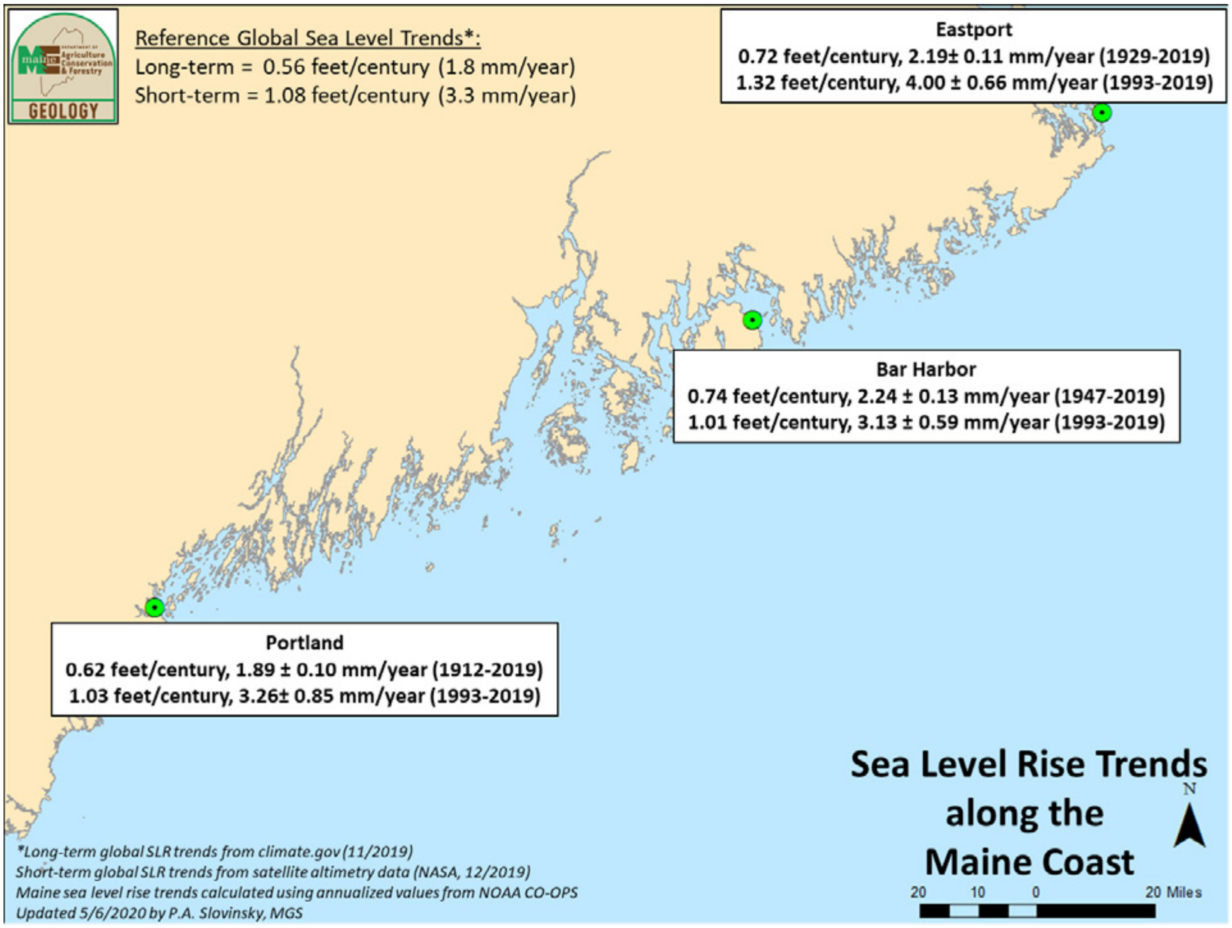
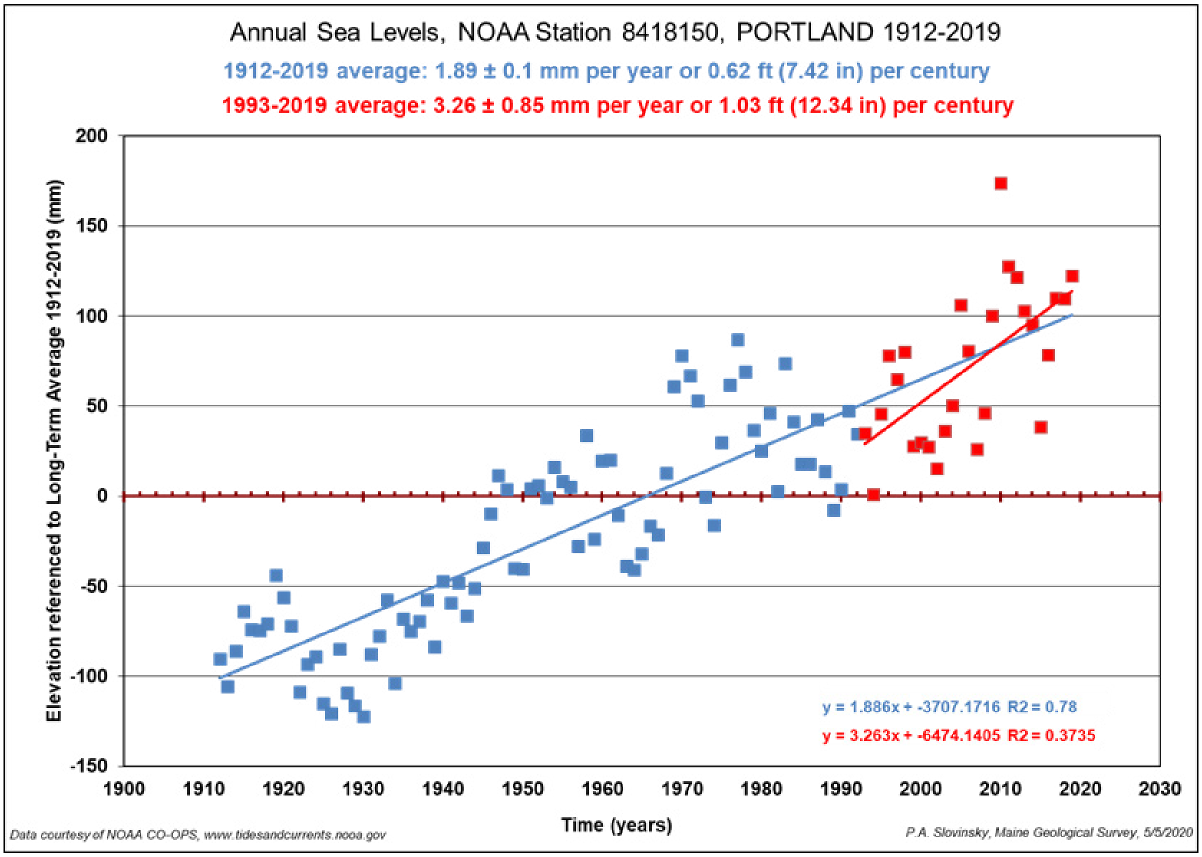


Figure 1. Long-term and short-term sea level trends along the Maine coast from three tide gauges through December 2019. Global sea level trends are in the top left.



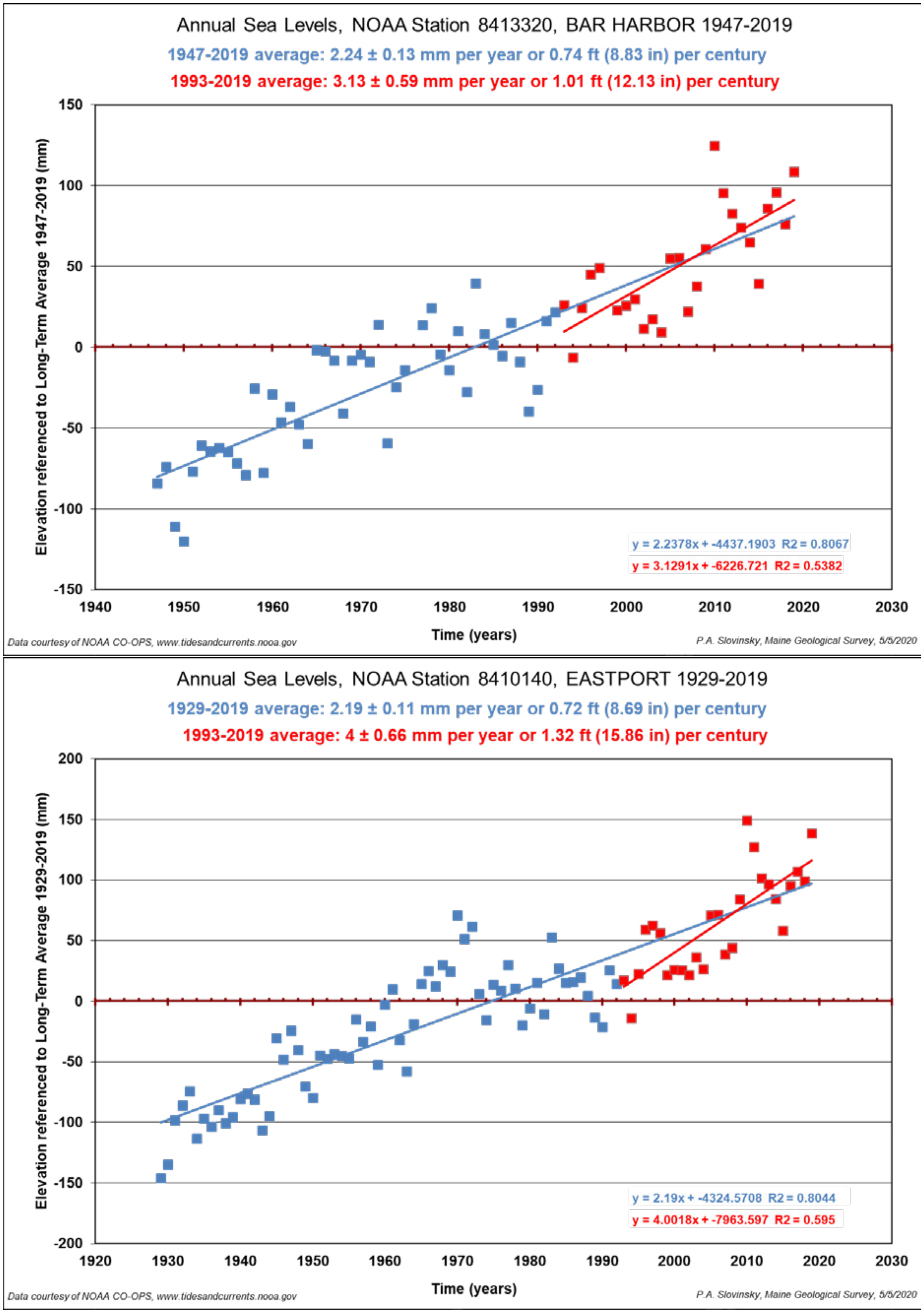


Figure 2. Graphs of modern sea level trends based on NOAA tide gauge records in Portland (top), Bar Harbor (middle), and Eastport (bottom). Note data collection started in 1912, 1947, and 1929 at Portland, Bar Harbor, and Eastport, respectively. Since 1993, the rate of rise has been between 1 to 1.3 feet/century (3 to 4 mm/year) with considerable interannual variability (red). Annual sea level values are plotted in millimeters relative to the average of all the tide gauge for each gauge. Note that the R^2 values for 1993-2019 are generally not statistically significant largely because of the outlier in 2010. Data source: NOAA Tides and Currents.

Maine Geological Survey analysis of monthly average sea levels from Portland, Bar Harbor, and Eastport determined that 83% (11 of 12), 100% (12 of 12), and 100% (12 of 12), respectively, of the *highest monthly averages occurred in the last decade* (Table 1). Conversely, almost all the lowest averages occurred in the first 10 years that a gauge was installed. Monthly averages from 2019 ranked first for one month at Portland, three months at Bar Harbor, and three months at Eastport.

Month	Portland (1912-2019)					Bar Harbor (1947-2019)					Eastport (1929-2019)				
	1st	2nd	3rd	Lowest	2019	1st	2nd	3rd	Lowest	2019	1st	2nd	3rd	Lowest	2019
January	2010	2011	1998	1922	5th	2010	2016	2011	1950	4th	2019	2010	2011	1930	1st
February	2010	1998	1978	1934	31st	2010	2017	1978	1951	16th	2010	2011	1998	1935	5th
March	2018	2010	2013	1913	16th	2018	2013	2010	1950	10th	2018	2013	2010	1943	7th
April	2010	2005	1961	1930	23rd	2017	2010	2012	1964	N/A	2010	2012	2011	1930	5th
May	2017	2005	2011	1929	4th	2017	2008	2019	1950	3rd	2017	2019	2011	1950	2nd
June	2012	2011	2009	1914	4th	2012	2011	2019	1950	3rd	2011	2018	2012	1930	4th
July	2009	2019	2011	1923	2nd	2019	2011	2017	1950	1st	2011	2019	2009	1938	2nd
August	2011	2012	2018	1921	4th	2011	2019	2018	1950	2nd	2011	2019	2018	1940	2nd
September	1996	2018	2010	1923	9th	2010	2017	1996	1955	5th	2010	1996	2019	1934	3rd
October	2019	2012	2011	1916	1st	2019	2011	2014	1947	1st	2019	2010	2011	1929	1st
November	1970	1983	1995	1930	6th	2019	1983	2016	1959	1st	2019	2010	1983	1934	1st
December	2010	2012	1970	1928	5th	2010	2012	2019	1949	3rd	2010	1968	2012	1936	4th
Since 2009	83%	67%	67%	0%	--	100%	83%	83%	0%	--	100%	83%	83%	0%	--

occurred since 2009 (red)
2019 ranked first (hatched)
data from NOAA CO-OPS 8418150, 8413320, 8410140

Table 1. Maine Geological Survey analysis of tide gauge data at Portland, Bar Harbor, and Eastport showing the top 3 highest monthly mean sea levels (first 3 columns), the lowest (fourth column), and 2019 ranking since data collection began at each gauge. Red boxes indicate that the highest monthly average occurred in the last 10 years. Diagonally hashed boxes show where 2019 rankings set new average monthly records.

Seasonal Sea Level Changes

Sea level along the Maine coast varies seasonally. In general, average monthly sea levels along the Maine coast are higher during the late spring and summer months, and lower during winter months (Figure 3). This is due to predominant weather patterns which either blow water against the coast (such as during the summer with southeast to southwesterly winds, which raise water levels), or blow water away from the coast (such as during the winter with strong north or northwesterly winds which drop water levels). However, most of Maine's highest recorded water levels occur from storm surges during winter storms (December through March; Figure 3). Winter storm tides typically occur when water levels are a few inches lower but overcome by surges of 1 foot or more (see section below). Seasonality in sea level slightly adds to the natural resiliency of Maine's coastline during the winter storm season.

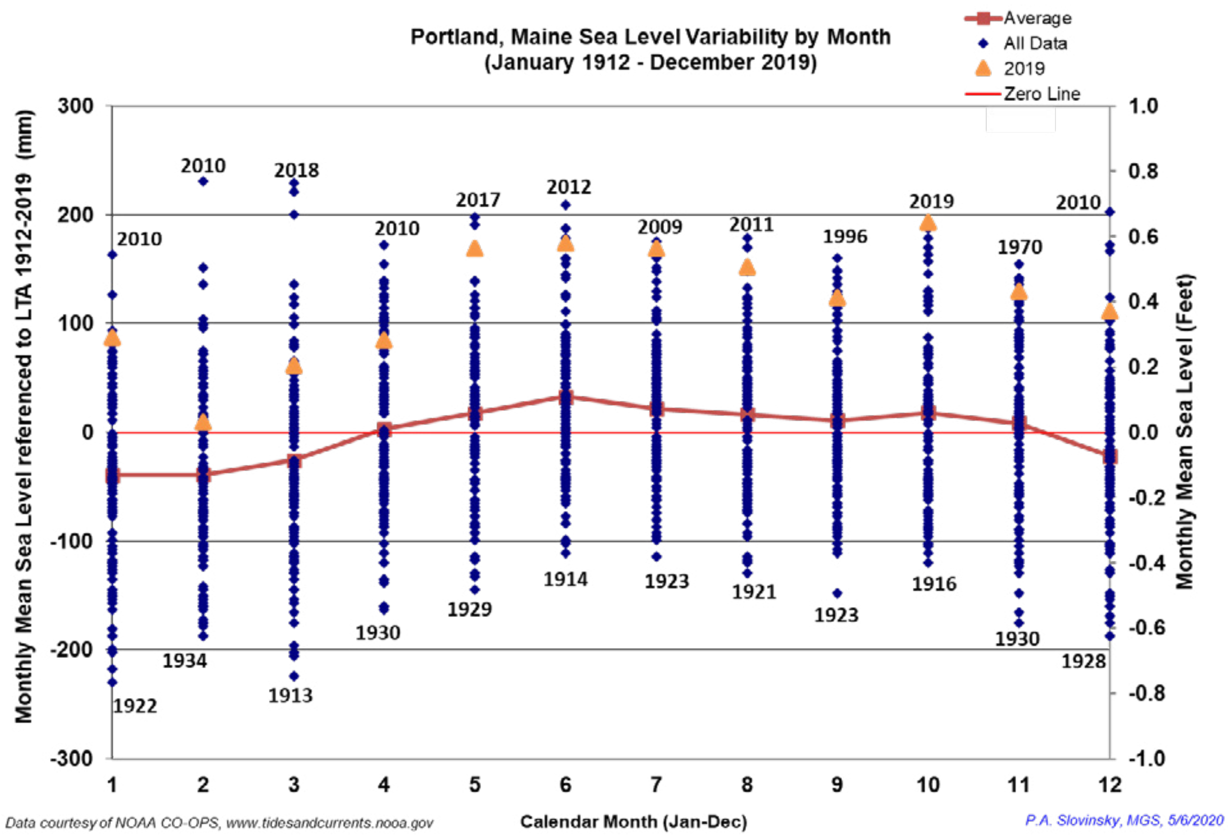


Figure 3. Maine Geological Survey analysis of mean monthly sea level values in Portland in relation to the long-term average (LTA, the "zero line") of all the data from January 1912 through December 2019. The average year has seasonal variability in sea level as shown by the dark red line with a high in June and a low in January. Record high and low values have the calendar year shown. The 2019 values all exceeded the long-term average, with October 2019 setting a new high monthly record

Abrupt Sea Level Rise

Abrupt sea level changes can and do occur in Maine. Large-scale atmospheric conditions, weather patterns, and ocean circulation cause interannual (year-to-year) variation in sea level in the Gulf of Maine. For example, during part of the summer of 2009 and especially in the winter of 2010, sea levels along the entire East Coast of the United States were several inches higher than normal and unprecedented in the tide gauge record (Goddard et al., 2015; Sweet et al., 2009). In northern New England, higher than normal sea levels were most pronounced in the winter of 2010. The 2009-2010 event led to 5 of the highest monthly sea levels ever recorded in Portland (Figures 2 and 3; Table 1). The winter sea level of 2010 was on the order of 4-5 inches higher than the previous 3 months and a foot higher than March 2007 (Figure 4; Slovinsky and Dickson, 2011b). Also shown in Figure 4 is the abnormally high monthly water level from March 2018, which set a record for the highest monthly average water level for March.

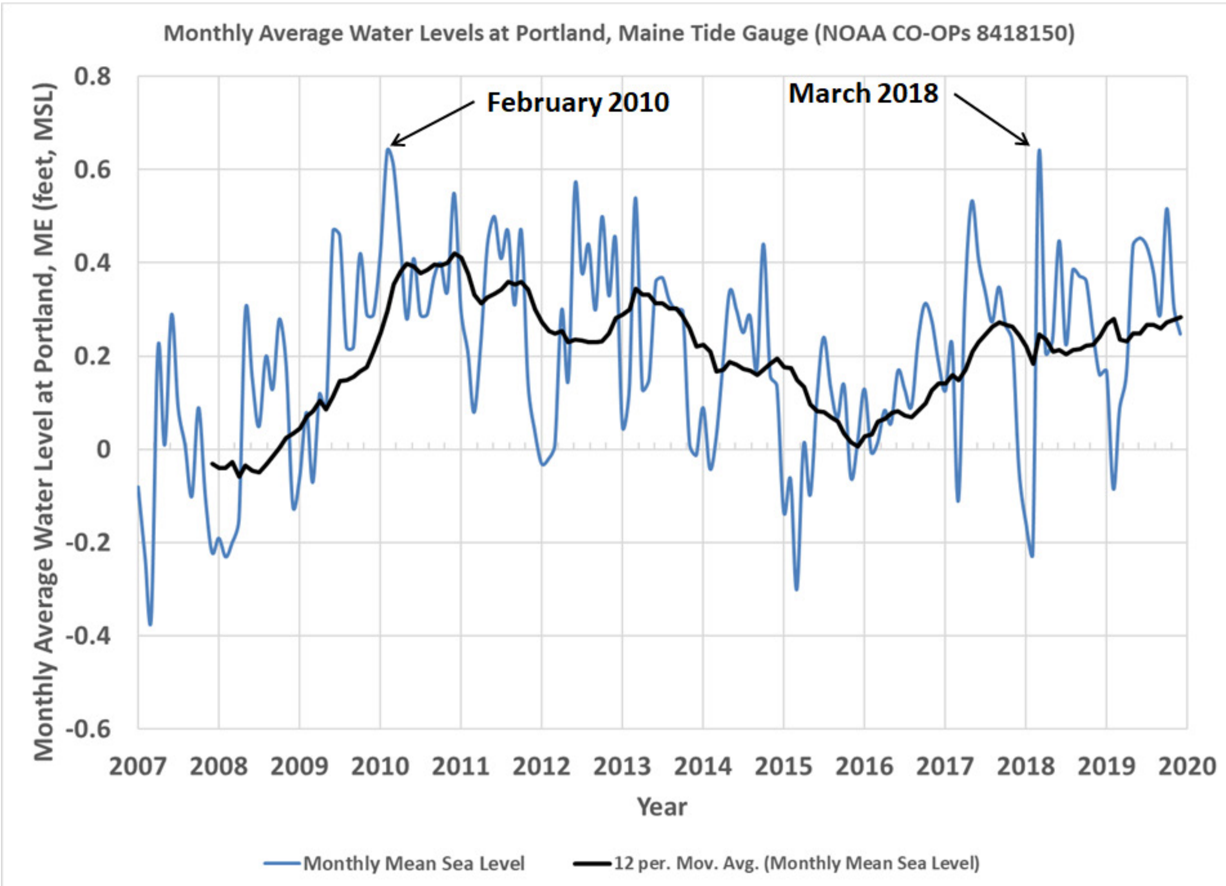


Figure 4. Monthly averaged water levels (blue line) from the Portland tide gauge from January 2007 through December 2019 shows the highest monthly sea level in February 2010. This high value had an average sea level that was just about 0.3 to 0.4 feet (4 to 5 inches) above that of the previous three months. Note March 2018 high water level as well. Black line is a 12-month moving average.

Sea level rise is not necessarily a slow and steady phenomenon but can change abruptly in a matter of months and result in increased coastal erosion and flooding along Maine's coastline. During the winter of 2010, many northeasters moved up the East Coast of the United States and caused very high levels of beach and dune erosion in Maine (Slovinsky and Dickson, 2011b). This abrupt sea level rise event was likely caused by wind patterns associated with a strongly negative North Atlantic Oscillation (NAO) in combination with a reduction in the Atlantic Meridional Overturning Circulation (AMOC) and a slower Gulf Stream (Goddard et al., 2015; Rossby et al., 2014). The 18.6-year lunar cycle can also affect decadal calculations of sea level rise (Baart, et al., 2012).

Potential Sea Level Rise Scenarios for Maine

By simply extrapolating the long-term linear trends calculated for Portland, Bar Harbor, and Eastport, potential averaged future sea level rise scenarios for 2030, 2050, 2070, and 2100 are shown below in Table 2. This type of projection *assumes that past conditions will dictate future conditions* and does not account for future greenhouse gas emissions, subsequent changes in thermal expansion, volumetric increase from ice melting, or other factors.

Decade	Portland	Bar Harbor	Eastport	Average
2030	0.2	0.2	0.2	0.2
2050	0.3	0.3	0.4	0.3
2070	0.4	0.5	0.5	0.5
2100	0.6	0.7	0.7	0.7
Relative Sea Level Rise (feet) from 2000				

Table 2. Potential relative sea level rise scenarios based on linear-best-fit to long-term tide gauge data. Data is rounded to tenths of a foot and presented in feet above a year 2000 starting point. Data from NOAA CO-OPs.

The Virginia Institute of Marine Sciences (VIMS) produced Sea-Level Report Cards for Eastport, Portland, and Boston (Boon et al., 2018; VIMS 2019). This analysis included calculating best-fit linear and quadratic equations to plotted data to make projections of future sea level rise using tide gauge data from 1969 to 2018. This study relied on historical data and did not include future greenhouse gas emissions. The projections do include a quadratic best-fit estimate with 95% confidence intervals out to the year 2050, but not beyond. Table 3 shows projections for three locations in the Gulf of Maine.

Location	SL Rise Rate 1969-2018 (mm/yr)	Acceleration 1969-2018 (mm/yr^2)	Linear Projection for 2050 (feet)	Quadratic Projection for 2050 (feet)
Eastport	1.83	0.20	0.33	1.35 $\pm$ 0.32
Portland	1.26	0.17	0.24	1.15 $\pm$ 0.39
Boston	3.15	0.18	0.59	1.54 $\pm$ 0.39

Table 3. A summary of sea level rise projections from the 2019 Sea Level Report Cards from three tide stations. Data from 1969-2018 were used in the trends. Early in 2020, the report will use 1969-2019 tide gauge data. The + values are a 95% confidence interval. Full descriptions and graphs are available at Boon et al. (2018) and VIMS (2019).

Instead of extrapolating potential future sea level rise using historic data only and not accounting for climate change impacts, the STS recommends adopting a scenario-based approach which considers a range of potential future Maine sea levels. Future sea level rise scenarios are closely aligned with the different Representative Concentration Pathways (RCPs), which are modeled global greenhouse gas concentration scenarios (van Vuuren et al., 2011). These are summarized below:

- RCP2.6 - Carbon emissions start declining in 2020. Global temperatures rise by 2.8°F by 2100 compared to 1850-1900. This scenario assumes substantial reductions in global greenhouse gas emissions.
- RCP4.5 - Carbon emissions stabilize and slowly decline after 2050. Global temperatures rise by 4.3°F by 2100 compared to 1850-1900.
- RCP6.0 - Carbon emissions stabilize in the latter half of the 21st century. Global temperatures rise by 5.4°F by 2100 compared to 1850-1900.
- RCP8.5 - Carbon emissions continue to increase through the end of the century. Global temperatures rise by 7.7°F by 2100 compared to 1850-1900. This is sometimes referred to as the "business as usual" scenario since the observed increase in global carbon emissions over the last few decades are currently following this scenario.

Work by Kopp et al. (2014; 2017) used a probabilistic approach which tied potential sea level rise scenarios to these different RCPs. This work included estimates of the following inputs: mass balance of Greenland and Antarctic ice sheets and smaller glaciers and ice caps, thermal expansion and large-scale oceanographic processes, land-water storage patterns and glacial isostatic adjustments. This type of probabilistic approach was built upon by Sweet et al. (2017) for the Fourth National Climate Assessment, discussed below. Using Kopp's data, Table 4 and Figure 5 show the central estimates (50% probability of being met or exceeded) for potential sea level rise at Portland, Maine associated with

Year	Scenario (50% probability of being met or exceeded)	
	Kopp - RCP 4.5	Kopp - RCP 8.5
2030	0.5	0.6
2050	1.0	1.1
2070	1.4	1.6
2100	2.0	2.7

Relative Sea Level Rise (feet) from 2000

Table 4. Table showing central estimates (50% probability) of potential sea level rise scenarios (in feet, starting in 2000) for Maine using the Portland tide gauge and RCP4.5 and 8.5 developed by Kopp et al. (2014). Values rounded to the nearest tenth of a foot.

RCP4.5 (red) and 8.5 (black) scenarios along with the "likely" band for each scenario (67% probability that SLR will fall between these values).

Building on work by Kopp, Sweet et al. (2017) developed both global and regional sea level rise scenarios in support of the 4th U.S. National Climate Assessment. Regionalized scenarios were developed for 1-degree grids along the U.S. coastline, and included the following key sources of information: ice sheet mass changes; glacier mass changes; thermal expansion and ocean dynamics; land-water storage contributions; and glacial isostatic adjustment, tectonics, and sediment compaction. It is important to note that regionalized sea level scenarios for Maine could potentially rise higher than global averages due to gravitational effects from Antarctic ice melt, reduced volume transport of the Gulf Stream, increased Antarctic ice melt, and reduced Atlantic ocean meridional overturning circulation (Ezer, 2013; Hu et al., 2009; Kopp et al., 2014; 2017; Sweet et al., 2017). These considerations have been included in the scenarios developed by Sweet et al. (2017).

Sea level scenarios based on Sweet et al. (2017) for about every 20 years out to the year 2100 and averaged from the three Maine tide gauges (Portland, Bar Harbor, and Eastport), including vertical land movement (VLM) are shown in Table 5. Figure 6 shows the intermediate-low, intermediate, intermediate-high, and high scenarios for Portland, Maine plotted at decadal time steps relative to sea level in the year 2000 in relation to the long-term trend.

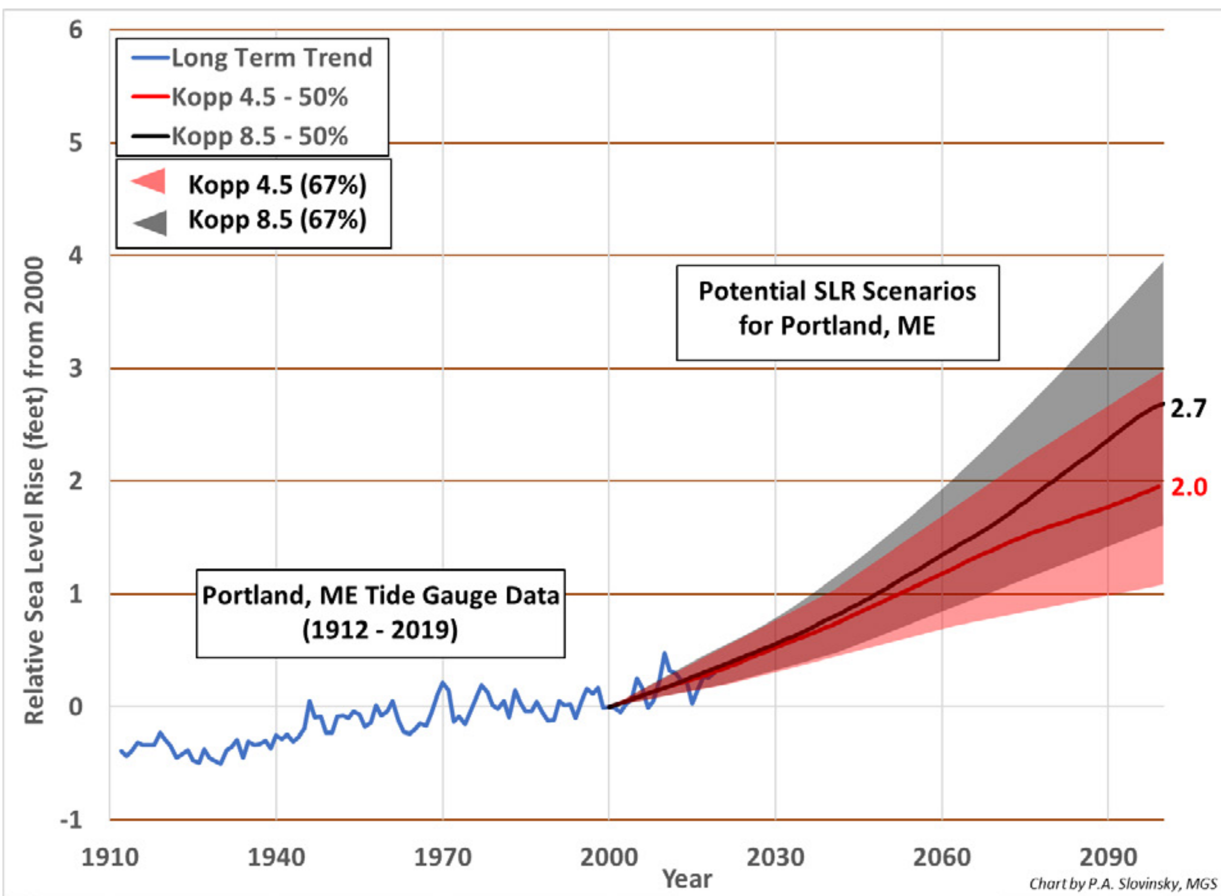


Figure 5. This graph illustrates historical sea level rise in Portland (1912-2019, dark blue line) and shows probabilistic scenarios from 2000-2100 for the central estimate (50% chance of being met or exceeded) associated with RCP4.5 (red line) and RCP8.5 (black line) and likely (67% chance the value will fall between) range probabilities (red and black bands, respectively). Scenarios based on Kopp et al. (2014). Annualized tide gauge data from NOAA CO-OPs. SLR scenarios developed from Kopp et al. (2014) using the 50% exceedance probabilities and 67% likelihood probabilities for RCPs 4.5 and 8.5.

Year	VLM	Scenario (50% probability of being met or exceeded)					
		Low	Int-Low	Intermediate	Int-High	High	Extreme
2030	0.0	0.4	0.5	0.8	1.1	1.4	1.5
2050	0.0	0.7	0.9	1.5	2.2	3.0	3.4
2070	0.1	0.9	1.2	2.4	3.5	5.0	6.0
2100	0.1	1.2	1.6	3.9	6.1	8.8	10.9
Relative Sea Level Rise (feet) from 2000							

Table 5. Table showing the potential sea level rise scenarios (in feet, starting in 2000) for Maine using averages from Portland, Bar Harbor, and Eastport and 50% probability scenarios developed by Sweet et al. (2017). Data were developed using the U.S. Army Corps of Engineers Curve Calculator (USACE, 2019). Scenarios for the year 2100 for Maine range from 1.2 to 10.9 feet and are shown graphically in Appendix A. Vertical land movement (VLM) values were derived from the Curve Calculator and Zervas et al. (2013). Values were rounded to the nearest tenth of a foot.

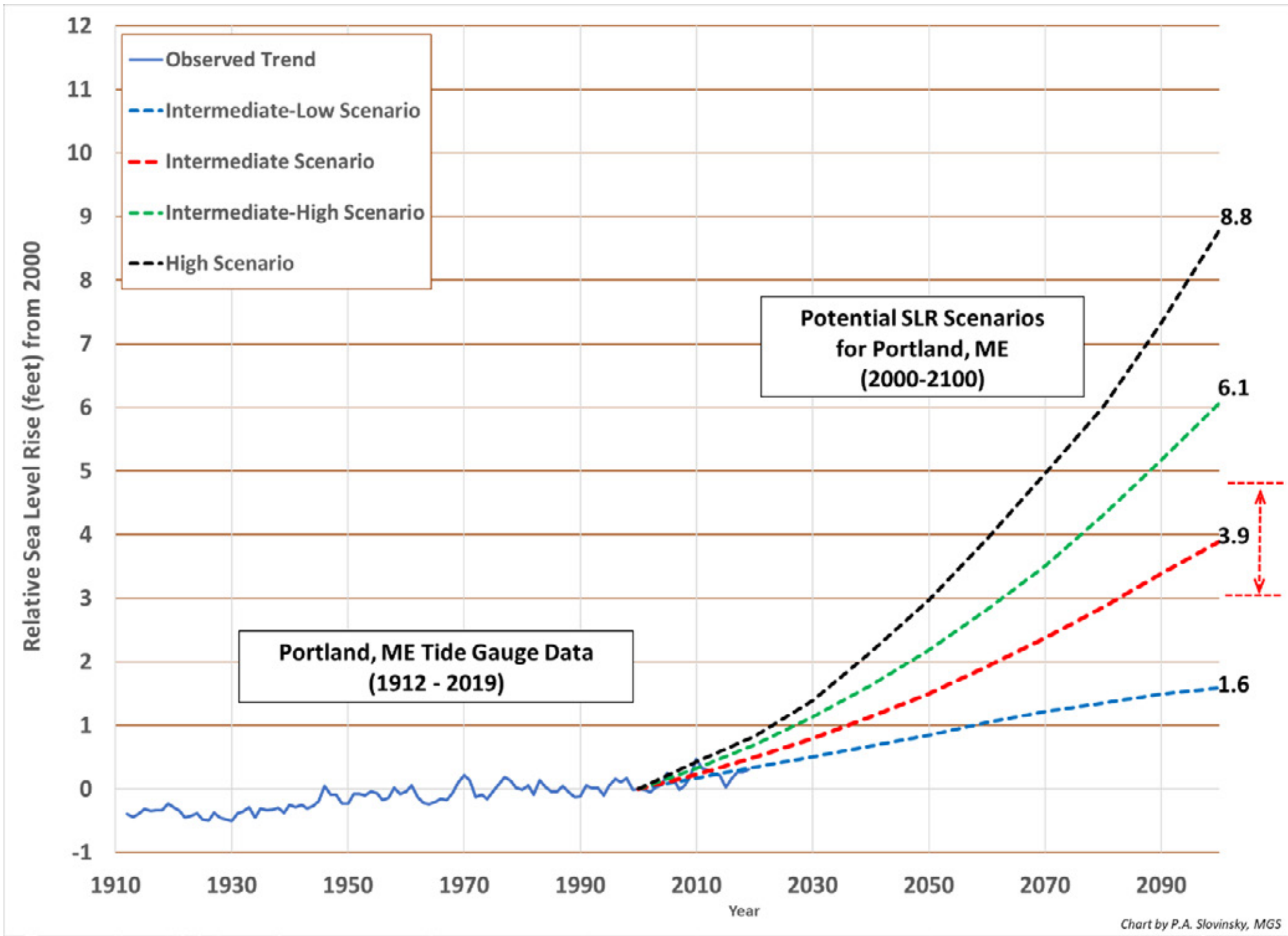


Figure 6. Graph illustrating historical sea level rise in Portland (solid blue line) and scenarios from 2000-2100 with central estimates (50% probability of being met or exceeded) for low-intermediate to high sea level rise scenarios from Sweet et al. (2017). The likely range of 3.0 to 4.6 feet (67% probability of sea level rise falling between these values) for the intermediate scenario is shown as a dashed red arrow and red lines on the right side of the figure. Values are presented in tenths of a foot and relate to a year 2000 starting point. Scenario data from the U.S. Army Corps of Engineers Sea Level Change Calculator (2019).

Table 6 summarizes and compares the different sea level rise scenarios using a probabilistic approach for the years 2030, 2050, 2070, and 2100 for Sweet et al. (2017) and Kopp et al. (2014) in comparison with linear extrapolation of the average of long-term trends from the three Maine tide gauge stations.

Year	Long-Term Trend *	Central Estimate 50% Probability SLR meets or exceeds					Likely Range 67% Probability SLR is between					1-in-20 Chance 5% Probability SLR meets or exceeds**	
		K14-4.5	K14-8.5	SW17-I	SW17-IH	SW17-H	K14-4.5	K14-8.5	SW17-I	SW17-IH	SW17-H	K14-4.5	K14-8.5
2030	0.2	0.5	0.6	0.8	1.1	1.4	0.3-0.7	0.3-0.8	0.6-1.0	0.7-1.3	1.3-1.6	0.9	1.0
2050	0.3	1.0	1.1	1.5	2.2	3.0	0.6-1.4	0.7-1.5	1.1-1.8	1.5-2.5	2.6-3.2	1.7	1.8
2070	0.5	1.4	1.6	2.4	3.5	5.0	0.8-2.0	1.0-2.4	1.8-2.8	2.5-4.1	4.2-5.2	2.6	3.0
2100	0.7	2.0	2.7	3.9	6.1	8.8	1.1-3.0	1.6-3.9	3.0-4.6	4.5-7.0	7.7-9.3	3.9	5.0

** Long-term trend from average of Portland, Bar Harbor, and Eastport*
K14-4.5 = Kopp et al. (2014) RCP 4.5 Scenario
K14-8.5 = Kopp et al. (2014) RCP 8.5 Scenario
SW17-I = Sweet et al. (2017) Intermediate Scenario
SW17 -IH = Sweet et al. (2017) Intermediate-High Scenario
SW17-H = Sweet et al. (2017) High Scenario
***SW17-I, SW17-IH, and SW-H do not have 5% probabilities calculated*

Table 6. This table compares potential sea level rise scenarios based on the long-term trend extrapolated to 2100 and the probability of sea level rise associated with different emission scenarios (4.5 and 8.5) from Kopp et al. (2014) and intermediate, intermediate-high, and high sea level rise scenarios from Sweet et al. (2017) for the years 2030, 2050, 2070, and 2100. The 5% probability scenario was not developed by Sweet et al. (2017). Values are rounded to tenths and presented in feet above a year 2000 starting point.

Recommended SLR Scenarios for Maine

The 4th US National Climate Assessment (Hayhoe et al., 2018) states that *relative to the year 2000, sea level is very likely to rise 1 to 4 feet (0.3 to 1.3 m) by the end of the century.* The range of sea level projections is driven by factors such as the amount of heat absorbed by the ocean and the volume of land-based ice that melts and flows into the ocean. Future greenhouse gas emissions are often described by Representative Concentration Pathways (RCPs) in order to model climate change. A survey of climate scientists with expertise in sea level rise found a median (50th percentile) global sea level rise projection for 2100 of 1.5 feet (0.45 m) under RCP2.6 and 3.1 feet (0.93 m) under RCP8.5 (Horton et al., 2020). The same survey found for 2100 a *very likely* range representing the 5th to 95th percentiles of 0.7 to 2.7 feet (0.21 to 0.82 m) for RCP2.6 and 1.5 to 5.4 feet (0.45 to 1.65 m) for RCP8.5.

The low and extreme scenarios presented by Sweet et al. (2017) are scientifically plausible lower and upper boundaries for potential sea level rise. In relation to RCPs 4.5 and 8.5, the low sea level rise scenario has a 98% and 100% probability of being exceeded, respectively. Because of the high probability of exceedance, the STS recommends using a higher sea level rise scenario for planning purposes.

The intermediate-low scenario has between a 73% and 96% probability of being exceeded in relation to RCPs 4.5 and 8.5, respectively. The intermediate scenario has a 3% probability of being exceeded under RCP4.5 and a 17% probability under RCP8.5. This relates to a 1 in 30 chance for RCP4.5 and 1 in 6 chance for RCP8.5 that the central estimate of sea level rise will be met or exceeded.

For the intermediate-high scenario, the probability of exceeding central estimates drops to 0.5% (1 in 200 chance) and 1.3% (a 1 in 80 chance) for RCPs 4.5 and 8.5 respectively. The high scenario has between a 0.1% (a 1 in a 1000 chance) and 0.3% (a 1 in 300 chance) for RCP4.5 and RCP8.5, respectively. The probability of an extreme sea level rise event, although physically possible, fall even more.

With each new scientific report on sea level rise (e.g., NOAA reports approximately every 5 years), the amount of sea level rise associated with emission scenarios increases as does the probability of higher sea level being achieved for various scenarios. Increase in the rate of change (acceleration) reflects a trend that has continued for over 100 years. With intermediate and higher emission scenarios, acceleration continues and sea level rise per decade increases through the year 2100. A recent survey of scientific experts determined that there is up to a 10% chance under RCP8.5 that by 2100 global sea level will reach 7.9 feet (Horton et al., 2020). The most extreme projection by NOAA (Sweet et al., 2017) currently projects a sea level rise of 10.9 feet by 2100 (without a probability; Appendix A).

The STS recommends that the Climate Council consider an approach of ***committing to manage*** for a certain higher probability / lower risk scenario, but also ***preparing to manage*** for a lower probability / higher risk scenario. This approach is one that has been adopted by several New England states and municipalities (e.g., O'Donnell, 2019; NH Coastal Flood Risk STAP, 2019; City of Portland et al., 2019). In the context of this concept should be the consideration for the *risk tolerance of different kinds of infrastructure.*

The STS recommends that the Climate Council consider **committing to manage** for a likely range of sea level rise associated with the **intermediate scenario** from Sweet et al. (2017). **By the year 2050, Maine will likely see between 1.1 and 1.8 feet of relative sea level rise, and potentially between 3.0 and 4.6 feet of sea level rise by the year 2100**. This likely range of scenarios generally incorporates the central estimate (50% probability or 1 in 2 chance) of Kopp for RCP8.5 (2.7 feet) at its lower end, yet also approaches the 5% probability (1 in 20 chance) scenario (5.0 feet) for that same RCP. It also includes the 5% probability for Kopp's RCP4.5 estimate (3.9 feet). Similarly, it correlates well with the very likely (1-4 feet) finding from the 4th U.S. National Climate Assessment.

Year	Central Estimate 50% Probability SLR meets or exceeds	Likely Range 67% Probability SLR is between
2030	0.8	0.6-1.0
2050	1.5	1.1-1.8
2070	2.4	1.8-2.8
2100	3.9	3.0-4.6

Table 7a. Relative sea level rise values (in feet, starting in 2000) based on the intermediate sea level rise scenario from Sweet et al. (2017) averaged for Portland, Bar Harbor, and Eastport. Values have been rounded to tenths of a foot. Presented are the central estimates and likely range values for State of Maine commitment to adaptation planning.

The central estimates and likely ranges from the intermediate scenario are presented below in Table 7 for data averaged from the Portland, Bar Harbor, and Eastport tide gauges.

Additionally, because of the evolving science regarding potential future contributions to global and regional sea level rise by the Greenland and especially the Antarctic ice sheet (DeConto and Pollard, 2016; Morlighem et al., 2020; Wilson et al. 2018), the accuracy of predicting an extreme sea level rise scenario of 1% probability for 2100 is difficult (Miller et al., 2018). Currently, the NOAA extreme projection of 10.9 feet by 2100 has an unquantified low probability but high impact (Graph A.1. in Appendix A). The STS recommends that the Climate Council also consider ***preparing to manage for a potentially higher sea level rise scenario***. The STS recommends that the Climate Council consider **preparing to manage** for a likely range of sea level rise associated with the **high scenario** from Sweet et al. (2017). **By the year 2050, Maine may see between 2.6 and 3.2 feet of relative sea level rise, and potentially between 7.7 and 9.3 feet of sea level rise by the year 2100** (Table 7b).

The STS also recommends that scenarios for regionalized sea level rise adaptation be revisited **approximately every four years** in order to update projections based on available science and in conjunction with the latest release of the U.S. National Climate Assessment (NCA). The Maine Geological Survey updates the sea-level rise mapping portal (Appendix A) within a year of each new National Climate Assessment and will revise the Highest Astronomical Tide level used in the simulations if a new National Tidal Datum Epoch (NTDE) is released by NOAA. The NTDE might be revised ahead of the next NCA.

Planning Scenario	"Commit to Manage"	"Prepare to Manage"
Year	Intermediate Scenario	High Scenario
2030	0.8	1.4
2050	1.5	3.0
2070	2.4	5.0
2100	3.9	8.8
Relative Sea Level Rise (feet) from 2000		

Table 7b. Central estimates of relative sea level rise (in feet, starting in 2000) based on the intermediate and high scenarios from Sweet et al. (2017) averaged for Portland, Bar Harbor, and Eastport. Values have been rounded to tenths of a foot. Presented are the central estimates for State of Maine commitment or preparation for adaptation planning.

Storm Surges, Storm Tides, and Nuisance Flooding

Storm Surges

Each year, coastal storms such as nor'easters pile water up against portions of the Maine coastline due to onshore winds, causing predicted tidal water levels to be exceeded. This abnormal rise of water generated by a storm, over and above a predicted astronomical tide, is called storm surge (NOS, 2019). The amplitude of storm surge at any given location depends on the orientation of the coastline with respect to the storm track, intensity, size, speed of the storm, and local bathymetry (topography of the river or ocean floor underwater). Because of this, certain areas of the Maine coastline are susceptible to storm surges from different kinds of storm events. For example, the coastal community of Camp Ellis in Saco is especially susceptible to storm surges resulting from nor'easters due to its orientation facing northeast. Conversely, Bangor is susceptible to storm surges resulting from southeasters, which pile water up into the enclosed Penobscot Bay and up the Penobscot River. This was especially evidenced by the Groundhog Day Storm of February 2, 1976, which resulted in devastating flooding in areas of downtown Bangor (Morrill et al., 1979). Tidal surge up the Penobscot River can be significantly amplified in relation to other locations due to local geography, bathymetry, and tide-surge-river interaction in the Penobscot Bay estuary (Spicer et al., 2019).

As a result of the different locations and orientations of long-term operating tide gauges along the Maine coast (Portland, Bar Harbor, and Eastport), the highest storm surges along the Maine coastline vary. Portland's tide gauge is located within the Fore River and has exposure to the northeast and Casco Bay (Ward et al., 2018). Bar Harbor's gauge also faces northeast, but is within the enclosed Frenchman Bay, where northeast winds typically blow water out of the bay, but southeast winds blow water into the bay.

Since 1912, the highest recorded storm surge (occurring during any tide) in Portland was 4.6 feet during a nor'easter on March 3, 1947, which sank the SS Oakley Alexander at Portland Head Light. The second highest was from a nor'easter in February 2010, and the third from a nor'easter in April 1974 (Figure 7). By comparison, the highest recorded annual surge in Bar Harbor was 4.9 feet during the Groundhog Day Storm of 1976, a southeaster. None of the top three annual surge events from Portland registered high at Bar Harbor. Figure 8 shows the difference in the top 20 annual storm surges at Portland, Bar Harbor, and Eastport. Additional highest annual storm surge charts are in Appendix B.

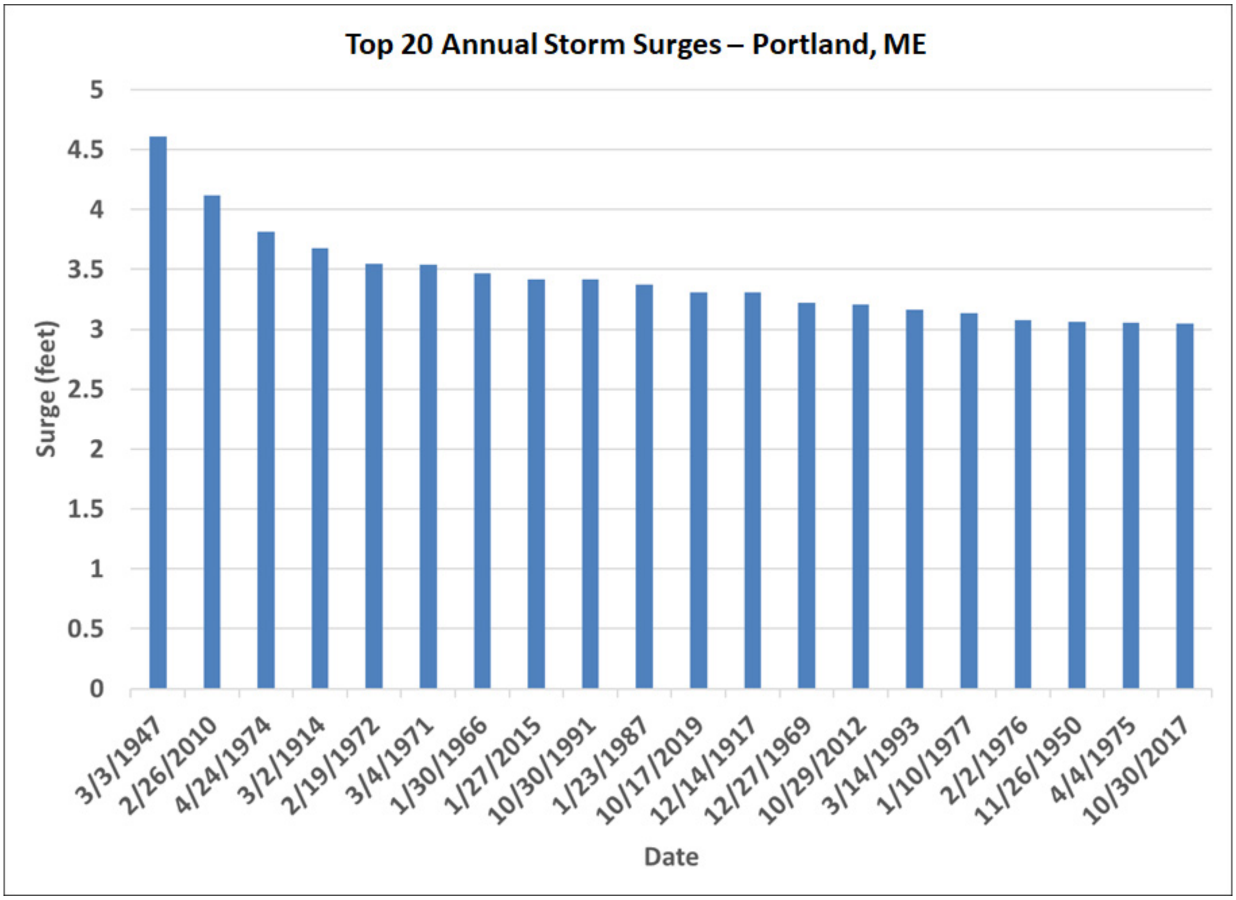


Figure 7. Top 20 highest annualized surge values at Portland, ME (1912-2019) based on verified hourly water levels.

When comparing the recurrence interval of storm surges at the three tide gauges (determined from best-fit lines through the data), the statistics for surges occurring at any tide are very similar (Table 8).

Recurrence Interval	% Annual Chance	Storm Surge (feet)		
		Portland	Bar Harbor	Eastport
1	100%	2.0	1.8	2.0
5	20%	2.9	2.8	2.9
10	10%	3.3	3.3	3.3
25	4%	3.9	3.9	3.9
50	2%	4.3	4.3	4.3
100	1%	4.7	4.7	4.7

Table 8. Calculated recurrence intervals in years for storm surges at Portland, Bar Harbor, and Eastport based on best-fit equations and annualized surge data. Data through December 31, 2019 from NOAA CO-OPs.

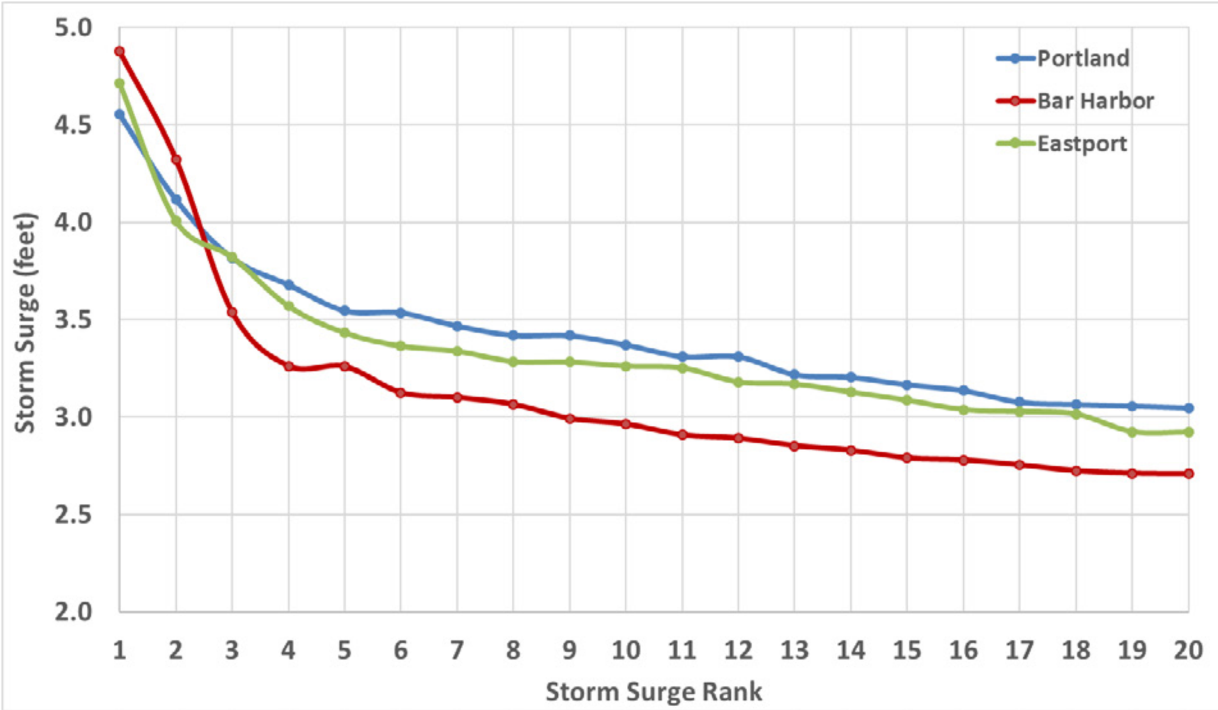


Figure 8. Top 20 annual storm surges for Portland (blue line), Bar Harbor (red line), and Eastport (green line). The highest surges were 4.6 feet at Portland (3/3/1947), 4.9 feet at Bar Harbor (2/2/1976), and 4.7 feet at Eastport (2/19/1972). Although Bar Harbor had the highest recorded surge (4.9 feet), the majority of its top 20 surge events are lower than at Portland and Eastport. Data from NOAA CO-OPs.

However, given Maine's large tidal range (9 feet along the southwest coast and near 20 feet in Downeast Maine), storm surges by themselves may not necessarily cause flood damage. Peak storm surges that occur during low to mid-tide are often below the highest astronomical tide level or flood stage. The National Weather Service defines flood stage as "an established gage height for a given location above which a rise in water surface level begins to create a hazard to lives, property, or commerce." This large tide range in the Gulf of Maine helps reduce the duration of coastal flooding and results in a natural resiliency for Maine's coastline.

How storm surges in Maine might be impacted by climate change has been only recently studied. Combined climate and weather dynamics may result in storm surges in the Gulf of Maine increasing 0.3 to 0.5 feet (10 to 15 cm) in the next 40 years independent of rising sea level (Yin et al., 2020). In general, storms with higher sustained onshore wind and lower central pressures could increase the magnitude of storm surge. Both extratropical and tropical storms may become more intense and possibly more frequent (Kossin et al., 2020; Tebaldi, et al., 2012) and result in higher and more common storm surges in Maine. An increase in tidal heights due to increasing sea level will have an impact on the underlying water level onto which storm surges would be superimposed. This is discussed below under Storm Tides.

Storm Tides

The combination of an astronomical tide with a storm surge is called storm tide. Storm tides cause most of the salt-water flooding in Maine's coastal communities. Because of the natural resiliency afforded to the Maine coastline by a large tidal range, it takes special conditions for a large storm surge to coincide with a high astronomical tide, resulting in a high storm tide. However, sea level rise will elevate future high tide levels, so that when surges do occur, they would combine with already elevated water levels and increase both the frequency and depth of inundation (Tebaldi et al. 2012). For more information, see the Nuisance Flooding Section below.

The top 20 annual storm tides for Portland, Maine are shown in Figure 9 in reference to the published flood stage (12 feet Mean Lower Low Water or MLLW) from the National Weather Service. The predicted tide component of the storm tide is shown in blue, while the storm surge is shown in red. The tidal component of the storm tide averages 11.3 feet MLLW – about 0.7 feet below flood stage. The surge from these events averages about 1.7 feet – less than the 1-year recurrence interval (100% chance) storm surge. All the top 20 storm tides exceeded flood stage, and the highest recorded water level was from February 7, 1978. Note that none of the top 20 highest annual storm tides occurred where the tidal component by itself met flood stage.

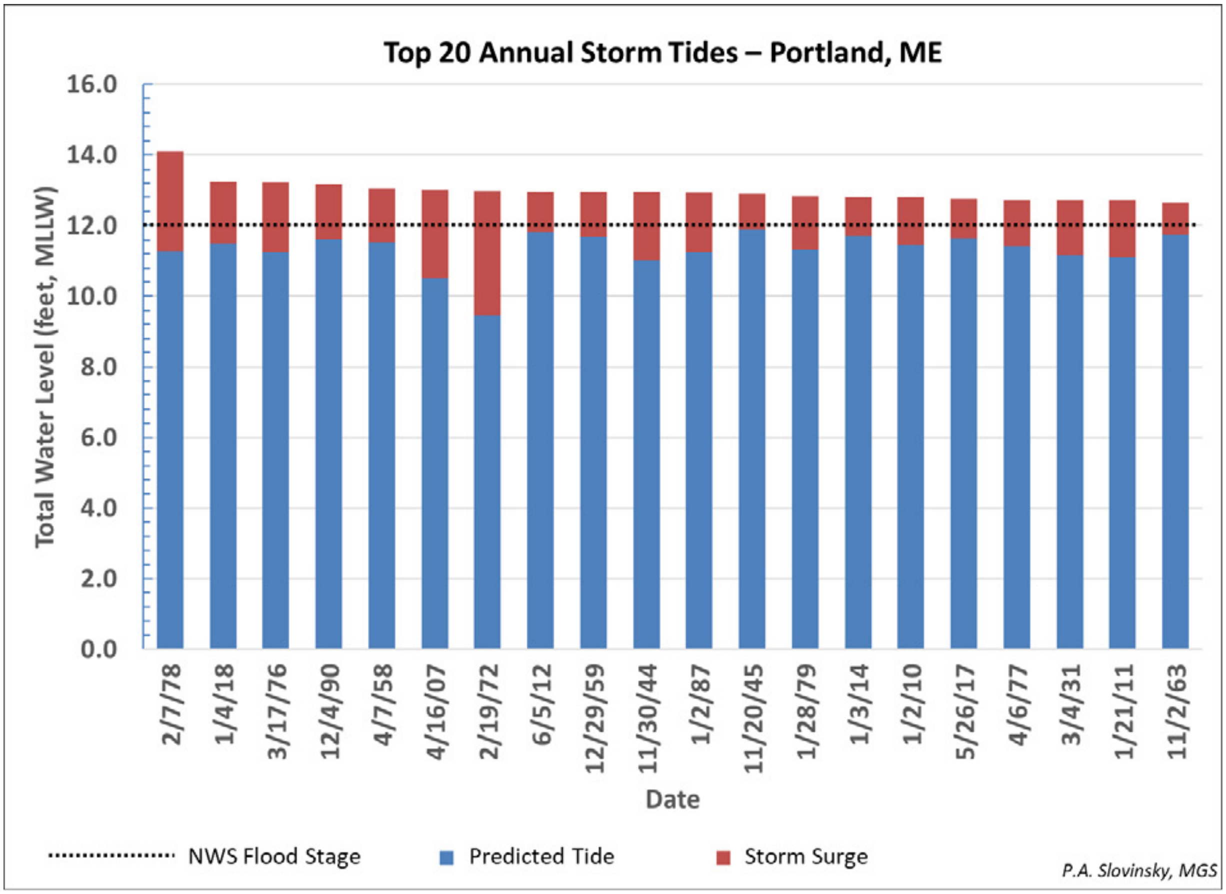


Figure 9. Top 20 annual storm tides for Portland, ME from 1912-2019. Tidal component is shown in blue and storm surge in red. The published National Weather Service (NWS) flood stage – considered to be 12 feet MLLW – is shown as a dashed black line. Data from NOAA CO-OPs.

For reference, the published Bar Harbor flood stage is 15 feet MLLW. For the top 20 events, only 2 annual storm tide events exceeded this value. The average predicted tide was 13 feet, with an average surge of 1.5 feet. The average tide is about 2 feet below flood stage and the highest event was from March 17, 1976. In Eastport, the published flood stage is 23 feet MLLW. For the top 20 events, all events exceeded flood stage. The average tidal elevation was 22.3 feet, about 0.7 feet below flood stage, and the average surge among these events was only 1.1 feet, and the highest event was from January 10, 1997. Additional storm tide graphs for Bar Harbor and Eastport are in Appendix B.

Figure 10 shows how the different storm tides from each tide gauge rank in terms of their top 20 in reference to meeting or exceeding the published National Weather Service flood stage. Portland data is shown in blue, Bar Harbor in red, and Eastport in green.

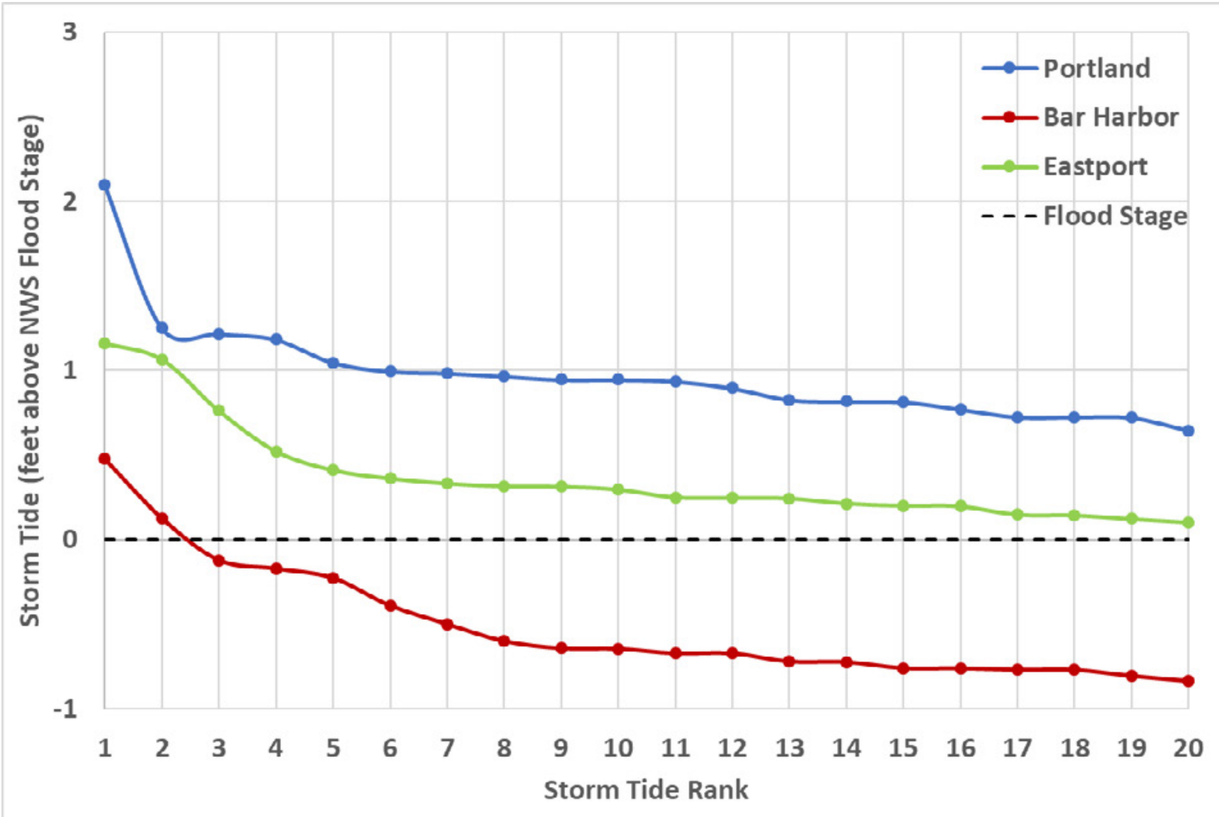


Figure 10. Top 20 annual storm tides from available data (through 2019) for Portland (blue), Bar Harbor (red), and Eastport (green) in reference to published flood stage elevation (0 value, dashed black line) from the National Weather Service. Six of Portland's top 20 storm tides were a foot or more above flood stage, while only 2 storm tides were more than a foot above flood stage at Eastport. None of the top 20 storm tides were more than a foot above flood stage at Bar Harbor, and only 2 storm tides exceeded flood stage. Data from NOAA CO-OPs.

Table 9 compares the storm tide recurrence intervals for each tide gauge. Elevations which meet or exceed published flood stages are shown in red. Flood stage is met or exceeded at a 5-year (20% chance of occurring in any year) recurrence interval for both Portland and Eastport, while it takes a 25-year (4% chance of occurring in any year) event to exceed flood stage at Bar Harbor.

There is only about a 1-foot difference between the storm tide that has a 10% chance of occurring in any given year and the storm tide that has a 1% chance of occurring in any given year for each of the tide gauges. *This means that a foot of sea level rise would result in a 10-year event reaching the current 100-year event water level, or conversely, one foot of sea level rise would result in a 100-year storm tide having the recurrence interval of a 10-year event.*

Recurrence Interval	% Annual Chance	Storm Tide (feet, MLLW)		
		Portland	Bar Harbor	Eastport
1	100%	11.7	13.4	22.1
5	20%	12.6	14.2	23.0
10	10%	12.9	14.6	23.3
25	4%	13.4	15.0	23.8
50	2%	13.7	15.4	24.2
100	1%	14.1	15.8	24.6

Table 9. Calculated recurrence intervals (in years) for storm tides at Portland, Bar Harbor, and Eastport based on best-fit lines and annualized data. Red text indicates that the published NOAA National Weather Service (NWS) flood stage has been met or exceeded. Data through December 31, 2019 from NOAA CO-OPs.

Nuisance Flooding

When predicted or observed water levels approach "flood stage," coastal flood advisories are typically issued by the National Weather Service for minor, or "nuisance" flooding, which occurs in several low-lying areas of Portland (e.g., along Commercial Street and Marginal Way). According to NOAA's Advance Hydrologic Prediction Service, flood stage at the Portland tide gauge is 12 feet MLLW. Analysis of hourly tide level data at Portland from January 1912 – December 2019 indicates that the 12-foot flood stage has been met or exceeded about 3.4 times per year on average (Slovinsky, 2019). Over the past decade (2009-2019), exceedance of flood stage increased to around 12 times per year. In comparison, 2010 and 2018, flood stage was met or exceeded 26 and 22 times, respectively (Figure 11).

If a 1-foot rise in sea level occurred on top of the historical data (1912-2019), flood stage would have been exceeded around 54 times per year (Figure 12). **This is more than a fifteen-fold increase in flood frequency**. This increase in flood frequency is in line with projections for other cities in New England (Ezer and Atkinson, 2014; Sweet et al., 2019).

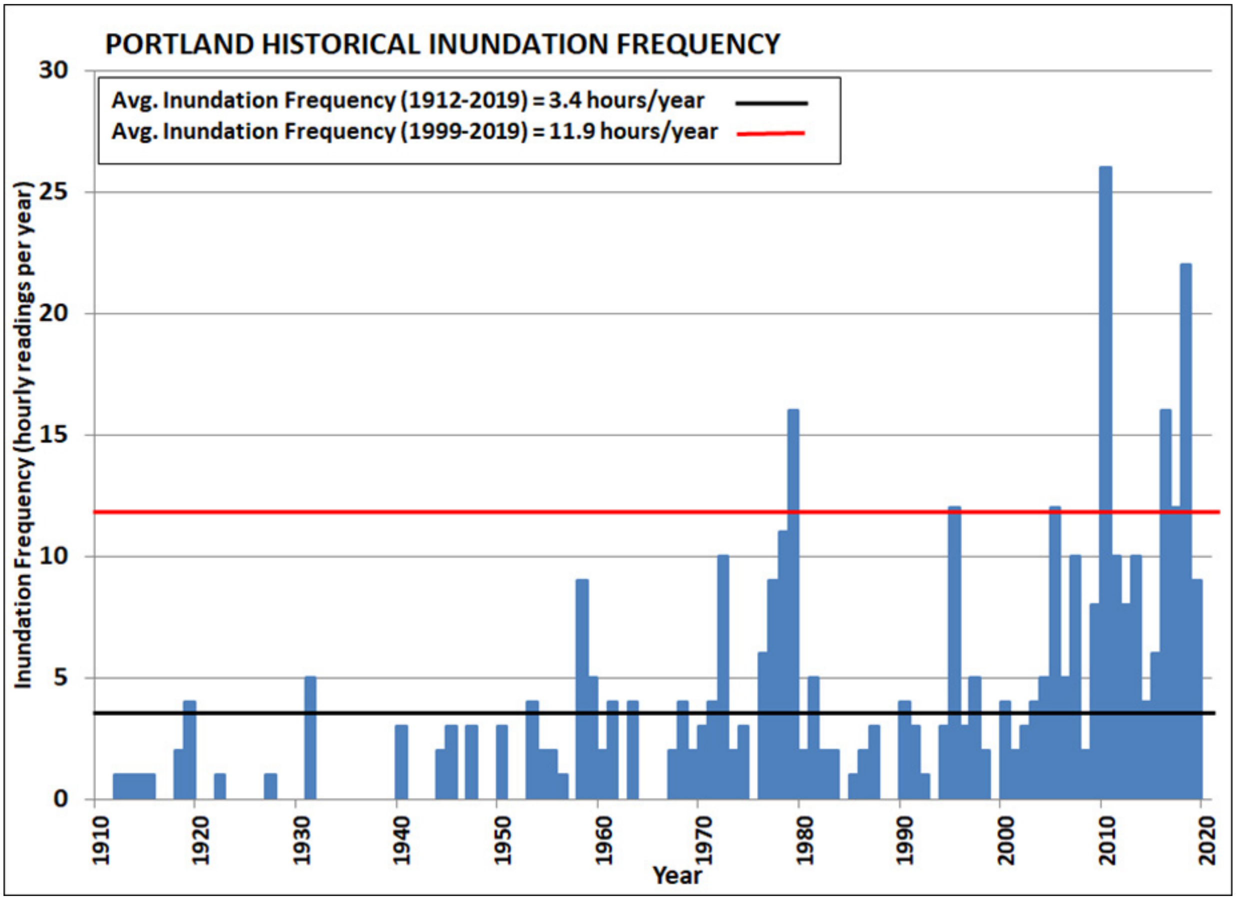


Figure 11. Frequency of flood stage (12 feet MLLW) being met or exceeded at Portland, Maine from 1912 through 2019. The long-term average is 3.4 events per year (black line). Over the past decade, the average was about 12 events per year (red line).

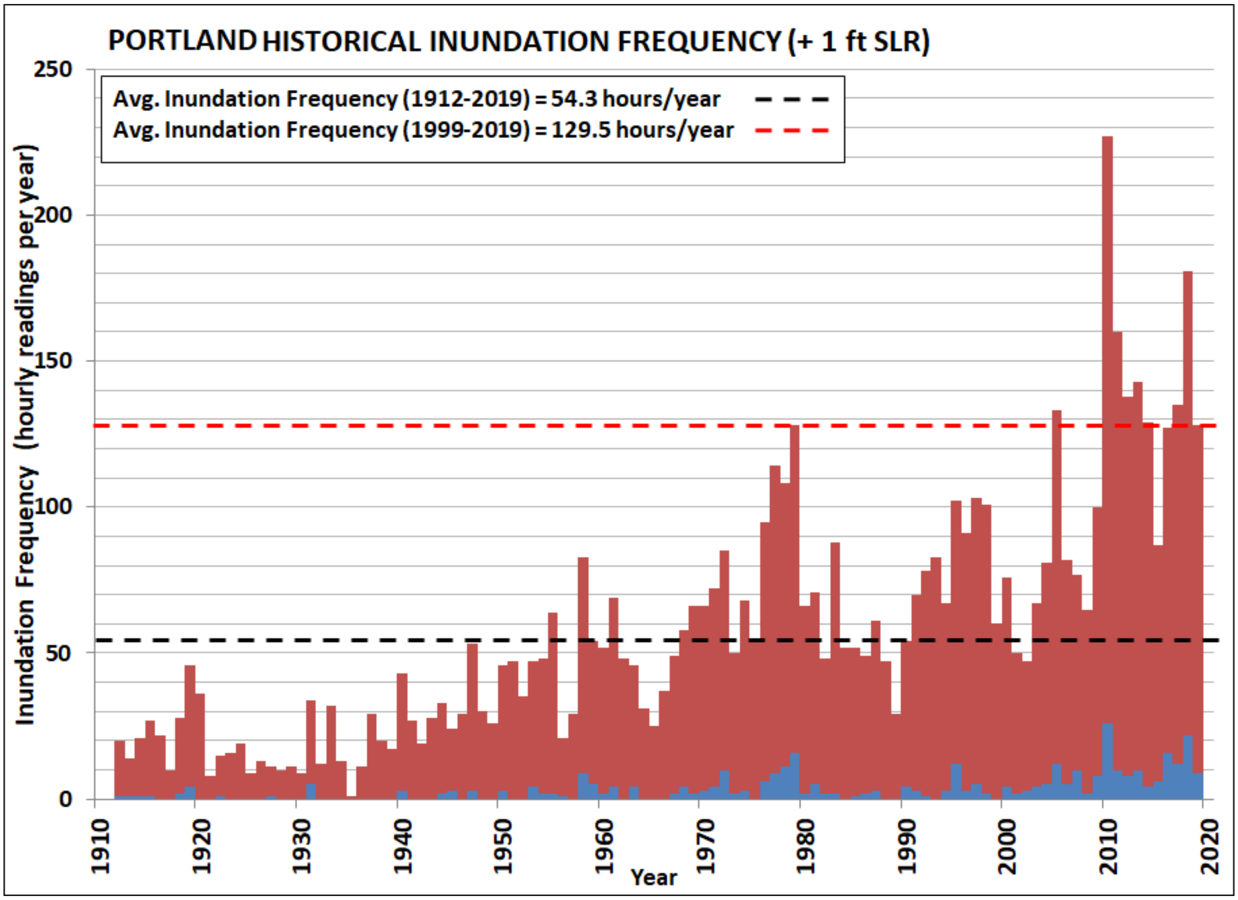


Figure 12. Comparison of historic long-term frequency of inundation (blue bars) with the frequency if 1 foot of sea level rise had occurred on top of the long-term data (red bars). The long-term average would have been 54 events per year (dashed black line) – over a fifteen-fold increase. From 2009 through 2019, the average would have been about 130 events per year (dashed red line).

Coastal Landscapes and Sea Level

Inundation of Uplands

The Maine Geological Survey has an online interactive mapping tool that displays the geographic extent of the central estimates of sea level rise scenarios for the year 2100 from Sweet et al. (2017) and shown in Table 5 (MGS, 2019). These scenarios show the extent of upland inundation above the Highest Astronomical Tide (HAT) or upper boundary of tidal action in the most recent National Tidal Datum Epoch (NTDE). For example, a sea level rise of 3.9 feet above the HAT results in over 28,000 acres (45 square miles) of coastal lowlands becoming tidal multiple days per year (Table 10). Several examples of the geographic impacts of the 3.9-foot scenario from around Maine are shown in Appendix A.

County	Sea Level Rise Scenario*					
	1.2 ft	1.6 ft	3.9 ft	6.1 ft	8.8 ft	10.9 ft
York	1,195	1,604	4,011	6,097	8,627	10,821
Cumberland	1,127	1,501	3,758	5,917	8,255	10,889
Sagadahoc	1,435	1,870	4,286	5,874	7,425	8,979
Kennebec	112	202	611	848	1,115	1,290
Lincoln	621	854	2,122	3,403	4,911	6,508
Knox	754	1,018	2,788	4,764	6,841	9,242
Waldo	317	375	669	974	1,253	1,819
Penobscot	27	36	103	181	281	364
Hancock	1,517	2,002	5,152	8,127	11,687	15,721
Washington	1,390	1,933	5,191	8,529	12,764	16,948
Maine Total	**8,494**	**11,394**	**28,690**	**44,715**	**63,157**	**82,580**

Scenarios are 50% Probability Estimates from Sweet et al. (2017) for low to extreme scenarios

Inundation area rounded to nearest acre

Table 10. This table shows the area of current upland (in acres) that may become inundated during the highest tides under different sea-level rise scenarios in each of the 10 coastal counties in Maine. For reference, there are 640 acres per square mile. Analysis by H. Corney, MGS and rounded to the nearest acre.

Table 10 estimates static inundation of the existing land surface at higher sea and tide levels in each Maine county; it does not account for dynamic changes in the land surface due to sedimentation, erosion, or accretion. Modeling of dynamic coastal responses to higher sea level has not been done. Also, these data do not include future areas inundated by storm tides on higher sea levels that would briefly result from coastal flooding.

Using static topography of Maine's coastal landscape, and discounting area changes from erosion and deposition above the Highest Astronomical Tide elevation, inundation scenarios show a relatively linear rate of inundation with rising sea level (Figure 13). For every foot of sea level rise, there are approximately 7,400 acres (11.6 square miles) of upland that becomes tidal.

There are a variety of different coastal landforms in Maine that would be impacted directly by rising sea levels. Work compiled by the Maine Coastal Program (2015) with data from the Maine Geological Survey summarizes the geological types of coastal shorelines (Table 11) and their general vulnerability to sea level rise (Table 12). About two thirds of Maine's shoreline, primarily beaches and coastal bluffs, are subject to change through erosion and deposition (Table 13)

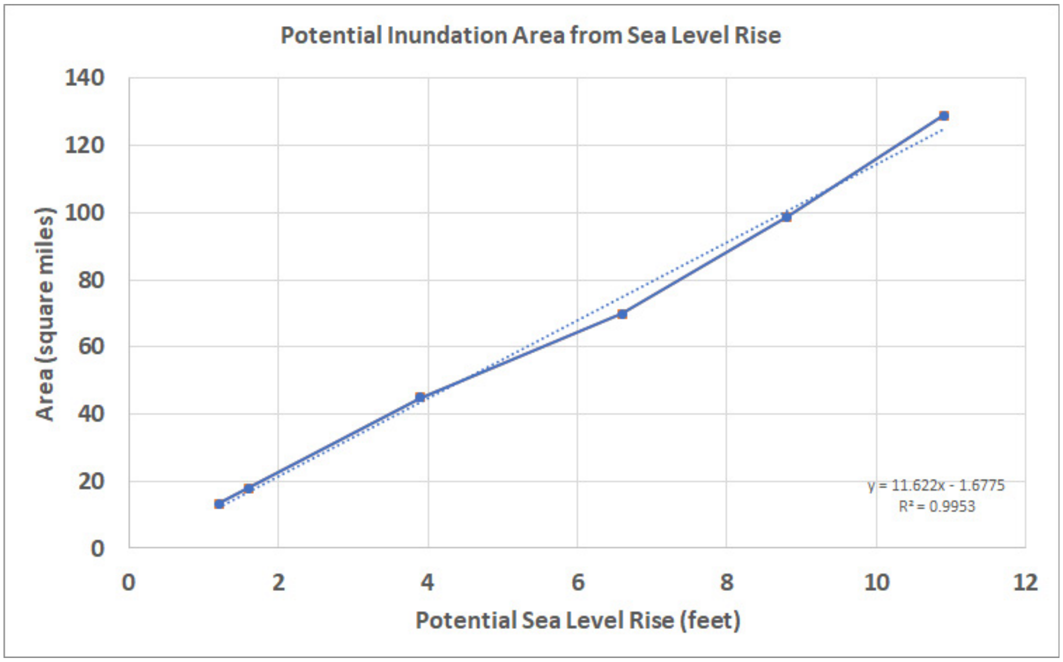


Figure 13. Rising sea level results in a relatively constant rate of area inundated for every foot of sea level rise (solid blue line). There is almost a perfect linear relationship (dashed blue line) between potential sea level rise and the area of potential inundation. This graph uses data from Table 10. Low to extreme sea level rise scenarios from Sweet et al. (2017).

Shoreline Types		
Shoreline Type	**Percent**	**Miles**
Armored	5%	252
Sand Beaches and Dunes	4%	211
Coarse Beaches	7%	355
Flats	30%	1607
Rocky	29%	1575
Vegetated	26%	1407
Total Shoreline Length	**100%**	**5407**

Table 11. The geological composition of the Maine coast broken down by shoreline type at or near the highest annual tide level. These numbers were derived from analysis of MGS Coastal Marine Geologic Environment Maps (CMGE), Coastal Bluff Maps, and Coastal Sand Dune Geology Maps. In southern Maine, approximately 16 miles of sand beaches and dunes have seawalls or other form of armor. Source: MCP, 2015, p. 20.

Sea Level Rise Vulnerability (CMGE and Bluff Types)	**Miles**	**Percent**
Very Low (Rocky, Armored)	1827	34%
Low (Coarse Beaches)	355	7%
Moderate (Stable Bluffs)	942	17%
High (Sand Beaches and Dunes, Unstable Bluffs)	617	11%
Very High (Flats, Highly Unstable Bluffs)	1667	31%
Total Shoreline	**5408**	**100%**

Shoreline Change Vulnerability (CMGE and Bluff Types)	Miles	Percent
Very Low (Rocky, Armored)	1827	34%
Low (Flats, Stable Bluffs)	2549	47%
Moderate (Coarse Beaches)	355	7%
High (Unstable Bluffs)	406	8%
Very High (Sand Beaches and Dunes, Highly Unstable Bluffs)	271	5%
Total Shoreline	**5408**	**100%**

Table 13. About two thirds of the Maine coast is subject to shoreline change by modern processes. Coastal sedimentary shorelines that can be modified by sea level rise, storms, and waves total 3,600 miles. Source: MCP, 2015, p. 13.

The Maine Geological Survey mapping tool can be used to simulate future storm tides (future HAT plus a storm surge) for a few storm surge values. For example, a Low-Intermediate sea level rise plus a 2.3-foot storm surge results in a 3.9-foot inundation area. Similarly, an Intermediate sea level rise scenario plus a 4.9-foot surge results in an 8.8-foot inundation area. The Maine Geological Survey web site also includes separate inundation scenarios Category 1-4 hurricanes using the National Hurricane Center's Sea, Lake and Overland Surges from Hurricanes (SLOSH) mapping tool. These hurricane simulations can also be used as a proxy for inundation mapping that includes wave runup on exposed shorelines.

Saltwater Intrusion

With coastal inundation and the rise of the tides is an increased risk of salt contamination of coastal ponds and groundwater aquifers. Salt can compromise freshwater ponds through coastal flooding and more permanently through sea level rise. Groundwater is subject to lateral and vertical migration of salt water beneath the ground due to the density contrast between salt water and fresh water. In Maine, there are both bedrock and sand and gravel aquifers that can be affected by sea water (Caswell, 1987; 1979). Vulnerability of coastal aquifers is geographically complicated by the shape of estuaries, local and regional freshwater hydrology, surficial geology, bedrock geology, bedrock fractures, and groundwater withdrawal.

To date, only a few investigations of the vulnerability of aquifers to sea water have been completed in Maine. Fractures in Maine's bedrock can be reservoirs of groundwater and conduits for groundwater migration. Even without sea level rise, coastal bedrock wells can become contaminated by salt water intrusion if the rock fracture pattern allows seawater to flow inland. This has been documented for domestic wells in Harpswell, Maine (Barlow, 2003).

Popham Beach State Park in Phippsburg, Maine relies on two million gallons of fresh water per year to be drawn from a sand aquifer that is between a beach and a salt marsh. This aquifer is hydraulically connected to the rise and fall of the tides and fresh water is recharged only by precipitation through a relatively small area of back dunes in a pitch-pine forest. Saltwater intrusion has the potential to both decrease the size of the fresh aquifer and elevate the fresh water table, which could compromise the function of the park leach field. Both vulnerabilities were investigated by the Maine Geological Survey (Gordon and Dickson, 2016) for current conditions and sea level 3.3 feet (1 m) higher than present. In a similar but larger scale study, modeling of sea level rise in coastal New Hampshire investigated impacts from up to 6.5 feet (2 m) of rise, with rising groundwater reaching farther inland than future coastal flooding (Knott et al., 2019; NH Coastal Flood Risk STAP, 2019; Wake et al., 2019).

Salt Marshes and Sea Level Rise

Salt marshes are coastal landforms built by successive generations of plants over millennia (Redfield, 1972). In Maine they comprise more than 22,000 acres (34 square miles; Cameron and Slovinsky, 2014 with about 68% south of

Penobscot Bay (Ward, 1999). Salt marshes serve as a vital habitat for a variety of different species and serve as an important natural buffer from coastal flooding and storm waves. In Maine, they exist as discrete low- and high-marsh plant communities. About 65-70% of Maine's existing salt marshes are high marsh dominated by *Spartina patens* with *Spartina alterniflora* dominant across the low marsh (Ward, 1999).

The low marsh occupies elevations between the mean tide elevation (mean sea level) and mean higher high water (MHHW) and high marsh thrives from MHHW to the highest astronomical tide (HAT; Nixon, 1982; Ward et al., 2008; Watson et al., 2017). HAT is the highest predicted astronomical tide expected to occur at a specific tidal station over 19 years. MHHW is the average of the higher of the two high water heights of each tidal day over a 19-year National Tidal Datum Epoch, or NTDE. As sea level rise continues, tidal datums such as mean sea level and MHHW will need to be recalculated perhaps with greater frequency (Gill et al., 2014).

Since salt marsh elevations are closely tied to sea level, marsh peat cores hold a record of past sea level along the Maine coast (Gehrels 1994; Gehrels et al., 1995 1996; Gehrels, 2000). Research indicates that the tidal range (from high to low) has increased in the Gulf of Maine over the past few thousand years (Gehrels et al., 1995; Shaw et al., 2010a, b). There was a slight acceleration in the rate of sea level rise several thousand years ago (Gehrels, 2005). Sea level rise can amplify tides and thus increase the Highest Astronomical Tide in a non-linear way (Devlin et al., 2017). It is possible that, due to increased resonance in the Gulf of Maine, high tide could rise from 1 inch in Portland to 4 inches in Eastport if sea level rises between 0.5 and 3 feet (Gehrels et al., 1995).

As sea level rises, salt marshes are likely to be submerged under deeper water if there is insufficient sedimentation to match the pace of the rise of the tides. Inundation, without additional net sediment deposition, can be used to approximate the impact of sea level rise on the geographic extent of salt marshes.

Cameron and Slovinsky (2014) developed a static submergence model for Maine which used the HAT as the upper boundary of the wetland and added sea level rise scenarios of 1, 2, 3.3, and 6 feet in order to simulate potential migration of the existing 22,000 acres of tidal marsh on a state-wide scale. This analysis also included inspecting the dominant land cover type classes into which marshes may migrate. Results indicated that the existing state-wide acreage of marsh could increase anywhere from 17-77%, depending on the sea level rise scenario. However, this work did not account for how the lower edge of marshes might convert to mudflat or open water as the sea rises.

Slovinsky (2013, unpublished) used specific tidal elevations as proxies for different dominant marsh communities to simulate existing marsh conditions and investigate how different marsh communities might respond to sea level rise at Scarborough Marsh, Maine's largest marsh system (approximately 3,200 acres). Roughly 70% of the existing marsh is high marsh, while 30% is low marsh (Figure 14). The same sea level rise scenarios from Cameron and Slovinsky (2014) were added to the existing land surface, not accounting for dynamic erosion and accretion (Komar and Moore, 1985; Wood et al., 1990). Results indicated that Scarborough Marsh, like many marshes in Maine, was "at capacity", with adjacent steep sloped or developed uplands that limit marsh migration. Results also indicated that marsh loss or marsh conversion will likely outweigh marsh migration in some locations and under certain scenarios (Figure 14; detailed maps provided in Appendix C).

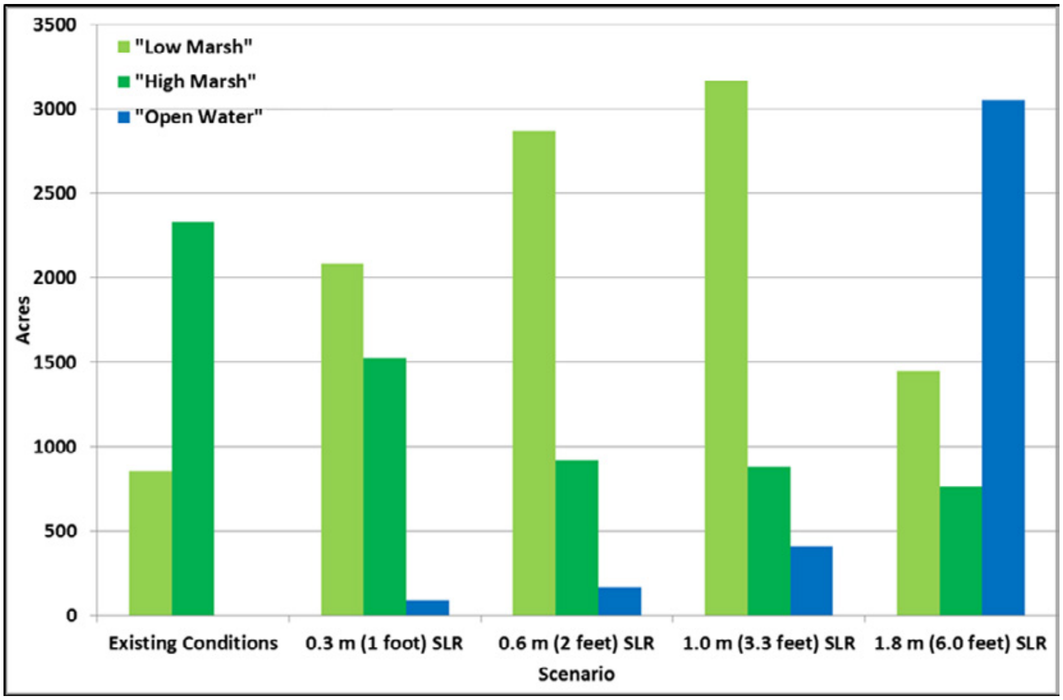


Figure 14. Simulated existing and potential future acres of low marsh, high marsh, and open water at Scarborough Marsh, Scarborough, Maine without additional sedimentation. Figure from Slovinsky (2013, unpublished). Refer to Appendix C for maps supporting the data in this graph.

Water levels and frequency of inundation are not all that drive salt marsh response to sea level rise. Marsh plants annually add their biomass (roots and above-ground plant matter) to their soils and, with mineral matter (inorganic sediment) brought in by tides, build upward. Storm tides are especially important because the flooding water moves faster than normal and carries more suspended sediment to the marsh surface (Turner et al., 2006; Stumpf, 1983. Thus, salt marshes can sometimes maintain themselves as sea level rises and have done so for millennia (Kirwin et al., 2016). When sea level exceeds the rate of upward growth of the marsh surface, however, marsh destruction occurs (Morris et al., 2002). This is evident in two settings: along tidal creek edges and in open bodies of water on the marsh surface (salt marsh pools; Marani et al., 2011; Phillips, 1986; Ravens et al., 2009). Along tidal creek banks, when sediment is abundant, marshes grow out laterally onto tidal flats. When sediment is less abundant, small local waves can attack the marsh margins and leave a vertical scarp. The scarp is then subject to erosion by several processes including ice in the winter (Argow et al., 2011). Rates of bank retreat range from inches to feet per year (centimeters to meters per year; Francalanci et al., 2013).

Marsh	Year	% of marsh that is pooled
Ogunquit	1956	4
	2003	7
Brunswick	1964	17
	2001	18
Gouldsboro	1966	14
	2009	24
Addison	1969	21
	2004	25
Lubec	1957	18
	2009	16

Table 14. Percentage of marshes that became pooled (open water) for 5 marshes along the Maine coastline. Adapted from Wilson (2010).

Salt marsh pools are permanent, open bodies of water on the salt marsh that are devoid of salt marsh grasses (Wilson et al., 2009). Pools form in several ways but have been taken as an indicator of salt marsh drowning in regions of rapid, relative sea-level rise (DeLaune et al., 1994; Kearney et al., 1988; Ravens et al., 2009). Pools lead to a collapse or breakdown of salt marshes by submerging vegetation for longer durations and eroding downward. Limited research in Maine indicates that four salt marshes along the length of the coast lost 1-10% of their area to pools between the 1950s and 2009 with only one of five studied marshes gaining land (Table 14).

With an increased rate of sea-level rise, salt marshes globally are at risk of drowning or experiencing a vegetative shift as low marsh plants (*Spartina alterniflora*) replace high marsh plants (*Spartina patens;* Blankespoor et al., 2014; Crosby et al., 2016; Spencer et al., 2016). In a study of Maine salt marsh sediment accumulation rates from 1986-2003, sediment accumulated on the marsh surface between 5 to 17 inches/century (1.4 to 4.2 mm/year; Goodman et al., 2007; Wood et al., 1989). Although vegetative shifts have occurred, most marshes were maintaining themselves. The marshes are not expected to survive, however, if the rate of sea-level rise exceeds about 1.3 feet/century (about 4 mm/year; Goodman et al., 2007). In areas with abundant sediment supply marsh sedimentation may be able to keep pace with faster rates of sea level rise (Kirwan et al., 2016). Although the studied sites were all along the Maine coast, more measurements are needed in large marshes and more marshes in remote areas need observations. As such, *measurement of sediment accumulation rates in marshes across the state is a critical data need to predict the future geographic extent of high- and low-marsh communities as sea level rises.*

Beaches, Dunes, and Sea Level Rise

Beaches are unconsolidated deposits of sand or gravel formed by waves along coastlines. Dunes and wind-blown deposits of sand are commonly found adjacent to beaches. Rising sea level is not something new that these environments must endure, as they have migrated into their present locations over the past 5,000 years or so by a slow rise of the sea. Over centuries to millennia, beaches and dunes can recycle their sand through wind and wave action to maintain the dynamic landform through transgression of coastal lowlands as sea level rises.

Sea level rise today is happening much faster than in the past few thousand years and is coupled with the presence of people on the coast. While the beaches-dune system can naturally migrate up gentle coastal gradients, the system faces an impediment when people and communities build seawalls and other coastal engineering structures to hold the sea back or intentionally alter coastal sediment budgets.

Maine has just under 3,000 acres of sand beaches and another 4,150 acres of gravel beaches. This is a small portion of more than 145,000 acres (225 square miles) of marine intertidal and supratidal environments (Ward, 1999). Sand beaches are largely in southern Maine while gravel beaches are more abundant on the Downeast coast and on islands. The longest sandy beaches are all in southern Maine and most are developed with human infrastructure. Downeast beaches are abundant but typically very small (Ward, 1999).

An important consideration regarding how beaches will fare with increasing sea level is related to past and present sources and volumes of sandy sediment. Sand and gravel for beaches can come from rivers, eroding bluffs, the offshore seafloor, or marine shells. The largest beaches like the system from Phippsburg to Georgetown that includes Hermit Island, Seawall Beach, Popham Beach State Park, and Hunnewell Beach west of the Kennebec River and Mile and Half Mile Beaches at Reid State Park derived their sand from the Kennebec River. Seaward of this beach system is a vast, submerged paleo-delta that formed when sea level was lower at the end of the last Ice Age (Barnhardt et al., 1997). Kennebec River sand continues to supply the modern coast (Fenster et al., 2001). Spring floods contribute sand from the river to these beaches and sand also comes ashore from wave and current reworking of the offshore delta.

The largest contiguous beach system in Maine is in Saco Bay. This arcuate beach system stretches from Hills Beach in Biddeford to Prouts Neck in Scarborough. Like the mid-coast beaches, this system is supplied sand from the Saco River. These beaches still get some sand from the river during spring floods (Kelley et al., 2005; Brothers et al., 2008).

Eroding bluffs can supply sediment to adjacent beaches. However, many bluffs that provided sediment to beaches are now engineered to prevent bluff erosion and have reduced the sediment supply to the shore. The largest such beach system includes the beaches from Ogunquit, to Wells, and up to Kennebunk. Beaches in this broad area called Wells Embayment have had no significant sand supply from a river system.

Shell-dominated beaches are rare and include Sand Beach in Acadia National Park. This pocket beach has been remarkably stable over many years, suggesting that new shells are added regularly from offshore (Barnhardt and Kelley, 1995). Shell material is primarily of calcium carbonate and aragonite, both of which are corroded by cold sea water and ocean acidification.

Like salt marshes, low-lying beaches might be submerged with a rise in sea level if their sediment budgets become negative. However, there are mechanisms to accumulate or reposition sediment (such as beach nourishment or dune restoration) that can create a positive sediment budget and help beaches survive a rising sea. As undeveloped beaches experience a rising sea level, a negative sand budget, or both, they begin to migrate landward. Storms wash over the primary frontal dune and transport sediment landward. After a large storm, a beach may contain as much sand as before the storm, but the beach has geographically moved landward. On developed beaches, landward migration is impeded by seawalls and development. Where the dunes remain fixed in place and waves reflect off seawalls, the beach gets lower and narrower and sand is lost offshore or migrates along the shore. There are many beaches in Maine that have little or no dry beach at high tide to absorb storm wave energy. As sea level rises, wave forces on seawalls will increase and adjacent beaches will continue to lower. Sea level rise may result in the loss of almost half of the world's beaches by 2100 (Vousdoukas, et al., 2020).

From York County up to Waldo County, MGS calculated the approximate acreage of dry beach above the highest astronomical tide (reflecting existing conditions), and then for the area of dry beach lost from 1.6, 3.9, and 8.8 feet of sea level rise. At the time of this report, dry beach mapping was not complete for Hancock and Washington Counties. The dry beach area is a good proxy for recreation space since it represents sand area above tidal action on days without storms. The dry beach also acts as a storm buffer for dunes and seawalls. The dry beach is usually narrowest in late winter and early spring and wider in the summer and early fall (Slovinsky and Dickson, 2007). MGS did this analysis with the only available coast-wide digital elevation model, a composite of multiple dates and seasons. The upper beach and dry berm area have a low profile and are vulnerable to even a small amount of inundation (Table 15).

The simulation shows static inundation without the added effects of erosion and storms that, by themselves, could permanently alter beach topography over time. Under a 1.6-foot sea level rise scenario, depending on the county, between 39% and 72% of the dry beach area could be submerged during higher astronomical tides. Between 70% and 97% of the dry beach could be lost under a 3.9-foot sea level rise scenario, and over 90% of dry beach area could be lost under an 8.8-foot sea level rise scenario. These data show that there is over a 40% loss of dry recreational beach with 1.6 feet of sea level rise. Based on projections in Table 7, this loss may occur by the year 2050 and possibly sooner if erosion leads to net sand loss on the upper beach.

County	Existing Dry Beach	1.6 feet SLR			3.9 feet SLR			8.8 feet SLR		
		Dry Beach	Change	% Change	Dry Beach	Change	% Change	Dry Beach	Change	% Change
York	143	82	-61	-42%	36	-107	-75%	2	-141	-98%
Cumberland	48	27	-21	-44%	13	-36	-74%	1	-47	-97%
Sagadahoc	63	38	-25	-39%	20	-44	-69%	5	-58	-92%
Lincoln	2	1	-1	-67%	0	-2	-97%	0	-2	-100%
Knox	9	2	-6	-72%	1	-8	-94%	0	-9	-100%
Waldo	2	1	-1	-51%	0	-2	-91%	0	-2	-100%
TOTAL	**268**	**152**	**-116**	**-43%**	**69**	**-198**	**-74%**	**9**	**-259**	**-97%**

Dry beach is the approximate area between the seaward edge of dune or wall and the highest astronomical tide

** Dry beach area mapping not completed yet for Hancock or Washington Counties*

Table 15. Area (rounded to the nearest acre) of existing dry beach above the highest astronomical tide, and potential changes to the dry beach area after 1.6, 3.9, and 8.8 feet of sea level rise. Inundation based on sea level rise relative to the year 2000.

Coastal sand dunes in Maine are a limited resource that are regulated under the Natural Resources Protection Act (NRPA Chapter 355; Slovinsky and Dickson, 2011a). There are approximately 3,600 acres of mapped coastal sand dunes along the Maine coastline (Slovinsky and Dickson, 2020). In Maine's dune system, 1,500 acres are "frontal dune" (D1) and 2,100 acres are "back dune" (D2; Table 15). Frontal dunes are typically more at-risk to storm surge erosion and dynamic flooding due to wave runup, while back dunes are at-risk of stillwater flooding. Maine's Coastal Sand Dune Rules (Ch. 355; see Sea Level Policy in Maine below) limit development in frontal dunes because they are highly erosion- and flood-prone and the frontal dune ridge protects back dunes from erosion. Based on an analysis by MGS, currently about 19% of mapped frontal dunes and about 34% of mapped back dunes are considered "developed" (Table 16).

County	Existing Conditions								
	Undeveloped			Developed			% Developed		
	Front	Back	All Dune	Front	Back	All Dune	Front	Back	All Dune
York	306	513	820	205	519	723	40%	50%	47%
Cumberland	159	230	389	13	116	129	8%	34%	25%
Sagadahoc	137	214	351	6	48	55	4%	18%	13%
Lincoln	11	16	27	3	1	5	23%	7%	14%
Knox	81	35	116	13	2	14	14%	4%	11%
Waldo	26	31	57	4	7	10	13%	17%	15%
Hancock	238	184	422	28	15	43	11%	7%	9%
Washington	274	146	420	9	8	17	3%	5%	4%
TOTAL	1232	1370	2602	281	715	996	19%	34%	28%

Table 16. Area (rounded to the nearest acre) of undeveloped and developed frontal dunes and back dunes in each coastal Maine county. Also provided is the percent of each dune type that is "developed" based on analysis using a 10-m NOAA C-CAP landcover dataset.

MGS investigated how several different static sea level rise scenarios (1.6, 3.9, and 8.8 feet) might inundate these developed and undeveloped frontal and back coastal sand dunes. A summary of the results of this analysis for all mapped dunes are shown in Table 17. The table compares existing conditions with the acres and percentages of dunes inundated under scenarios of 1.6, 3.9, and 8.8 feet (see also Appendix D, Graph 1). These data show how vulnerable the low-lying dune system is to sea level rise. A rise of 1.6 feet submerges two thirds or 67% of Maine's coastal sand dunes and reduces the dry beach area by 43%.

This beach and dune analysis does not include the impacts of waves, erosion, or landward movement of beaches and dunes in response to sea level rise and assumes that existing seawalls remain in place. Examples of dune inundation of developed and undeveloped land in Wells Beach, Wells are provided in Appendix D. The appendix also includes a detailed breakdown of inundation of developed and undeveloped frontal and back dunes for each county.

Land Class	Dune Type	Existing	1.6 feet SLR		3.9 feet SLR		8.8 feet SLR	
		Acres	Acres	% Inundated	Acres	% Inundated	Acres	% Inundated
Undeveloped	Front	1232	787	64%	1127	92%	1183	96%
	Back	1370	796	58%	1284	94%	1363	99%
	All Dunes	2602	1583	61%	2411	93%	2546	98%
Developed	Front	281	181	64%	252	90%	280	100%
	Back	715	662	93%	700	98%	713	100%
	All Dunes	996	842	85%	952	96%	993	100%

Table 17. Areas (rounded to the nearest acre) of developed and undeveloped frontal and back dunes for existing conditions and inundation (including the percent inundation from existing conditions) for scenarios of 1.6, 3.9, and 8.8 feet of sea level rise on top of the highest astronomical tide. These simulations are based starting in the year 2000.

For this report, an MGS investigation of sea level rise on beach area was done for beaches statewide that are backed by sand dunes (Table 16). The study did not include inundation of beaches adjacent to coastal bluffs, rocky shores, or other uplands. Like the dune analysis above, a static topographic model was used and did not anticipate erosion or accretion that are likely to accompany sea level rise. This simple approach shows a loss of dry beach, the area between Mean High Water and the Highest Astronomical Tide. Results are presented in Appendix D. From York through Waldo County (all available data to date), a 1.6-foot sea level rise results in a loss of 116 acres or 43% of the dry beach area. A 3.9-foot rise results in a net loss of 198 acres or 74% of the existing beach width. After an 8.8-foot rise, all but 9 acres are gone, representing a net loss of 97% of the current dry beach width. This analysis suggests that the highest part of the beach profile is vulnerable to sea level rise. The dry beach area functions as a storm buffer and approximates recreational beach space at high tide.

In order to understand how many of Maine's beaches are changing in response to storms and ongoing sea level rise, several different monitoring programs have been initiated in Maine. In 1999, the Maine Geological Survey and University of Maine initiated the State of Maine Beach Profiling Program (SMBPP) with funds from Maine Sea Grant. With continued support from Maine Sea Grant, volunteer citizen scientists, and annual financial contributions from communities, this beach monitoring program has collected two decades of beach elevation data. These data have been used for beach management decisions (Briggs, 2020). Every two years, the Maine Geological Survey releases a *State of Maine's Beaches* report on the condition of Maine's large beaches and examines the effects of storms and sea level on beach erosion. The 2011 report (Slovinsky and Dickson, 2011b) investigated beach responses to the 2009-2010 high sea level anomaly (Figure 5). Beach erosion during this time was about as severe as that caused by the 2007 Patriots' Day Storm. A relative fall in sea level over the next few years allowed the beaches to recover. This monitoring program demonstrated that Maine beaches are very sensitive to changes in sea level.

A second, and complementary, monitoring program by the Maine Geological Survey measures annual shoreline change along large sandy beaches. This Maine Beach Mapping Program (MBMAP) tracks changes to the seaward edge of dunes, movement of the high tide line on the beach profile, the dry beach width (a proxy for the buffering capacity of the beach) and calculates erosion and accretion rates. Since 2007, these data have resulted in a better understanding of shoreline changes, sediment budgets, dune restoration, and redistribution of beach nourishment. The Maine Geological Survey has an MBMAP web mapping portal for display, download, and public use of these data. This program has been funded primarily by the Maine Coastal Program with funds from NOAA.

Bluffs, Landslides, and Sea Level Rise

Coastal bluffs in Maine are unconsolidated deposits of sediment largely of glacial origin. Sediment bluffs are distinct from crystalline bedrock (ledge) outcrops which do not erode appreciably on a century time scale (Kelley, 2004). Projections of future shoreline positions from inundation models depict coastal bluffs as the high ground and unaffected by rising seas. However, sedimentary bluffs can erode relatively rapidly and often by discrete slumps. Net erosion rates can be on the order of inches to feet per year (centimeters to meters per year; Hughes et al., 2007) and might increase with rising tides.

Bluffs occur along approximately 40% of the Maine shoreline (Table 13; Kelley, 2004; Kelley and Dickson, 2000). Bluffs are mostly formed of glacial till, a deposit of mixed mud, sand, and gravel or glacial-marine mud (Thompson, 2015). Till was once buried and compressed under glacial ice and is quite dense and resistant to rapid erosion. As till bluffs erode, they shed boulders to the base of the slope and accumulate in the intertidal zone. Toe deposition of bluff sediment can naturally inhibit, but not fully prevent, subsequent erosion. Sand and gravel from till bluff erosion can add sediment to beaches and gravelly tidal flats to help the intertidal zone build vertically with sea level rise.

Glacial-marine mud makes up another large proportion of Maine bluffs. This glacial-marine mud (also called the Presumpscot Formation) is primarily composed of silt and clay with minor amounts of sand and is much less resistant to erosion than glacial till (Thompson, 2015). Mud bluffs up to 50 feet (15 m) high occur along the sheltered coast of Maine such as in inner Casco Bay (Kelley and Dickson, 2000). Maine studies of recent bluff retreat rates suggest a range from 4 to over 40 inches (10 to over 100 cm) of horizontal erosion per year (Hay, 1988; Smith, 1990). As with till bluffs, sediment released by erosion often contributes to the sediment budget of salt marshes and intertidal mud flats.

Mud bluffs with relief of 20 feet (6 m) are also prone to episodic landslides as well as day-to-day chronic erosion from waves, tides, rain, surface water runoff, groundwater release, freeze-thaw cycles, sea ice, and upland land use (Dickson, 2017; Dickson and Johnson, 2015; Keblinsky, 2003). In addition to erosion enhanced by sea level rise, mud bluff land loss may also be affected by increased precipitation and the duration of coastal temperatures fluctuating near the freezing temperature of water.

A general cycle of bluff retreat suggests that following erosion events, bluffs experience a period of stability while sediment that accumulated at the base of the slope is removed by waves, ice, and tidal currents (Kelley and Dickson, 2000; Sunamura, 1983; Whiteman, 2019). The time frame of the bluff cycle is site-specific and not constant (Hay, 1988; Kelley, 2004; Whiteman et al., 2016). It is generally thought that landslides and major erosion events occurred on a decade to century time scale (Berry et al., 1997 but ongoing research (Dickson, 2017; Whiteman, 2019; Whiteman et al., 2016) suggests that forces driving bluff retreat are complex and often result in small annual slumps and cumulative land loss. Very little is quantitatively known about how rates of sea level rise will affect rates of bluff erosion, but it seems certain that higher water levels should induce more toe erosion and slope oversteepening and thus continued or accelerated land loss.

Sea Level Policy in Maine

Coastal Sand Dune System

Since 1998, Maine has included sea level rise in the Coastal Sand Dune Rules (096c355) as part of the Natural Resources Protection Act (Title 38, Chapter 3, §§ 480-A to 480-JJ). This policy was one of the first in the nation to address the uncertainty of sea level rise (Moser, 2005) and included anticipating a 3-foot rise over the next 100 years. In 2006, that policy was modified to a 2-foot rise over 100 years with the addition of erosion hazard areas, elevation requirements for flow-through foundations and re-development landward with frontal dune enhancement. In addition, dune site stability for large structures needed to be demonstrated for a combination of a 2-foot rise and a 100-year storm that could cause erosion at the structure's proposed footprint. The 2006 rules also clarified eligibility for rebuilding after repetitive structural damage from ocean storms.

Seawalls constructed in a natural area also reflect waves back to sea and cause intertidal beach erosion. Seawalls also focus erosion on abutting properties, leading to more armoring. The Natural Resources Protection Act (NRPA; Title 38, Chapter 3, §480-D(2)) precludes construction that:

> *"…unreasonably inhibit the natural transfer of soil from the terrestrial to the marine or freshwater environment."*

By building seawalls along the "soft" coast of Maine there is a risk of significantly cutting off the supply of sediment to coastal beaches, marshes and tidal flats. Sediment supply from uplands to the shore is important for deposition in the intertidal and subtidal environments. A reduced sediment supply could limit coastal environments from maintaining their elevation during sea level rise. Without adequate sediment, some coastal environments such as salt marshes or mud flats could decrease in geographic area.

Sea level rise is only peripherally included in two other Maine regulations: the Coastal Management Policies and the Coastal Barrier Resources System.

Coastal Management Policies

In 1985, the Maine Legislature passed the Coastal Management Policies with mention of coastal hazards to development from flooding and sea level rise (Title 38, Chapter 19 §§ 1801-1803). Section 1801(4) Hazard Area Development states:

> *"Discourage growth and new development in coastal areas where, because of coastal storms, flooding, landslides or sea-level rise, it is hazardous to human health and safety…"*

This legislation did not assign a state agency to oversee it or to develop regulations so the goal of guiding development away from areas susceptible to sea level rise was not implemented.

Maine Coastal Barrier Resources System

In 1985 the Maine Legislature passed laws related to the Coastal Barrier Resources System (Title 38, Chapter 21 §§ 1901-1905) that closely reflects a similar federal law (United States Coastal Barrier Resources Act of 1982, United States Code, Title 16, Section 3509). The CBRS consists of 32 locations that are recognized for their ecological and dynamic character. Seawalls and other shoreline engineering structures are contrary to this dynamic environment so state funds for infrastructure and development are prohibited. The Federal CBRA prohibits FEMA flood insurance policies in these areas.

Municipal Shoreland Zoning

Maine's Mandatory Shoreland Zoning Act (Title 38, Chapter 3 §428-449) sets new development an extra distance landward on coastal bluffs mapped by the state as *Highly Unstable* or *Unstable*. If a site is stabilized by construction of seawalls and other retaining structures, a bluff site can be reclassified as *Stable* and development can be built closer to the ocean.

Priority Information Needs

The list below identifies several priority information needs. These are not prioritized nor necessarily a comprehensive summary of the needs.

- Acquire topographic-bathymetric datasets at Maine's larger beach systems
- Create statewide coastal digital elevation models every 5 years to detect change and to be used for new sea level rise simulations
- Tide gauge data need to be regularly analyzed for sea level trends and to update storm surge statistics
- The NOAA tide gauge 8415490 should be re-established in Rockland Harbor to fill in a geographic gap and the station should also collect meteorological data
- NOAA should issue a new National Tidal Datum Epoch for Maine and post a revised Highest Astronomical Tide for all harmonic tide stations by 2021
- Monitor beach and dune erosion, accretion, and shoreline sediment budgets
- Beach nourishment and dune restoration should be monitored for longevity and efficacy
- Dynamic inundation and shoreline change from storm surge, higher sea level, and tides needs to be evaluated and numerically modeled
- Research is needed to evaluate how the frequency and height of storm surges will change in the future
- Flood or coastal inundation maps need to consider ocean runup at future sea levels
- Saltwater intrusion into groundwater aquifers needs further study, particularly related to the vulnerability of public water supplies
- Rates of bluff retreat should be monitored in a variety of settings using remote sensing
- Document coastal landslide occurrences, morphology, and evolution over time
- Increase the network of sediment elevation tables (SET) to collect salt marsh sedimentation rates
- Monitor salt marsh pools for changes in area and abundance statewide
- Relate duration of salt marsh submergence to plant species, community survivability, and lateral migration
- Design transferable green and gray-green engineering plans to compliment traditional shoreline stabilization that can be modified or adapted as sea level rises

In an assessment of coastal hazards in 2015, the Maine Coastal Program (Maine Department of Marine Resources) identified priority needs and data gaps. Some of these needs are starting to be addressed through National Oceanic and Atmospheric Administration (NOAA) grant funding. Recent efforts are primarily focused at the local and county level rather than statewide. A comprehensive, state-wide effort to monitor the coastal response to rising tides and effects of storms is needed.

There are several emerging issues directly related to rising tides and sea level (Table 18). Coastal erosion is driven, in part, by high ocean levels. Storm tides induce flooding and high-water levels for wave and current erosion and deposition along the shoreline. With higher sea level, the frequency of storm erosion is likely to increase. Erosion can steepen shorelines and increase the susceptibility of some shorelines to have abrupt landslides or to have chronic land loss through bluff recession. Coastal inundation can directly submerge coastal wetlands that may or may not be able to keep up with sea level rise depending on the rates of organic and inorganic sedimentation.

Higher tides and ocean flooding have the potential to salinize some drinking water sources and to generally raise the interface between freshwater and salt water in coastal groundwater. Higher water tables can reduce the depth or thickness of the unsaturated soil that can be important for the proper function of septic systems.

Research is evolving to better understand mitigating shoreline erosion by mimicking or enhancing natural shoreline features. Little is known about how construction of "living shorelines" will function in coastal Maine where sea ice can interact with the built or restored environment. Priority needs identified by the Maine Coastal Program are listed in Table 19.

Emerging Issue	Information Needed
Coastal landslides	More complete documentation of historic slides and increased understanding of the process
Bluff recession	Historic information on bluff position
Changes to coastal wetlands from sea level rise	Sedimentation rates for coastal marshes
Saltwater intrusion into drinking water supplies	More complete data on current occurrences; hydraulic connectivity to the ocean; recharge rates; withdrawal rates; desalination rates
Green infrastructure construction	BMPs for "green infrastructure" design and construction in cold climates; analysis of durability and cost/benefit of soft engineering vs. other alternatives

Table 18. Emerging issues and information needs related to coastal hazards. Source: MCP 2015, p. 65.

Priority Needs	Need? (Y or N)	Brief Explanation of Need/Gap
Research	Y	Shoreline response to small amounts of sea level rise (beaches and bluffs). Updated mapping of intertidal geology and habitats to replace low-resolution 50-year old data.
Mapping/GIS/modeling	Y	Modeling of mixed fresh/salt water and the influence of increased precipitation on storm water flow; water-penetrating LiDAR along coastal zone for seamless topo-bathy.
Data and information management	Y	Online access to coastal hazards data. Online access to development permits. Long-term measurements of the performance of coastal engineering methods and structures, wetlands restoration, and monitoring of cumulative impacts.
Training/Capacity building	Y	Local stakeholder training on using new data, resiliency tools, that are available from the State of Maine
Decision-support tools		Resiliency Toolkit (MPAP, DEP, MGS, etc.)
Communication and outreach	Y	Tools to help move discussion at the community level forward from vulnerability assessment to adaptation action including more focus on determination and assumption of risk.

Table 19. Priority research, mapping, data, training, tools, and communications needs related to coastal hazards. Source: MCP 2015, p. 70.

Conclusion

Sea level along the coast of Maine has shown signs of accelerating in the last 25 years. Furthermore, there is no scientific basis to expect that sea level will fall in the next few centuries. The STS recommends that the Climate Council consider *committing to manage* for 1.5 feet of relative sea level rise by 2050, and 3.9 feet of sea level rise by the year 2100. Additionally, the STS recommends that the Climate Council consider *preparing to manage* for 3.0 feet of relative sea level rise by 2050, and 8.8 feet of sea level rise by the year 2100.

There will be significant impacts to both the built and natural coastal environments from an intermediate path of sea level rise. As the sea and tides get higher, nuisance flooding will be much more common. Coastal landscapes, such as bluffs, beaches and dunes, will begin to submerge and erode. By 2030, just a decade away, sea level could be a foot higher than in 2000. Just a 1-foot increase in the tides, combined with storm surges typical of the last 100 years, could increase nuisance flooding 15 times more than what has been experienced. Between 2030 and 2050, the probability of flooding from a "100-year storm" would be 1 in 10 every year; conversely, this means that a "10-year" storm in the future would have the impact of the current "100-year" storm. Sea level rise, without a change in storm intensity or frequency, may result in a significant increase in storm damage and coastal flooding in Maine in the next 30 years.

Authors' Note, August 20, 2020

The graphs and tables in this report include analysis of data through the end of calendar year 2019. Although 2020 data are not included in this report, the authors feel it is imperative to note that water levels have continued to run high at the Eastport, Bar Harbor, and Portland tide gauges. Through July 2020, aside from the month of May, water levels from each of the other months were **among the top 10 highest ever recorded at each tide gauge** (Table 20). April 2020 set new highest monthly water levels **at all three tide gauges** and also set a new record storm tide at Eastport (24.3 feet) and the third highest recorded at Bar Harbor (15.0 feet). This was caused by an extratropical "bomb" cyclone on April 10, 2020 which knocked out the power to over 250,000 homes in Maine.

Month	Portland (1912-2019)	Bar Harbor (1947-2019)	Eastport (1929-2019)
January	3rd	2nd	4th
February	7th	5th	6th
March	8th	7th	6th
April	1st	1st	1st
May	24th	13th	10th
June	10th	9th	9th
July	2nd	3rd	3rd

Table 20. Ranking of monthly water levels for Portland, Bar Harbor, and Eastport using available tide gauge data through July 2020. April 2020 had the highest recorded monthly water level at all three tide gauges.

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APPENDIX A

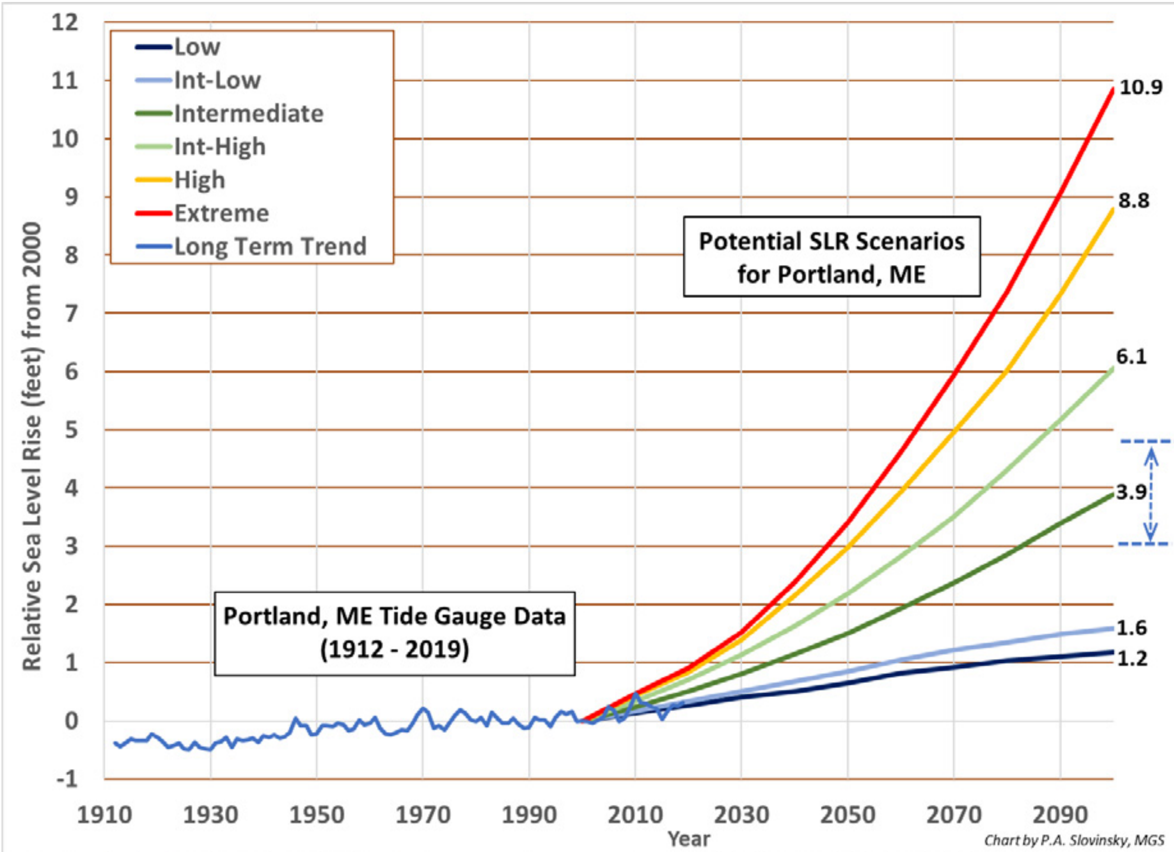
Maine Sea Level Rise Curves for All NOAA 2017 Scenarios

Example Inundation Maps for Highest Astronomical Tide (HAT) and HAT + 3.9 ft SLR

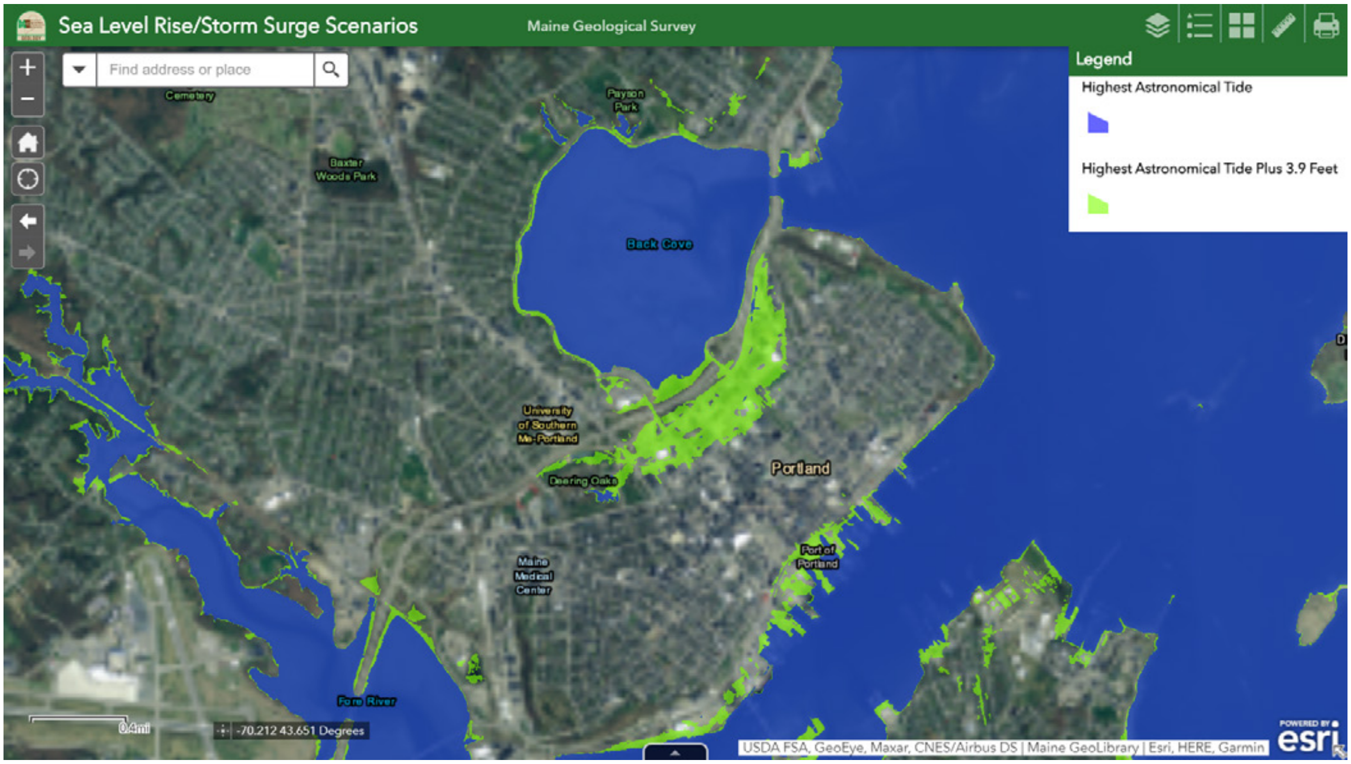
Included are maps depicting potential inundation for:

- **Portland area;**
- **Mount Desert Island area; and**
- **Machias area**

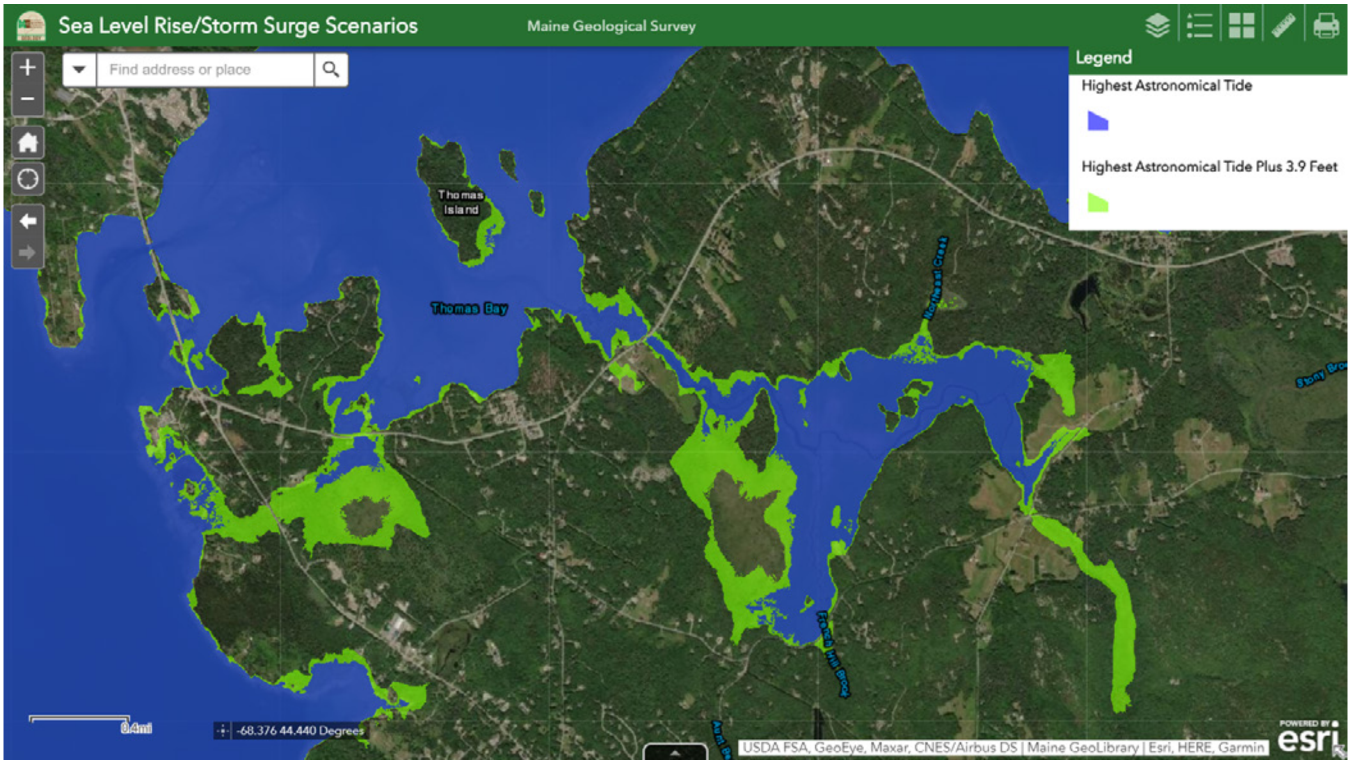
Source: Maine Geological Survey sea level rise/storm surge viewer
https://www.maine.gov/dacf/mgs/hazards/slr_ss/index.shtml



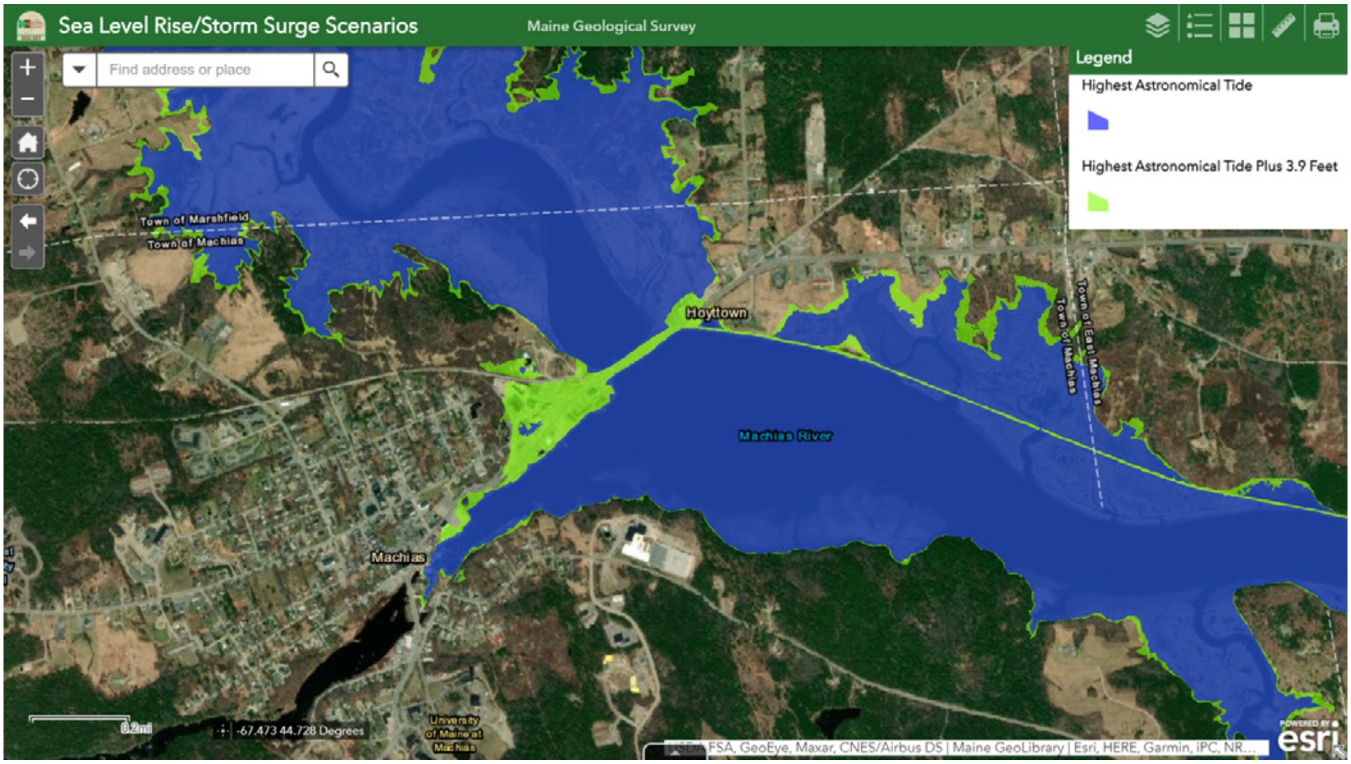
Appendix A, Graph 1. This graph illustrates historical sea level rise in Portland from 1912 through 2019 and shows seven scenarios from the year 2000 to 2100. Projecting a long-term (linear) trend based on historical tide gauge data predicts a rise of 1.2 feet by 2100 (black line). The five higher projections are based on different greenhouse gas emissions and physical changes (such as the amount of glacial melting) over time. Each line represents a central estimate with a 50% probability of being met in each scenario. For the intermediate scenario, a 50% probability results in a rise of 3.9 feet by 2100. With the intermediate scenario there is a 67% probability of sea level rising between 3.0 to 4.6 feet by 2100 (dashed blue arrow and lines on the right side of the graph). These scenarios are from the National Oceanic and Atmospheric Administration (Sweet et al., 2017) customized for Maine using the U.S. Army Corps of Engineers (2019) Sea Level Change Calculator. Additional information, projections, and probabilities of sea level rise are presented in the *Seal Level Rise and Storm Surge* chapter.



Appendix A, Image 1. Potential inundation for the area of Portland near Back Cove and Fore River areas. Areas inundated under the highest astronomical tide (HAT) are shown in blue. Areas potentially inundated by the HAT plus 3.9 feet of sea level rise are shown in green.



Appendix A, Image 2. Potential inundation for the area of Mount Desert Island near Thomas Bay and Route 3. Areas inundated under the highest astronomical tide (HAT) are shown in blue. Areas potentially inundated by the HAT plus 3.9 feet of sea level rise are shown in green.

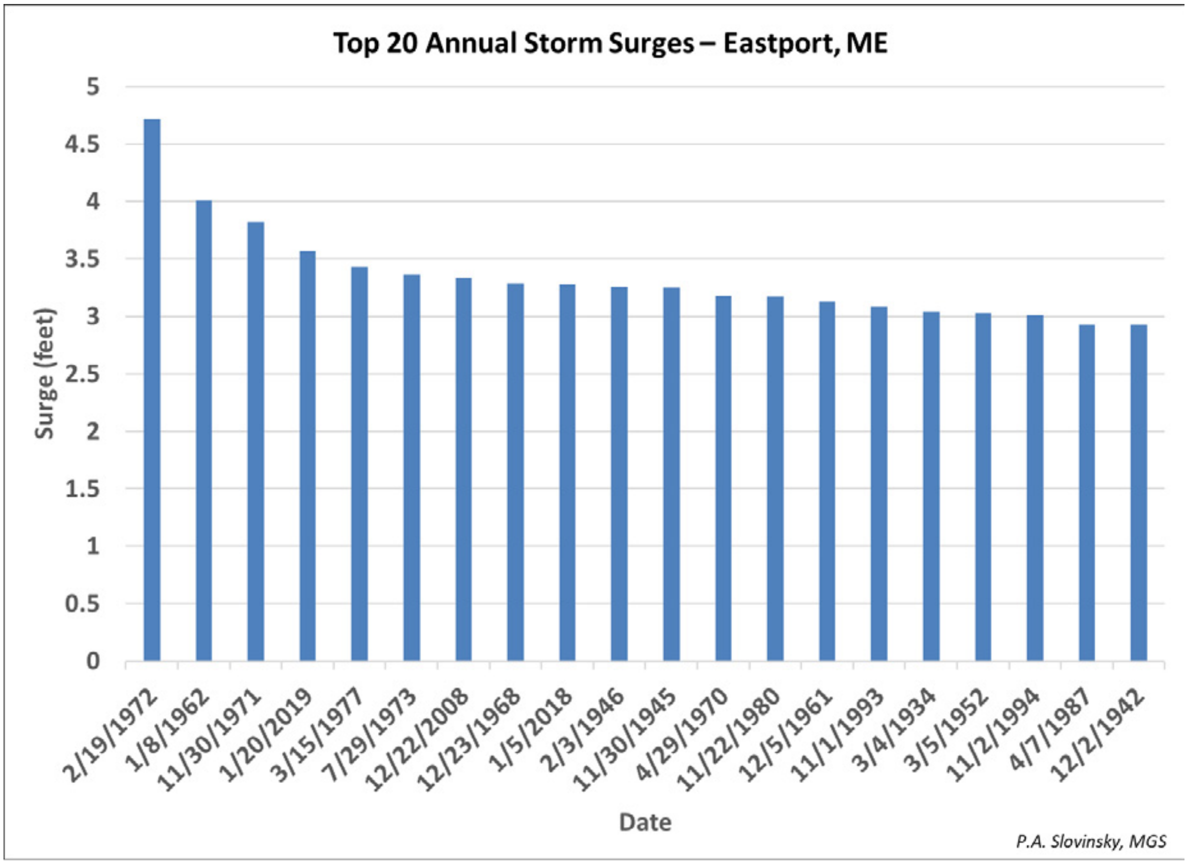


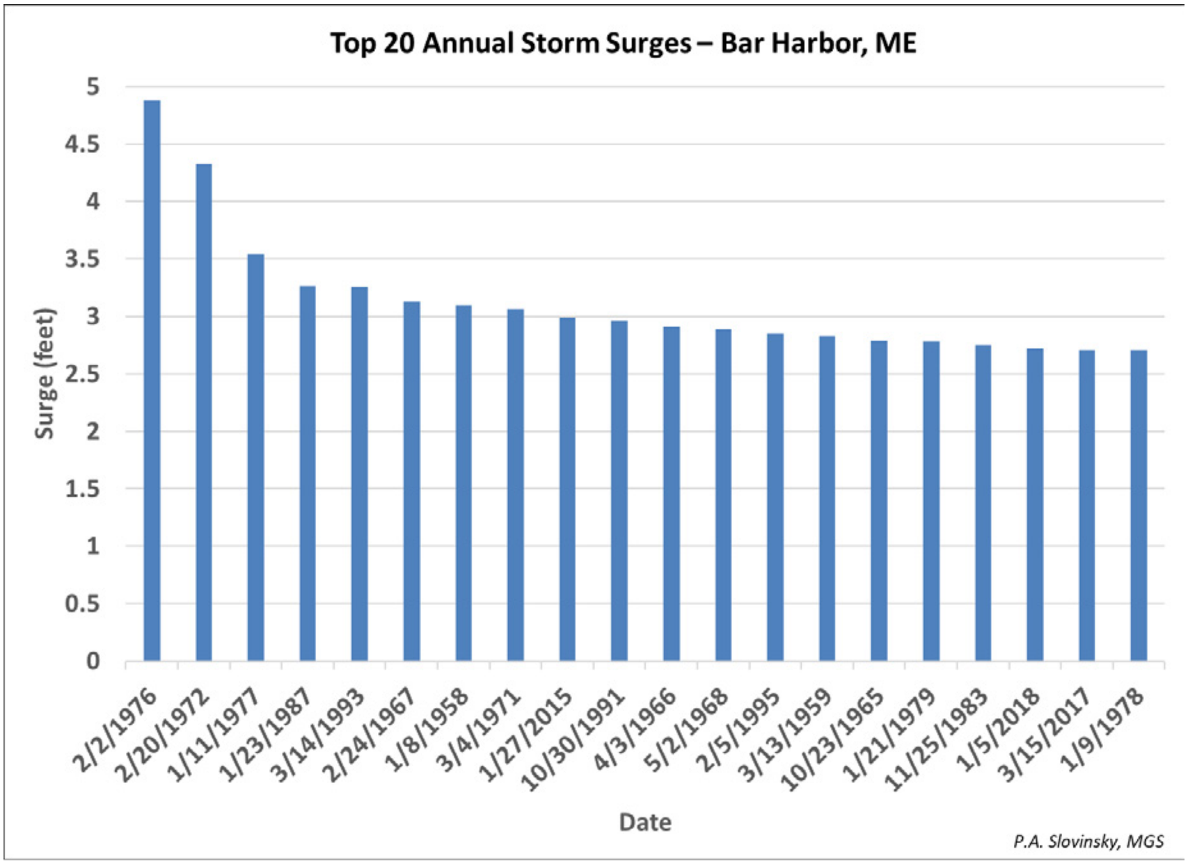
Appendix A, Image 3. Potential inundation for the area of Machias and the Machias River along U.S. Route 1. Areas inundated under the highest astronomical tide (HAT) are shown in blue. Areas potentially inundated by the HAT plus 3.9 feet of sea level rise are shown in green.

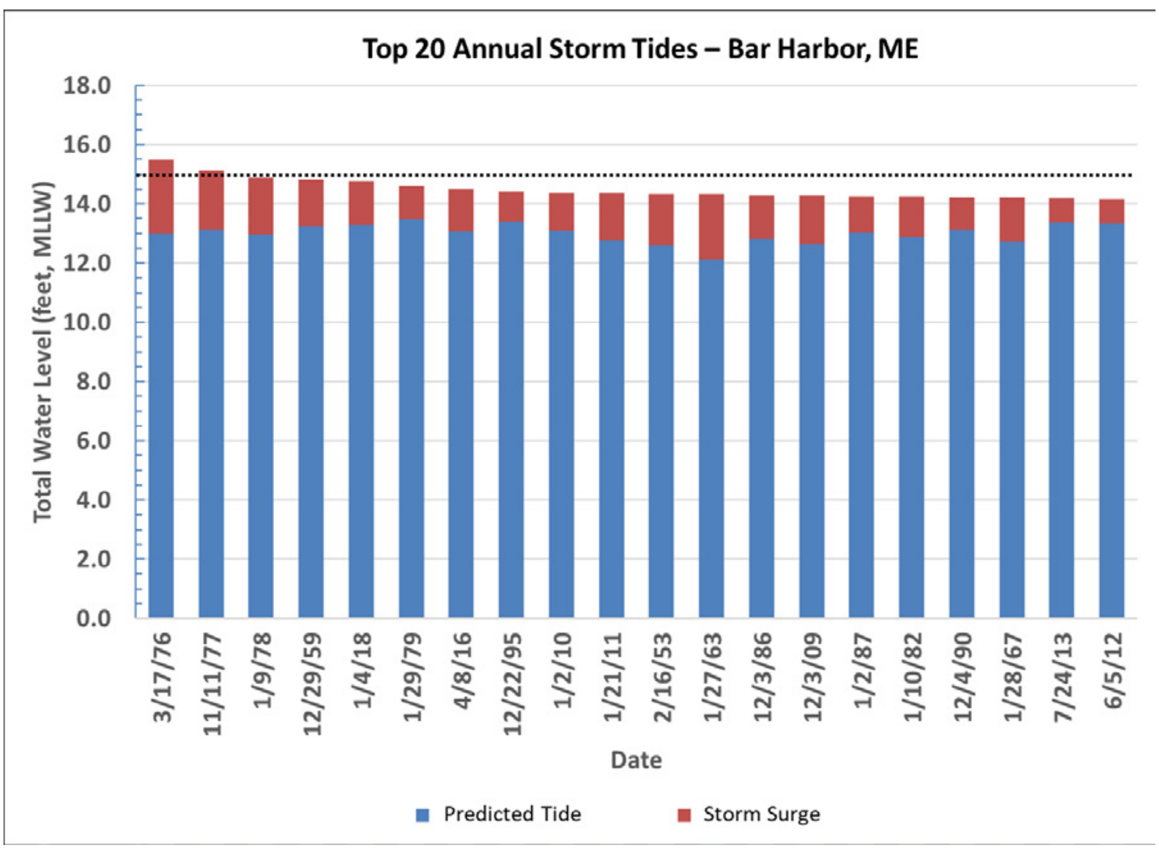
APPENDIX B

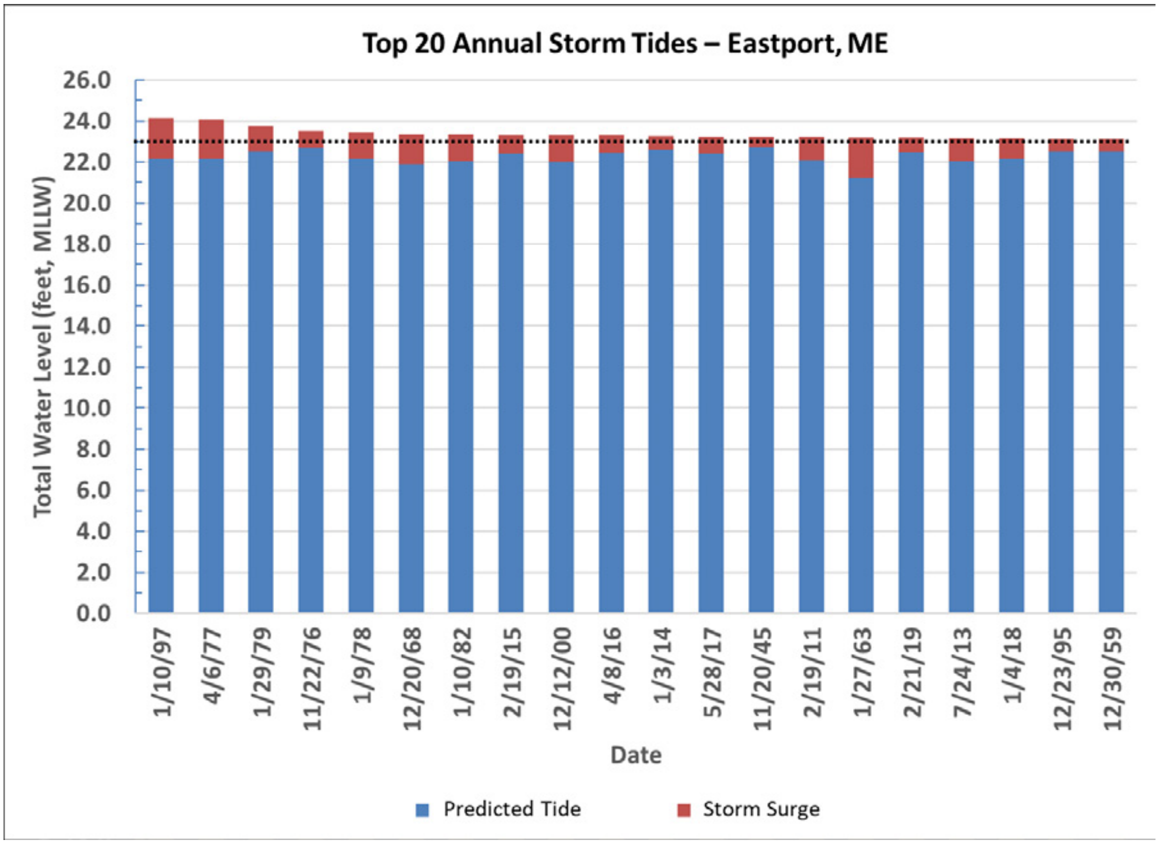
Highest Annual Storm Surge and Storm Tides for Bar Harbor and Eastport, Maine

Source: Analysis by P. A. Slovinsky, MGS, using tide gauge data from NOAA CO-OPS stations 8413320 and 8410140.




Top 20 Annual Storm Surges – Bar Harbor, ME
Surge (feet)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
2/2/1976
2/20/1972
1/11/1977
1/23/1987
3/14/1993
2/24/1967
1/8/1958
3/4/1971
1/27/2015
10/30/1991
4/3/1966
5/2/1968
2/5/1995
3/13/1959
10/23/1965
1/21/1979
11/25/1983
1/5/2018
3/15/2017
1/9/1978
Date
P.A. Slovinsky, MGS


Top 20 Annual Storm Tides – Bar Harbor, ME
Total Water Level (feet, MLLW)
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
3/17/76
11/11/77
1/9/78
12/29/59
1/4/18
1/29/79
4/8/16
12/22/95
1/2/10
1/21/11
2/16/53
1/27/63
12/3/86
12/3/09
1/2/87
1/10/82
12/4/90
1/28/67
7/24/13
6/5/12
Date
Predicted Tide
Storm Surge


Top 20 Annual Storm Tides – Eastport, ME
Total Water Level (feet, MLLW)
26.0
24.0
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1/10/97
4/6/77
1/29/79
11/22/76
1/9/78
12/20/68
1/10/82
2/19/15
12/12/00
4/8/16
1/3/14
5/28/17
11/20/45
2/19/11
1/27/63
2/21/19
7/24/13
1/4/18
12/23/95
12/30/59
Date
Predicted Tide
Storm Surge

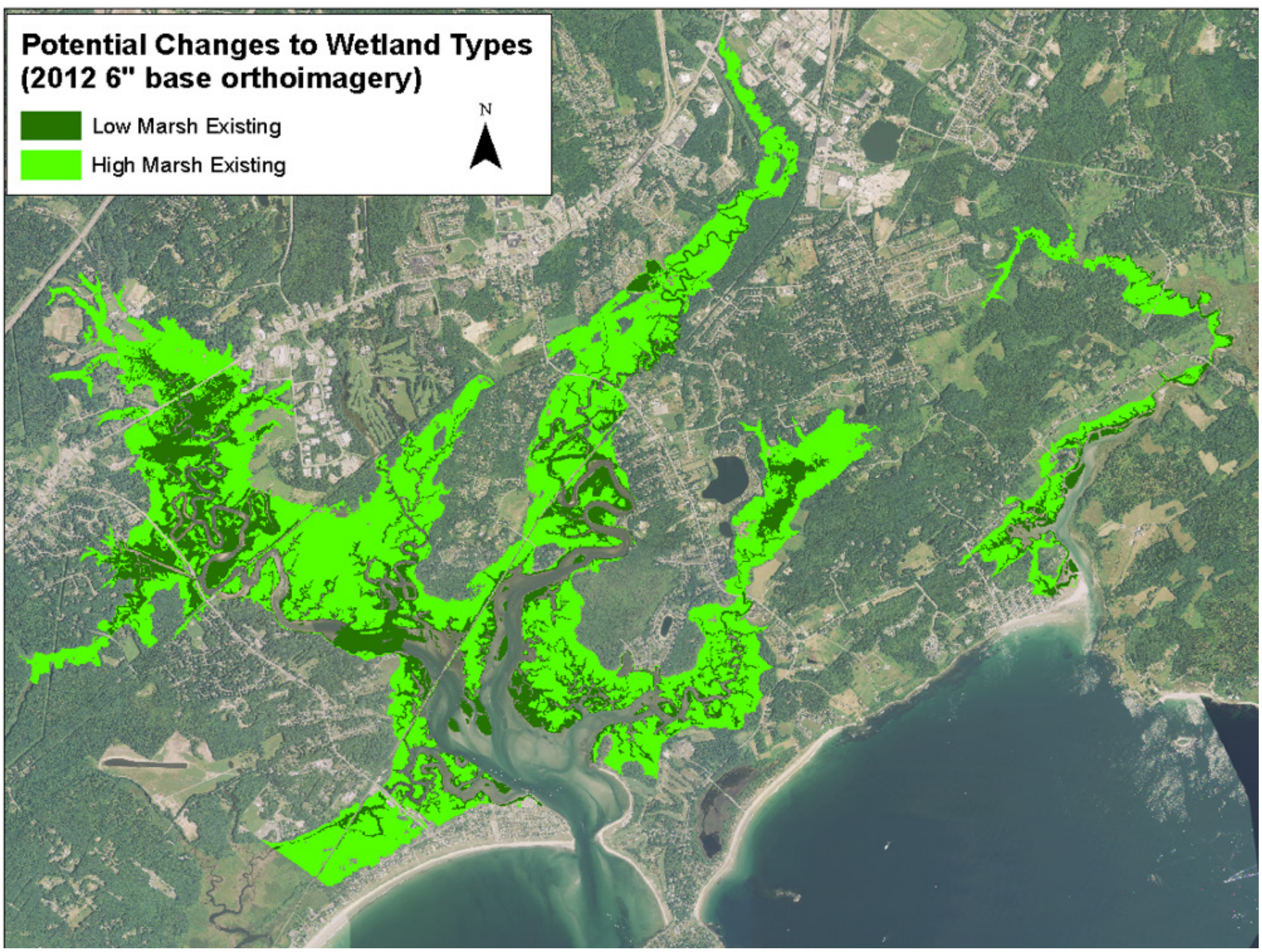
APPENDIX C

Potential Salt Marsh Inundation and Conversion Examples from Scarborough Marsh, Scarborough, Maine.

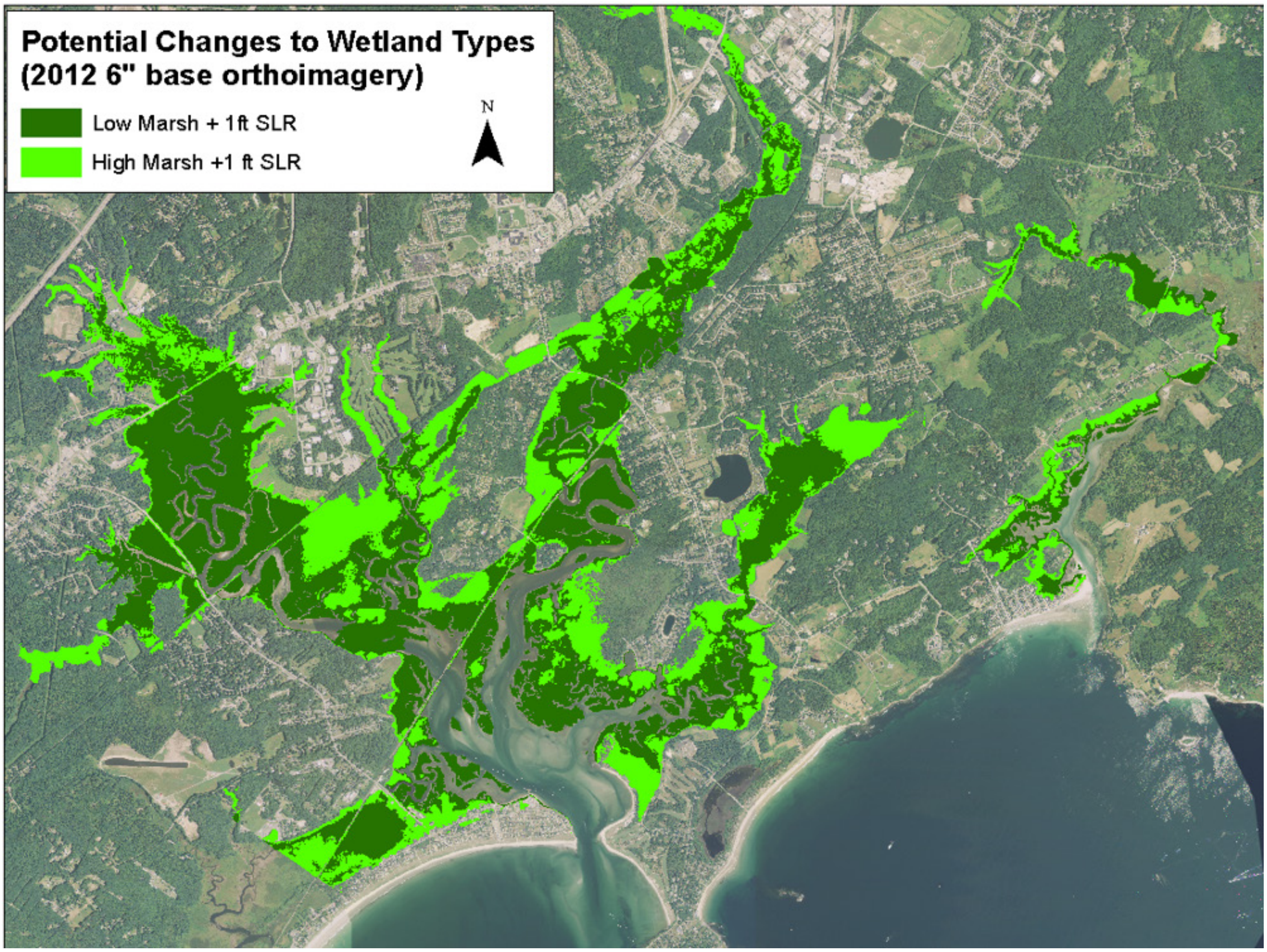
Included maps depict:

- existing conditions;
- existing conditions +1-foot SLR;
- existing conditions +2 feet SLR;
- existing conditions +3.3 feet SLR; and
- existing conditions +6 feet SLR.

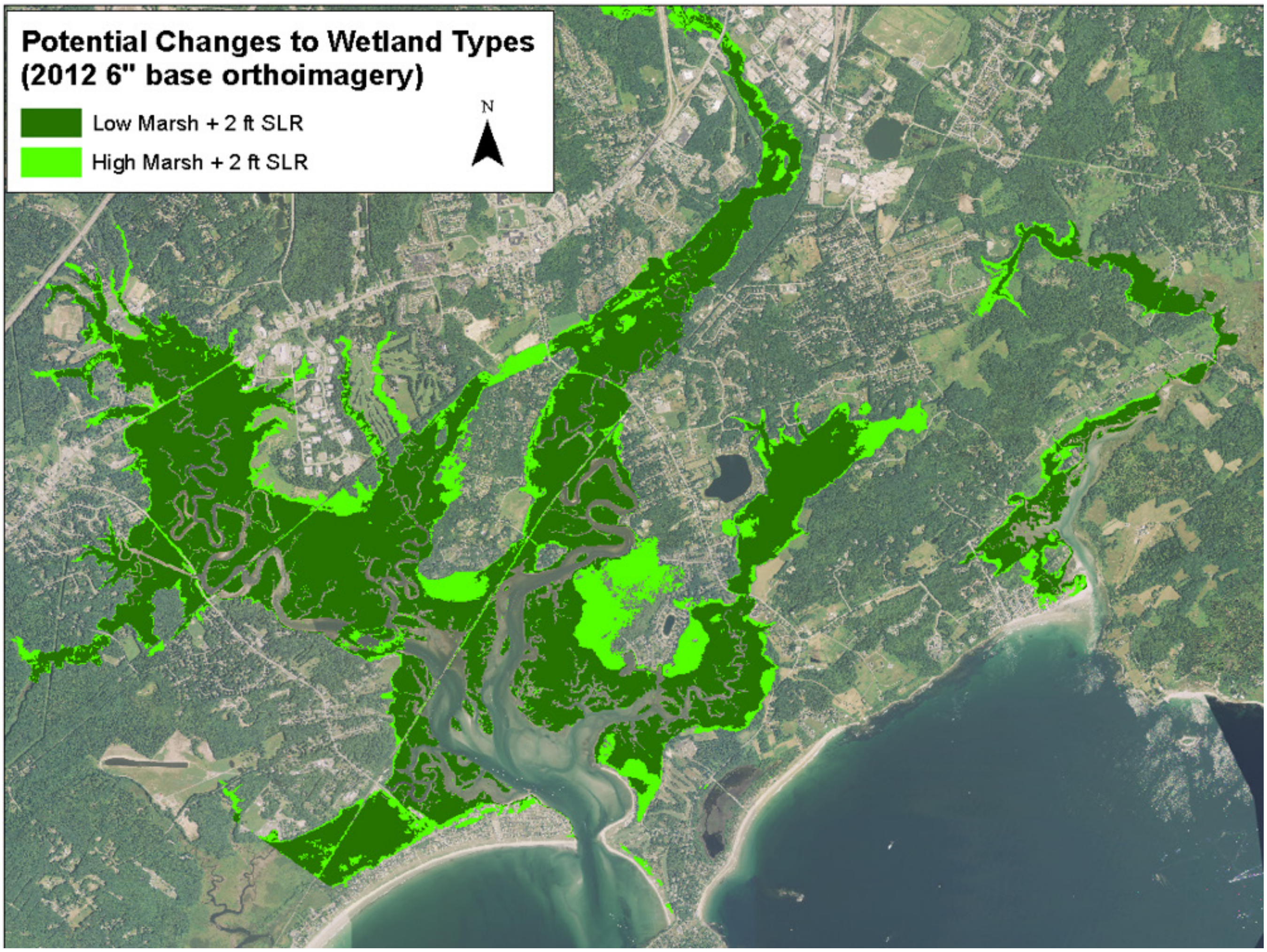
Source: Slovinsky (2013, unpublished).



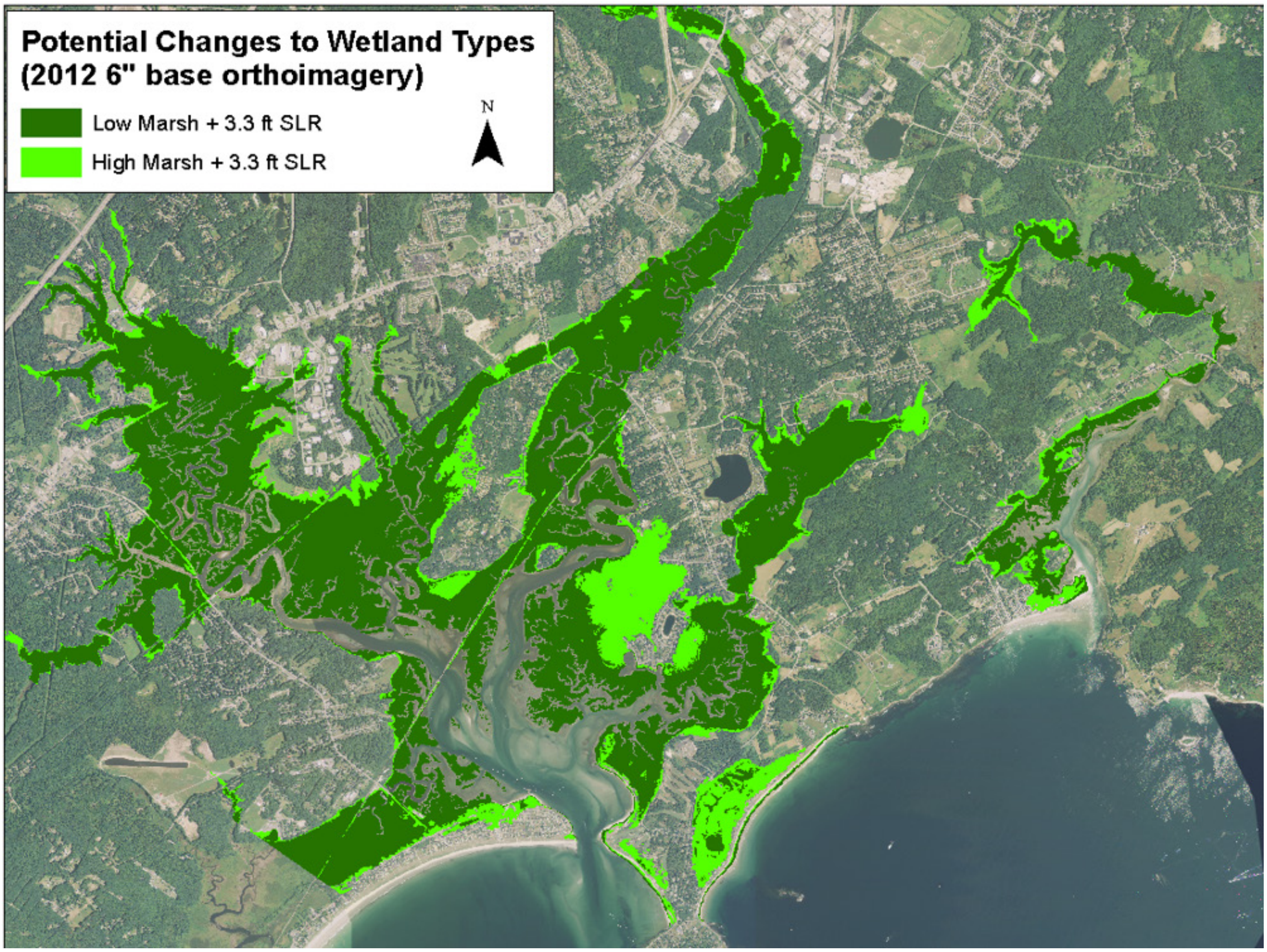
Appendix C, Image 1. Marsh distribution under existing conditions in the Scarborough Marsh.



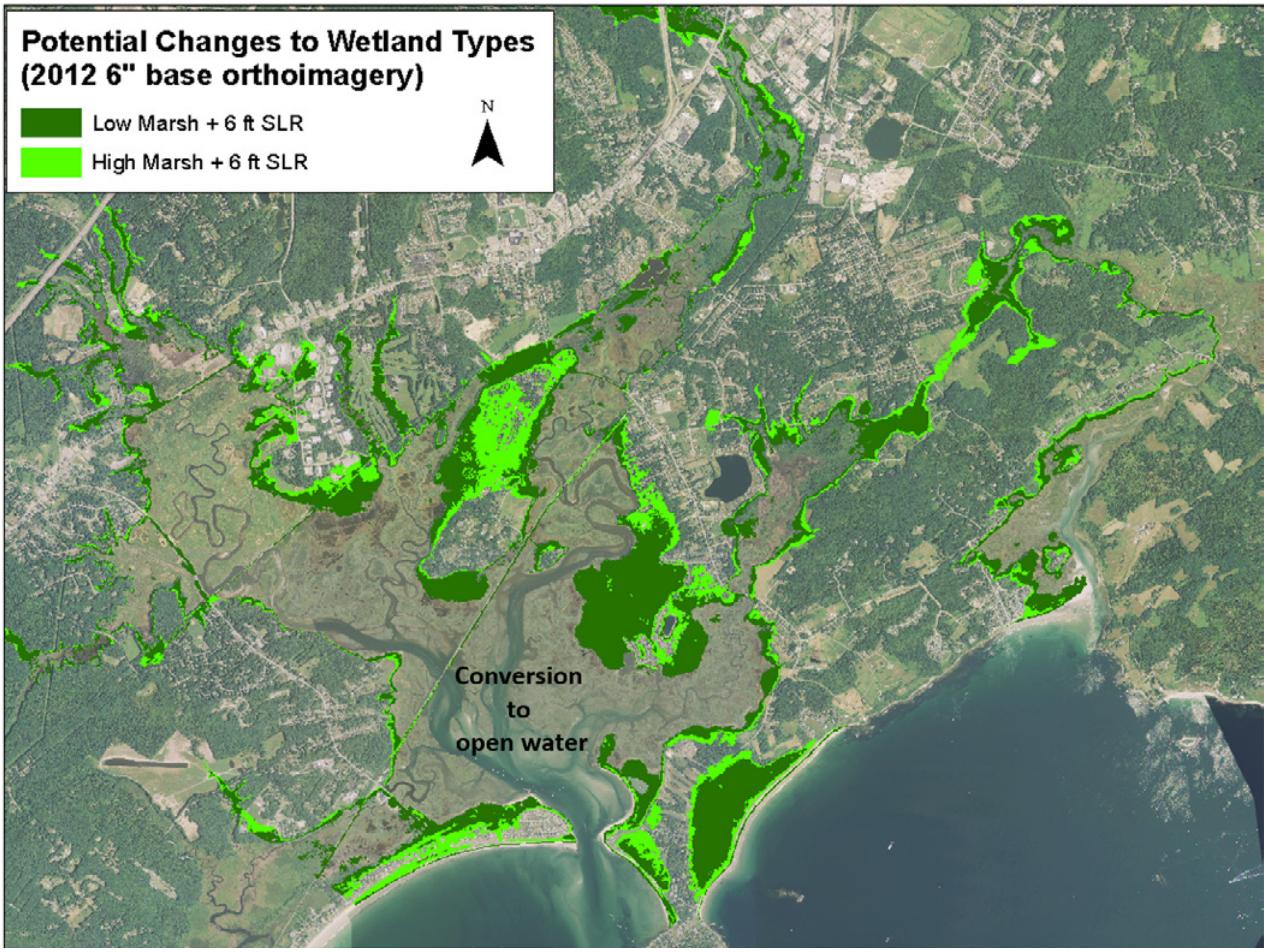
Appendix C, Image 2. Potential marsh distribution after 1 foot of sea level rise in the Scarborough Marsh.Appendix C, Image 3. Potential marsh distribution after 2 feet of sea level rise in the Scarborough Marsh.



Appendix C, Image 3. Potential marsh distribution after 2 feet of sea level rise in the Scarborough Marsh.



Appendix C, Image 4. Potential marsh distribution after 3.3 feet of sea level rise in the Scarborough Marsh.



Appendix C, Image 5. Potential marsh distribution after 6 feet of sea level rise in the Scarborough Marsh.

APPENDIX D

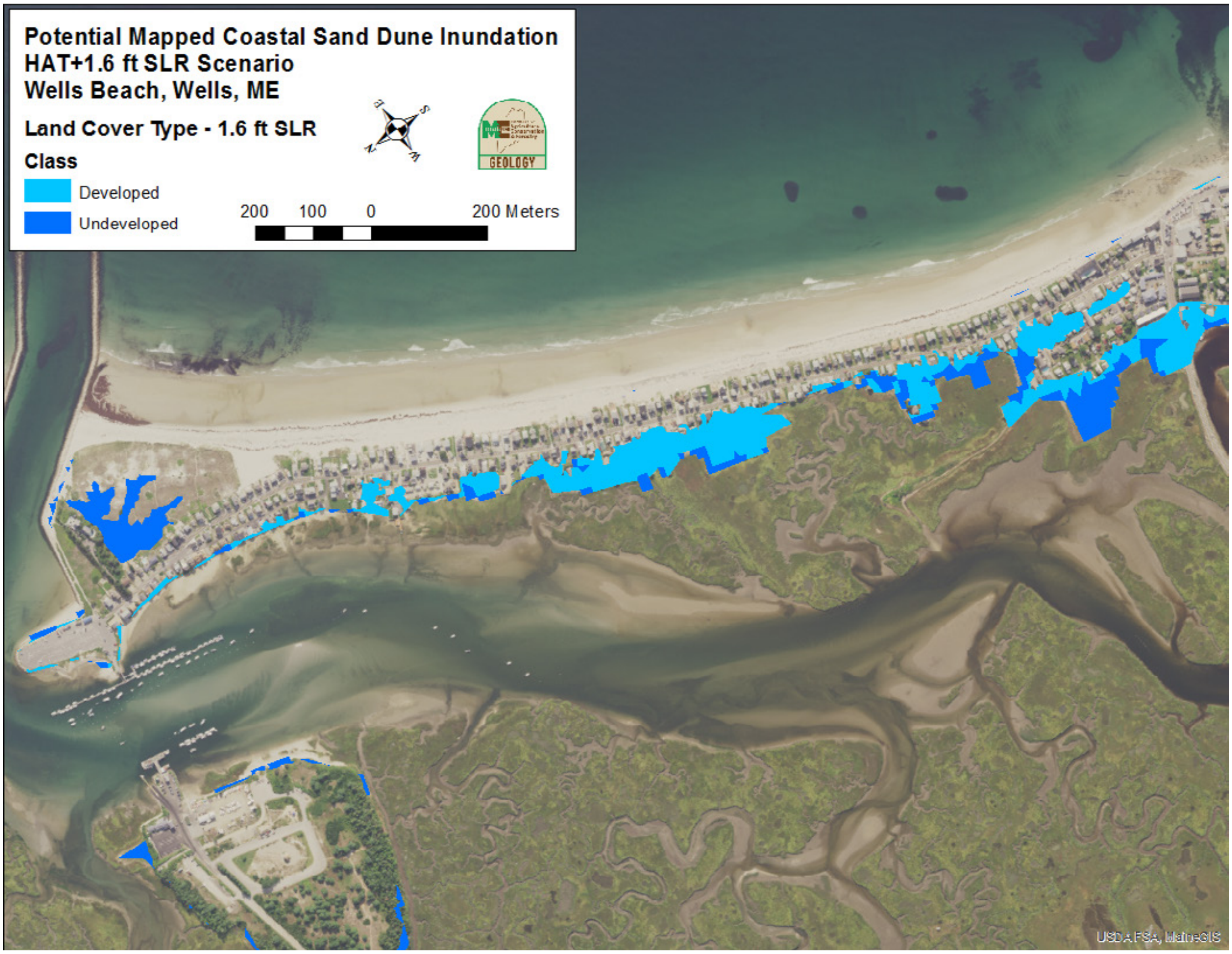
Potential Inundation of Coastal Sand Dunes and Beaches in Maine

**Included are maps depicting an example of potential inundation of developed and undeveloped coastal sand dunes for
Wells Beach, Wells for
HAT+1.6 feet, HAT+3.9 feet, and HAT+8.8 ft SLR**

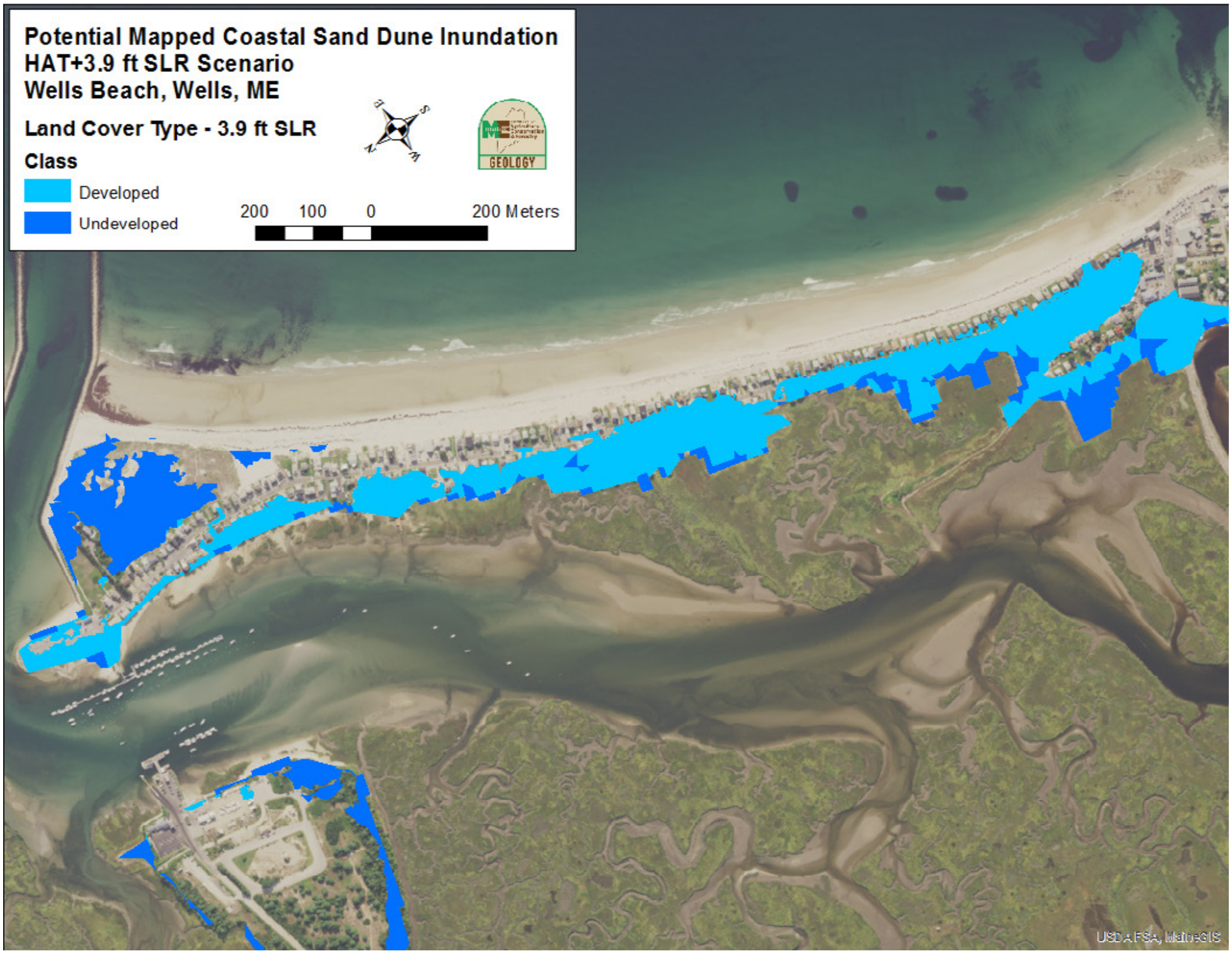
**Tables summarizing dune inundation for each County
Graph of dune area loss from inundation**

**Table of dry beach loss from inundation
Graph of dry beach loss from inundation**

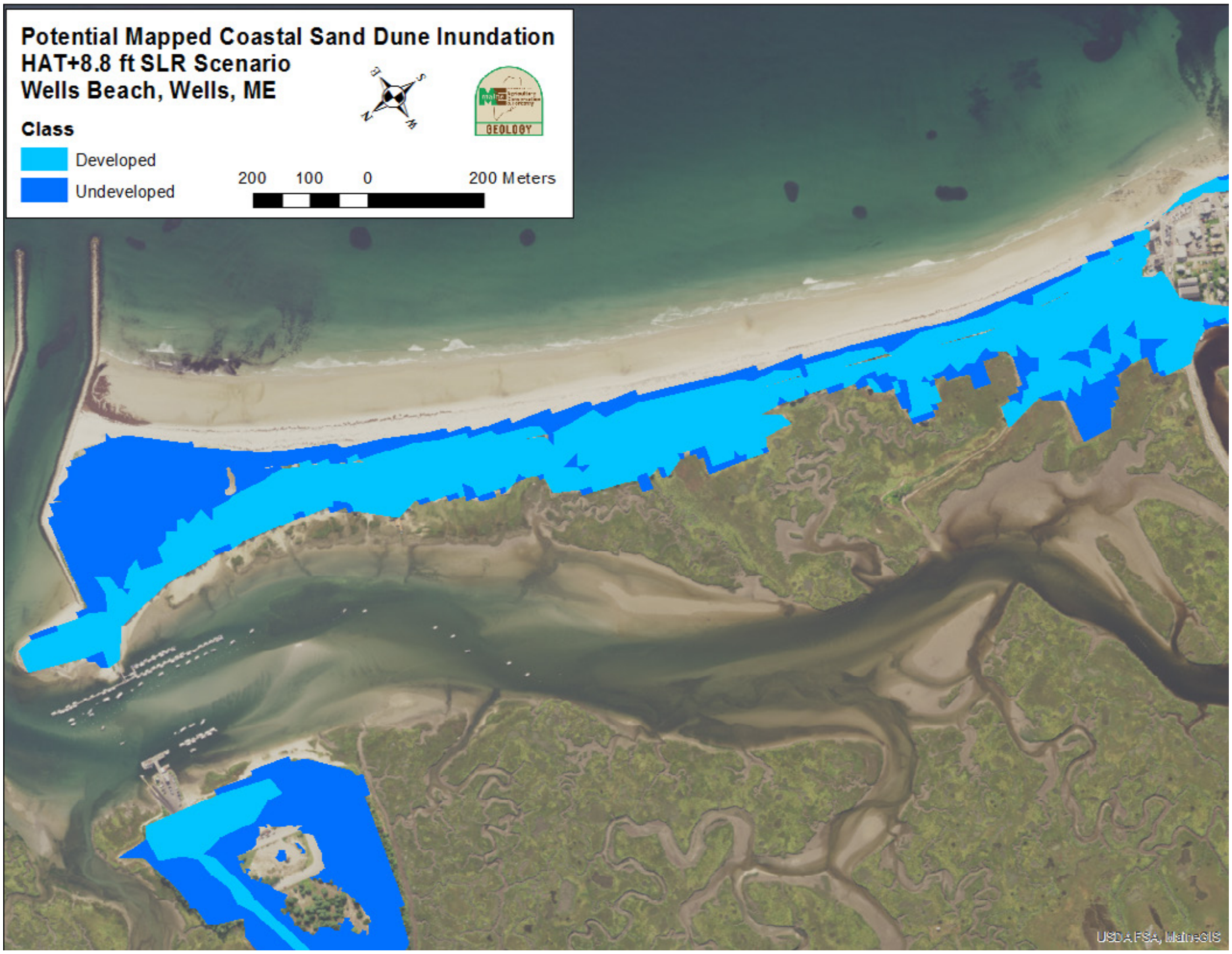
Source: Slovinsky (2020, unpublished).



Appendix D, Image 1. Potential inundation of developed and undeveloped coastal sand dunes in Wells, ME after 1.6 ft of SLR.



Appendix D, Image 2. Potential inundation of developed and undeveloped coastal sand dunes in Wells, ME after 3.9 ft of SLR.



Appendix D, Image 3. Potential inundation of developed and undeveloped coastal sand dunes in Wells, ME after 8.8 ft of SLR.

County	Existing Conditions (Acres)				Dunes Inundated by 1.6 feet SLR (Acres)				% Inundated (from Existing Conditions)			
	Undeveloped		Developed		Undeveloped		Developed		Undeveloped		Developed	
	Front	Back	Front	Back	Front	Back	Front	Back	Front	Back	Front	Back
York	306	513	205	519	32	207	121	486	10%	40%	59%	94%
Cumberland	159	230	13	116	94	58	7	109	59%	25%	52%	94%
Sagadahoc	137	214	6	48	85	176	2	40	62%	82%	27%	83%
Lincoln	11	16	3	1	8	10	3	1	76%	64%	100%	58%
Knox	81	35	13	2	74	29	13	2	91%	81%	98%	100%
Waldo	26	31	4	7	26	22	4	6	99%	72%	97%	98%
Hancock	238	184	28	15	218	167	26	12	92%	90%	90%	82%
Washington	274	146	9	8	251	127	7	6	91%	87%	74%	77%
TOTAL	**1232**	**1370**	**281**	**715**	**787**	**796**	**181**	**662**	**64%**	**58%**	**64%**	**93%**

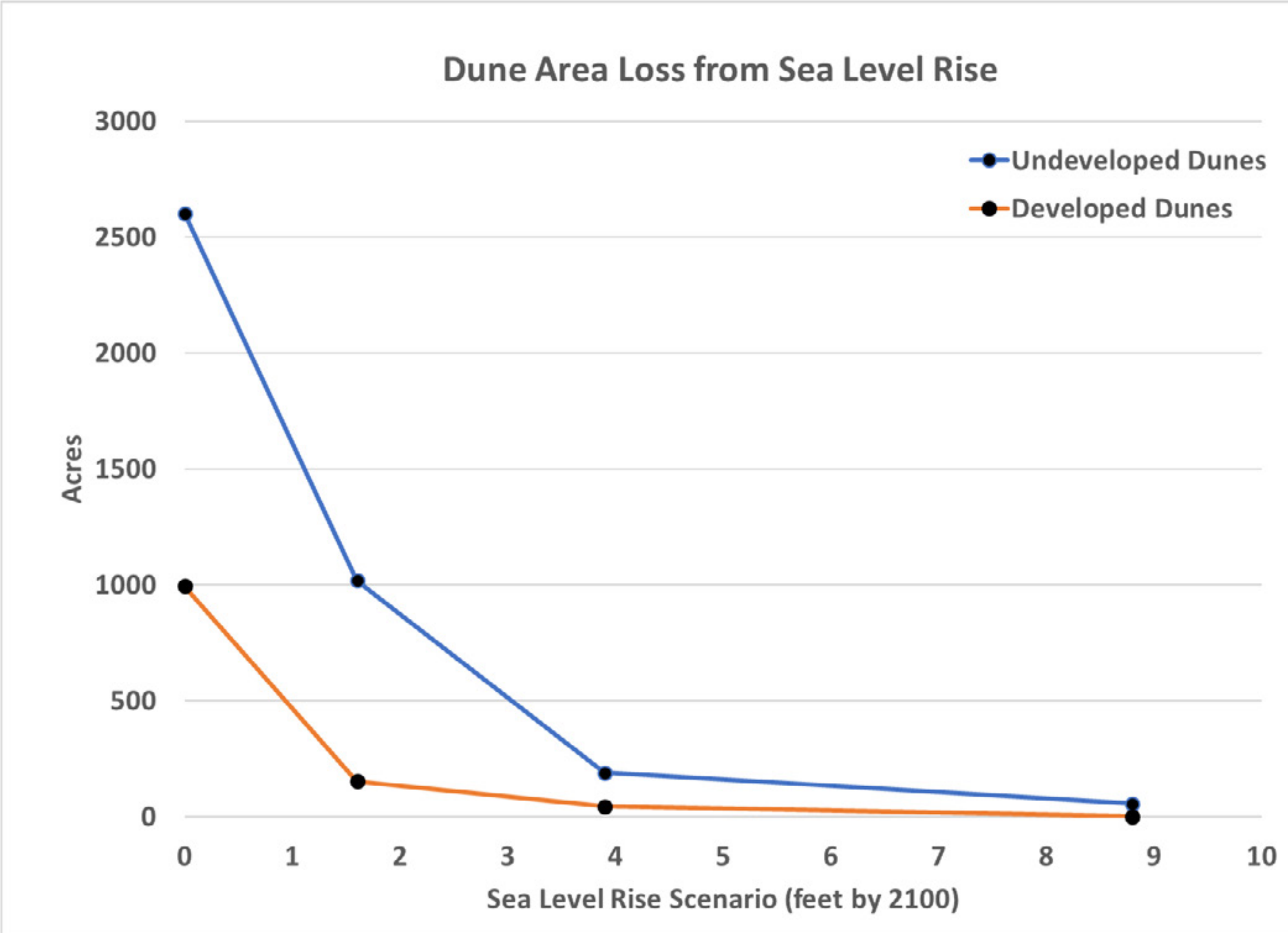
Appendix D, Table 1. Area and percentage (from existing conditions) of developed and undeveloped frontal and back dunes potentially inundated by 1.6 feet of sea level rise.

County	Existing Conditions (Acres)				Dunes Inundated by 3.9 feet SLR (Acres)				% Inundated (from Existing Conditions)			
	Undeveloped		Developed		Undeveloped		Developed		Undeveloped		Developed	
	Front	Back	Front	Back	Front	Back	Front	Back	Front	Back	Front	Back
York	306	513	205	519	241	480	184	510	79%	94%	90%	98%
Cumberland	159	230	13	116	144	196	10	114	90%	85%	75%	98%
Sagadahoc	137	214	6	48	123	199	3	45	90%	93%	52%	94%
Lincoln	11	16	3	1	10	15	3	1	95%	97%	100%	100%
Knox	81	35	13	2	81	35	13	2	99%	99%	100%	100%
Waldo	26	31	4	7	26	30	4	7	100%	97%	100%	100%
Hancock	238	184	28	15	234	183	28	15	98%	99%	99%	99%
Washington	274	146	9	8	269	145	7	7	98%	99%	81%	89%
TOTAL	**1232**	**1370**	**281**	**715**	**1127**	**1284**	**252**	**700**	**92%**	**94%**	**90%**	**98%**

Appendix D, Table 2. Area and percentage (from existing conditions) of developed and undeveloped frontal and back dunes potentially inundated by 3.9 feet of sea level rise.

County	Existing Conditions (Acres)				Dunes Inundated by 8.8 feet SLR (Acres)				% Inundated (from Existing Conditions)			
	Undeveloped		Developed		Undeveloped		Developed		Undeveloped		Developed	
	Front	Back	Front	Back	Front	Back	Front	Back	Front	Back	Front	Back
York	306	513	205	519	259	512	204	518	85%	100%	100%	100%
Cumberland	159	230	13	116	159	226	13	116	100%	98%	100%	100%
Sagadahoc	137	214	6	48	136	212	6	48	99%	99%	99%	99%
Lincoln	11	16	3	1	11	16	3	1	100%	100%	100%	100%
Knox	81	35	13	2	81	35	13	2	100%	100%	100%	100%
Waldo	26	31	4	7	26	31	4	7	100%	100%	100%	100%
Hancock	238	184	28	15	238	184	28	15	100%	100%	100%	100%
Washington	274	146	9	8	274	146	9	8	100%	100%	100%	100%
TOTAL	**1232**	**1370**	**281**	**715**	**1183**	**1363**	**280**	**713**	**96%**	**99%**	**100%**	**100%**

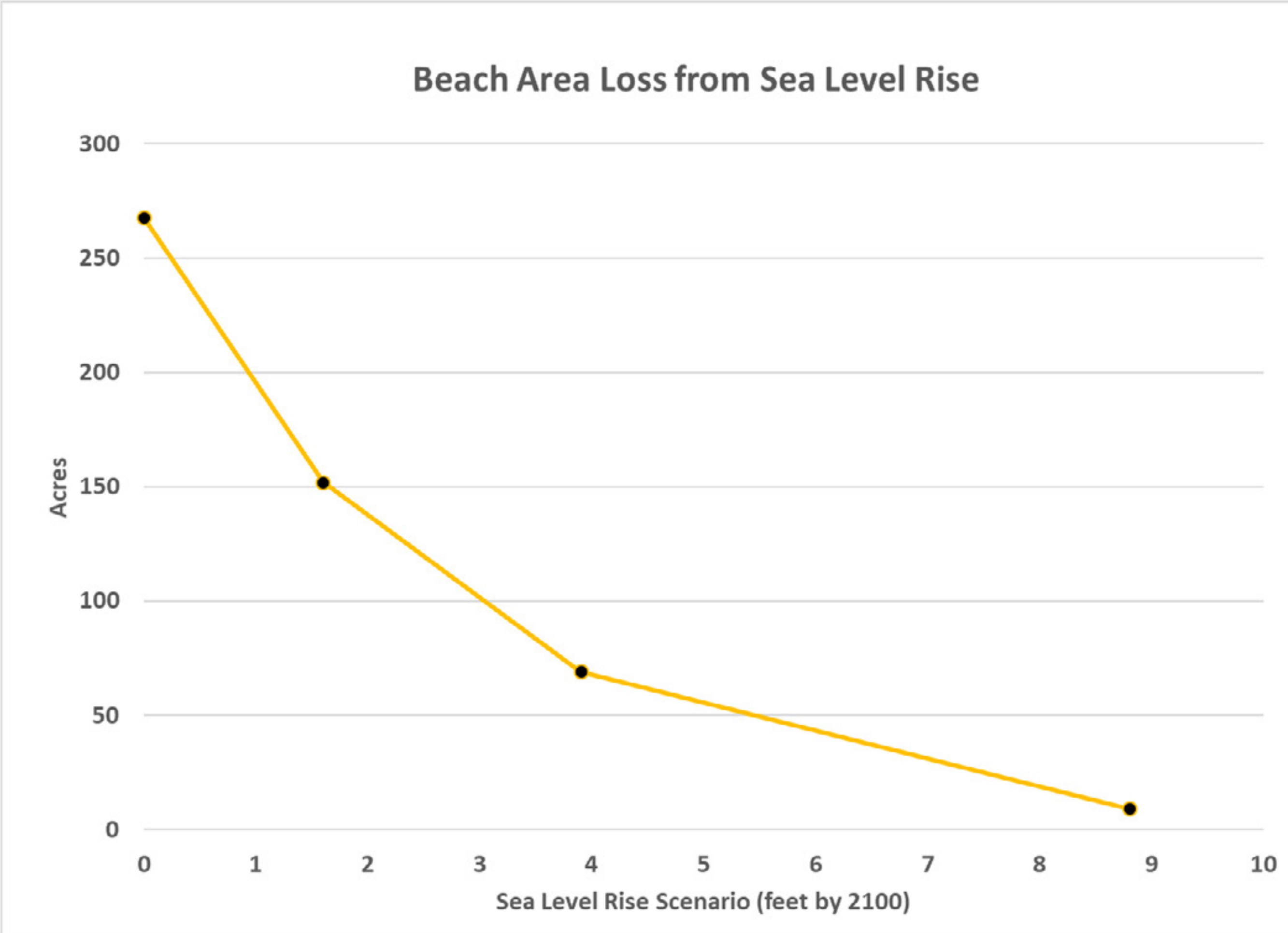
Appendix D, Table 3. Area and percentage (from existing conditions) of developed and undeveloped frontal and back dunes potentially inundated by 8.8 feet of sea level rise.



Appendix D, Graph 1. Sea level rise across all counties in Maine leads to inundation of both natural and developed coastal sand dunes. Compared to the present extent of dune area (0 sea level rise), the largest loss occurs with a sea level rise of 1.6 feet. Natural dunes lose more area than developed dunes initially, but both are reduced considerably after 3.9 feet of sea level rise. Data are from Table 17 and in greater detail in Tables D.1. through D.3. above. The loss of dune area is simulated using fixed topography and does not consider erosion, accretion, or modification by human action.

County	Existing	1.6 feet SLR			3.9 feet SLR			8.8 feet SLR		
	Dry Beach	Dry Beach	Change	% Change	Dry Beach	Change	% Change	Dry Beach	Change	% Change
York	143	82	-61	-43%	36	-107	-75%	2	-141	-99%
Cumberland	48	27	-21	-44%	13	-35	-73%	1	-47	-98%
Sagadahoc	63	38	-25	-40%	20	-43	-68%	5	-58	-92%
Lincoln	2	1	-1	-50%	0	-2	-100%	0	-2	-100%
Knox	9	2	-7	-78%	1	-8	-89%	0	-9	-100%
Waldo	2	1	-1	-50%	0	-2	-100%	0	-2	-100%
TOTAL	**267**	**151**	**-116**	**-43%**	**70**	**-197**	**-74%**	**8**	**-259**	**-97%**

Appendix D, Table 4. Area in acres and percentage (from existing conditions) of dry beach remaining after three sea level rise scenarios. These numbers are for a static inundation without consideration of erosion or accretion of sediment. No data were available for Hancock and Washington Counties.



Appendix D, Graph 2. The loss of dry beach area as sea level rises from the present (0) to 8.8 feet simulated from a static inundation without erosion or accretion (Table D.4.). The dry beach was approximated by the area between the elevation of the Highest Astronomical Tide to roughly the dune edge or a seawall. Only data from York through Waldo Counties were available for this graph.

OCEAN ACIDIFICATION

HIGHLIGHTS

Scientific data indicate that the rate of ocean 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.

Since the beginning of the 19th century, the world's surface ocean pH has decreased from 8.2 to 8.1, a 30% increase in the average acidity of ocean surface waters, most of which has occurred in the last 70 years. Ocean acidification is a relatively recent area of scientific research and regular measurements in the Gulf of Maine only started within the last decade.

Further reductions in ocean pH are expected, ranging from 0.05-0.33 pH units by 2100, depending upon emissions scenarios. It is not yet clear how conditions in the Gulf of Maine will deviate from these global estimates.

Ocean acidification in the Gulf of Maine is considerably different than acidification in its nearshore coastal estuaries. In addition to atmospheric CO_2, other drivers contribute to inshore acidification and are potentially very important to Maine's marine resources. Coastal acidification is often fueled by nutrients carried into the ocean by more acidic river discharge, stimulating phytoplankton blooms that subsequently decompose on or near the seabed. Because of variability in regional circulation, discharge and productivity patterns, long-term trends in coastal acidification may be more difficult to predict in the Gulf of Maine as compared to the adjacent Atlantic Ocean.

Other climate-induced impacts, like increasing amounts of fresh water supplied through Arctic outflow to the north and increases in average annual rainfall and the frequency of extreme precipitation and runoff events, will exacerbate the Gulf of Maine region's sensitivity to acidification. In fact, the combination of global and local drivers of acidification in the Northeast make New England's shellfisheries – including both its wild harvest fisheries and aquaculture production, and the communities that rely on them – potentially among the most vulnerable to ocean acidification in the United States.

Ocean and coastal acidification will most heavily impact those marine organisms that produce calcium carbonate to build shells such as scallops, clams, mussels, and sea urchins. The impacts on crustaceans such as lobsters and crabs are less clear, with some studies showing negative impacts and others showing that processes like warming are more likely the dominant factor to influence populations.

One of the most important and urgent challenges facing Maine as we try to understand and prepare for the impacts of ocean and coastal acidification is to determine how and where inshore causes of acidification contribute to Maine's "acidification budget" and what actions we can take at the local scale to reduce acidification, in addition to reducing atmospheric CO_2 levels.

DISCUSSION

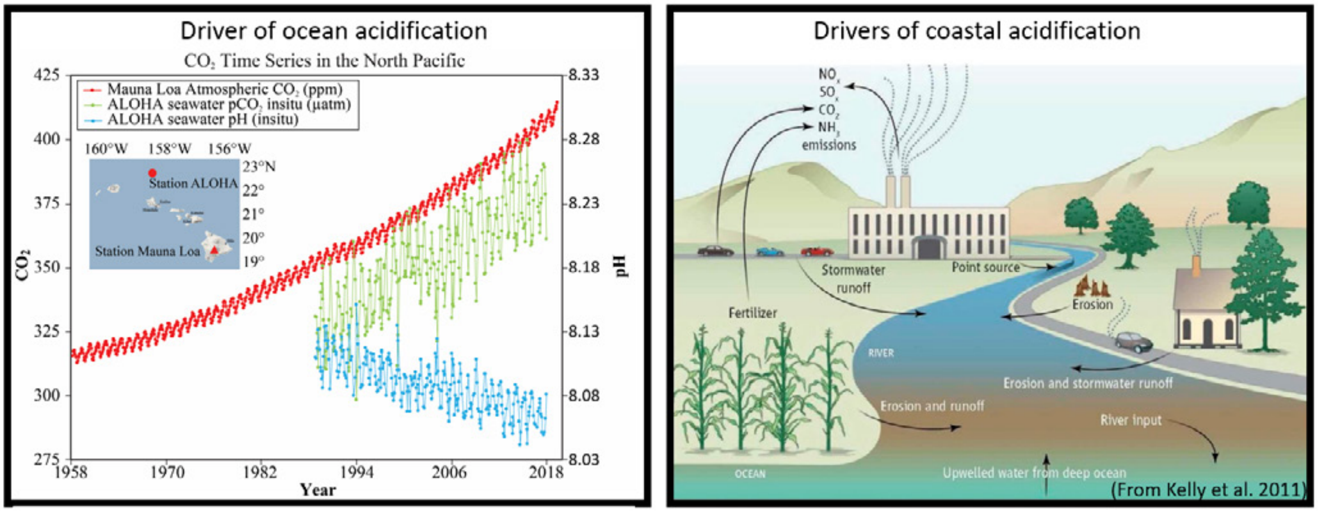
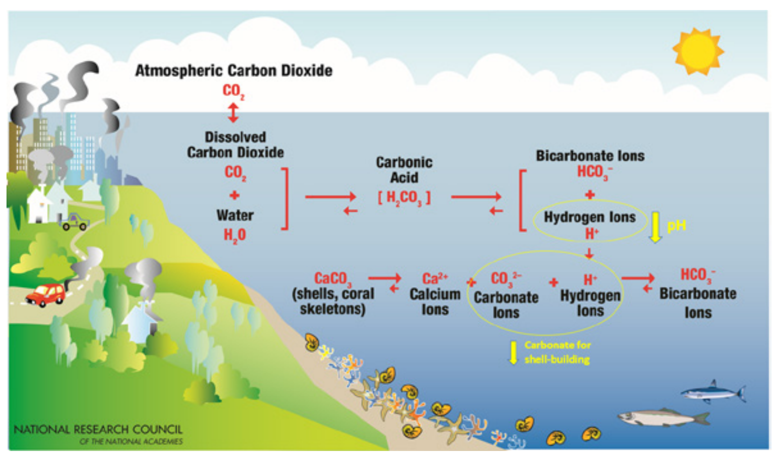


Figure 1. Drivers of ocean and coastal acidification. Left panel shows atmospheric CO_2 (red line) since 1958, a record of seawater CO_2 measurements (green line), and seawater pH (blue line) in the North Pacific Ocean near Hawaii. Inset map shows location of measurements. Right panel shows the major local contributors to coastal acidification.



Since the beginning of the industrial revolution, the oceans have been an important sink for carbon dioxide emissions (CO_2) from the atmosphere, absorbing ~30% of human-caused emissions and preventing an even faster rise in atmospheric CO_2 levels. However, a major negative side-effect occurs from this natural carbon sink: ocean acidification. Ocean acidification is a decline in seawater pH that occurs on a global scale and is caused primarily by CO_2 from the atmosphere entering the ocean. This leads to formation of carbonic acid (H_2CO_3). Ocean acidification (OA) is different from coastal acidification (CA), which is a more localized phenomenon often accelerated by excess nutrients carried by rivers. However, ocean and coastal acidification (OCA) both involve increases in carbon dioxide in the water.

Though complex, the chemistry of ocean acidification helps provide insight into why it has such important implications for shellfish in the Gulf of Maine. When the carbon dioxide combines with the seawater to form carbonic acid, almost immediately the carbonic acid dissociates to form bicarbonate ions (HCO_3^-) and hydrogen ions (H^+). As the concentration of hydrogen ions increases, the water becomes more acidic (decreasing pH). Some of the extra hydrogen ions react with carbonate ions (CO_3^{2-}) to form more bicarbonate. This makes carbonate ions less abundant – a problem for many marine species that use it to build calcium carbonate shells and skeletons. To calcify, many organisms incorporate calcium carbonate ($CaCO_3$) from dissolved calcium (Ca^{2+}) and carbonate ions (CO_3^{2-}) through the reaction $CO_3^{-2} + Ca^{2+} \rightarrow CaCO_3$. As carbonate becomes less abundant, these organisms have more difficulty building and maintaining their shells and skeletons. A variety of commercially harvested shellfish use a crystalline form of calcium carbonate called aragonite. Aragonite tends to be strong, yet it is quite susceptible to corrosion in acidic waters because it is 1.5 times more soluble than calcite, the dominant mineral form of $CaCO_3$.

The symbol Ω (omega) is used by scientists as shorthand for "calcium carbonate saturation state", or the tendency for the mineral calcium carbonate to form or dissolve. Ω is usually expressed with respect to aragonite. An aragonite saturation state (Ωar) of 1.0 represents a saturated state, but 1.6 has been identified as the threshold above which suitable larval shellfish growth occurs (Salisbury et al. 2008). There is still debate on the direct role that carbonate availability and its proxy Ω play in shell development (e.g., Cyronak et al. 2016), but it is agreed that reductions in carbonate and Ω create stress for a variety of marine shell-builders (e.g. Waldbusser et al. 2015). If the Gulf of Maine tracks the pace of ocean acidification in the open ocean, much of the region could experience persistent aragonite undersaturation in 30 to 40 years (GOM2050 - OCA Synthesis Paper).

Ω (omega) is used by scientists as shorthand for "calcium carbonate saturation state", or how easily the mineral calcium carbonate forms or dissolves. Higher Ω numbers means it's easier for calcium carbonate (and shellfish!) to form.

The deep Gulf of Maine is chemically more susceptible to acidification pressures than other waters on the east coast of the United States due to relatively low pH and a poor capacity to buffer against changes in pH (Wang et al, 2013). Thus, we are more vulnerable to CO_2 increase than a better buffered water body, such as the Gulf of Mexico. Also, because of this lower buffering capacity and average cooler temperature, the Gulf of Maine experiences the lowest Ω_{ar} values on the East Coast. There are several reasons for this. Five large rivers discharge into the Gulf of Maine. This freshwater is typically more acidic than ocean waters due to the local geology, land use patterns and relatively high acidity of precipitation (Salisbury et al. 2008). CO_2 dissolves more easily in colder water, so our region tends to absorb more atmospheric CO_2. Additionally, more cold, fresh water comes in from watersheds and melting ice to the north entering from the Scotian Shelf. Finally, the Gulf of Maine is downwind of many of the coal fired power plants that result in atmospheric deposition of acidic and alkaline compounds (Doney et al. 2007).

Like soda or seltzer water, the ocean can absorb CO_2 more easily when it's cold than when it's warm. This means the colder Gulf of Maine is at higher risk of ocean acidification than other areas of the U.S.

Maine's coastal waters are also impacted by the addition of nutrients, such as nitrogen and phosphorus from land use activities. Excess 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 (Cai et al. 2011). Nutrient loading can also result in eutrophication (when large phytoplankton populations decompose, releasing CO_2 and lowering pH while consuming oxygen), which can be lethal to marine life.

It is difficult to discuss trends in ocean and coastal acidification due to the relatively short duration of high-quality carbonate chemistry data in the Gulf of Maine, the earliest of which began in 2003 with the NOAA AOML Underway CO_2 program, followed by the deployment of the coastal Western Gulf of Maine Mooring in 2006 (surface only measurements located at 43.023, -70.542). In 2007, carbon cruises looking at the full water column along select transects commenced and have taken place every 3-4 years since, supplemented by yearly seasonal NOAA ECOMON surveys, as well as individual studies in coastal waters.

Sutton et al., (2016) performed an analysis of several buoyed assets in the region and, adopting assumptions about past atmospheric CO_2 values, concluded that Ω_{ar} never dropped below the critical 1.6 threshold throughout the preindustrial period. However, the threshold of Ω_{ar}=1.6 is currently exceeded in the surface waters of the Gulf 11-31% of the time from late winter to spring with peak exposure to low Ω_{ar} in February and March.

Salisbury and Jonsson (2018) determined that recent temperature and salinity changes in the Gulf of Maine (between 2005-2014) have dampened the effects of ocean acidification by causing a decadal increase in omega of 0.4 despite a pH decline of 0.018. The OA effect on Ω_{ar} is partially obscured by increased temperature and buffering by higher salinity waters entering the Gulf of Maine, and it may require up to 30 years of sustained measurements to observe a discernible OA signal in pH and up to a century to observe the OA signal in Ω_{ar} (Salisbury and Jonsson 2018).

Global and Regional Projections of Future Acidification

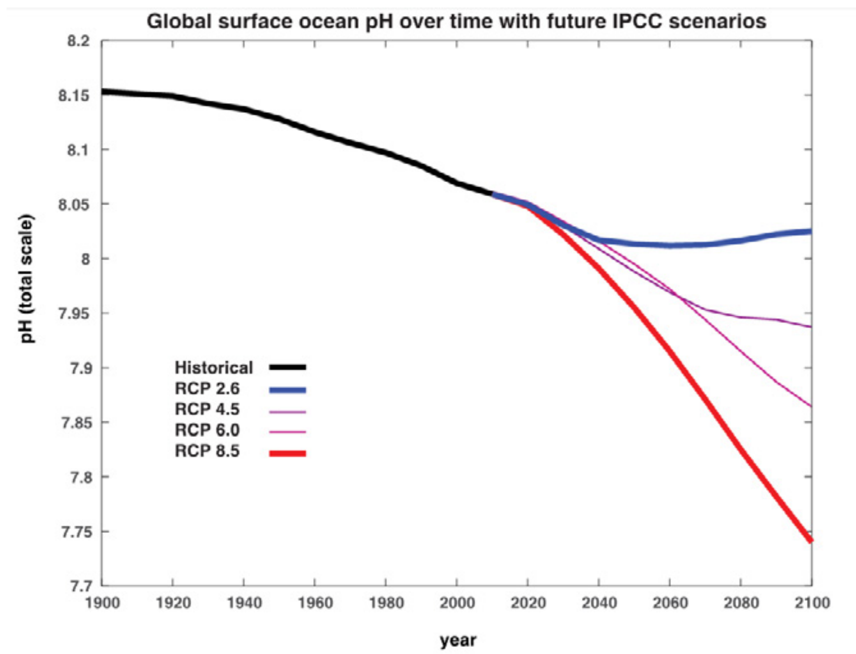


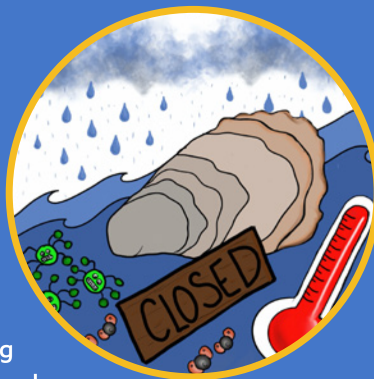
Figure 3. Globally averaged surface pH (total scale) over time with four IPCC scenarios for future conditions. Data from Jiang et al, 2020.

Earth systems models (ESMs) are used to project future conditions and are coordinated globally by the IPCC and referred to as the Coupled Model Intercomparison Project (CMIP). The latest round of projections (CMIP6), released in September of 2019, projects global surface open ocean pH values to decrease by 0.3 pH units by 2081-2100 relative to conditions in 2006-2015 under RCP8.5 (IPCC, 2019). (A fuller description of the CMIP and Relative Concentration Pathways [RCPs] can be found in the Climate chapter of this report.) For RCP2.6, these conditions will very likely be avoided this century (IPCC, 2019). The models used for CMIP6 are not high resolution (~1 degree) and can't effectively resolve local processes, such as interannual to decadal scale changes and trends in temperature and salinity caused by changing circulation patterns. The Gulf of Maine could follow a slightly different trajectory due to its unique warming and circulation.

Regional, higher resolution models are now being tested and point to less severe pH declines of about 0.1 pH units between 1991-2010 and 2041-2060 under RCP8.5. The decrease in pH is greater in the Gulf of Maine than in the Scotian Shelf and Gulf of St. Lawrence (Lavoie et al. 2019). Ω_{ar} goes below 1.5 at the surface by 2040-2060 and is already below 1.5 in the benthic environment by 2020 for aragonite and by 2060 for calcite in the southern portion of the Gulf of Maine.

Other climate-induced impacts, like increasing amounts of fresh water supplied through Arctic outflow to the north and increases in average annual rainfall and the frequency of extreme precipitation and runoff events (Rawlins et al. 2012), will exacerbate the Gulf of Maine's sensitivity to acidification. These freshening trends could more frequently result in larger corrosive river plumes. In fact, the combination of global and local drivers of acidification in the Northeast make New England's shellfisheries – including both its wild harvest fisheries and aquaculture production, and the communities that rely on them – potentially among the most vulnerable to OA in the United States (Ekstrom et al. 2015, Gledhill et al. 2015).

"Problems are the raw material for innovation" Mook Sea Farm- A model for adaptation to ocean climate change



For 35 years, Mook Sea Farm on the Damariscotta River has been supplying oyster seed to other east coast growers and market sized oysters to the U.S. half shell market. Bill Mook, founder and owner, estimates his business suffered thousands of dollars in losses due to ocean acidification for a period of several years starting in 2009. The oyster hatchery is the engine of the business. Along with the increasing frequency and intensity of rain storms, in 2009, Bill began noting a drop in pH during runoff events along with longer larval phases (sometimes an additional week or more), and in some cases larval deformities and complete losses of cohorts. Just two such extended larval phases adds up to the loss of one entire spawn, resulting in over $100,000 in lost seed sales. After conferring with oyster growers in the Pacific NW who had experienced similar problems, he started taking precautionary steps, including storing water ahead of rainfall events and raising the pH of the water used for larval culture. Mook Sea Farm was back in business, with better larval production than ever before.

Now, after partnering with UNH, Mook Sea Farm operates their own acidification monitoring equipment which allows them to track longer term changes in seawater chemistry and assess its potential impact on the farm.

New England is experiencing increasing heavy precipitation events more than any other area of the country. Over two inches of rain in 24 hours triggers closures to shellfish harvest. Mook Sea Farm has documented increased frequencies in these closures over time. Projections for continued increases in precipitation, particularly in the winter and spring, will lead to even lower saturation states, and an increasing need for adaptive strategies to successfully rear seed and work around harvest closures.

In addition to impacts from increased precipitation, there are a suite of other ocean climate stressors impacting shellfish growers. More frequent storms, combined with higher storm tides pull up moorings and entangle gear. Warmer water temperatures require immediate cooling of harvested oysters to prevent harmful bacteria from multiplying. To make the business more resilient to climate stressors, Mook Sea Farm constructed a new, land-based facility, completed in 2019, that can hold 500,000 oysters. It enables them to move oysters into a controlled environment prior to rainfall closure and shut off flow from the river. Being able to harvest during closures prevents tens of thousands of dollars in lost sales, enabling the business to maintain consistency of distribution despite environmental stressors. Mook Sea Farm was the only oyster business in Maine in 2019 that was able to harvest oysters during the week before Christmas due to flood closures.

Hatcheries will be an increasingly critical tool and need to be part of the statewide effort to understand and adapt to climate change. Not only can hatcheries augment wild fisheries and act as a test bed for understanding impacts on many other shellfish species, hatcheries can explore the genetic adaptive capacity within these populations and selectively breed for resistance to changing ocean chemistry and rising temperature. Mook Sea Farm plans to explore techniques for larval rearing of other commercially valuable species that are now completely reliant on wild set, like clams, mussels, and scallops. Enhancing opportunities for hatcheries to focus on research and testing of technology to improve shellfish production should be supported.

Impacts on Select Gulf of Maine Species

To date, studies indicate that Maine species most impacted by ocean and coastal acidification (OCA) are those that calcify, including crustaceans (e.g., lobster, crabs, shrimp), mollusks (e.g. clams, mussels, oysters, scallops, periwinkles), echinoderms (e.g., sea urchins), calcareous macroalgae and plankton. In Maine, over 80% of the landings value of harvested or grown species comes from shell-builders. A summary of impacts on species in the region appears in Gledhill et al. 2015, Supplemental Table S1. Since then, over 50 additional studies on species in the region have been published. Highlights from these studies can be found in Appendix 2 of this chapter. Below are highlights of impacts on some commercially important species.

American lobster accounted for 73% of the landed value of Maine's fisheries in 2019, making it, by far, the most critical species to Maine's marine economy. Studies to date on effects of OCA on lobster have produced varying responses at different life stages. Larval studies including up to stage IV of development found that warming had greater adverse effect than increased pCO_2 (partial pressure of carbon dioxide in seawater), with a significant interaction between temperature and pCO_2 that resulted in changes in dry mass, carapace length, swimming speed and feeding rates (Waller et al. 2017). Experiments with stage V American lobsters found increases in mortality, slower development, and increases in aerobic capacity with increasing pCO_2 (Menu-Courey et al. 2019). Similarly, McLean et al. (2018) found that increasing pCO_2 resulted in decreases in length and weight, longer intermolting periods, and more susceptibility to shell disease in juvenile lobsters. Keppel et al. (2012) also found increased days to molt and decreased carapace length in juveniles exposed to elevated pCO_2 and pH of 7.7. Juvenile lobsters showed various detrimental physiological responses when exposed to predicted end of century pH conditions (8.0 and 7.6) and acute thermal stress for 60 days, including immunosuppression and reduced cardiac performance under increased OA and temperature (Harrington and Hamlin 2019). In summary, depending on the life stage, the American lobster may respond differently to OCA and they may be more susceptible to warming temperatures in acidified conditions (e.g. Rheuban et al 2018) than to OA alone (e.g. Ries et al. 2009).

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, with early life stages typically more susceptible than juveniles and adults. This sensitivity can largely be attributed to the fact that bivalves build their larval shells from more soluble mineral forms of calcium carbonate (e.g., aragonite versus calcite), which is more readily dissolved in acidic conditions. Negative responses have been commonly obtained at $\Omega_{ar} < 2$ (see Gledhill et al. 2015). 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.

- No studies to date have been published on the response of Atlantic sea scallops to ocean acidification. This is the Northeast's second most valuable fishery, behind lobster. Preliminary data show some difference in the growth of the shell as acidity increases, but not much difference in tissue weight, indicating they may be putting their energy into tissue growth (Meseck, unpublished). Models suggest that under different emissions scenarios and management conditions, biomass could be reduced between 13-50% by 2100 (Cooley et al. 2015, Rheuban et al. 2018).

- Mussels may be inherently more vulnerable due to a thinner shell than other bivalves, and the byssal threads under high pCO_2 are weakened, decreasing individual tenacity by 40% (O'Donnell et al. 2013). However, genetic studies of two species of blue mussels sourced from the Gulf of Maine and exposed to simulated future conditions (increased temperature and acidity and decreased food supply) found positive results for mussel's adaptive capacity through an ability to change patterns of gene expression that help with heat stress and energy production (Martino et al. 2019). Further, calcification-related genes were identified and could be helpful for selective breeding aquaculture efforts (Kingston et al. 2018).

- Eastern oysters appear to be vulnerable at larval and juvenile life stages. Fortunately, hatcheries have the ability to control the environment during these stages. Under future pCO_2 scenarios, larvae exhibit decreased development, shell length and thickness, lipid content, calcification, and RNA:DNA ratios (Gobler and Talmage 2014). Juveniles exposed to pH~7.5 and pCO_2~3500 had increased mortality rates, inhibited shell and soft-body growth, and higher standard metabolic rates (Beniash et al. 2010). Adults exhibit minimal change in length or gaping behavior with OCA (Clements et al. 2018), but more research is needed on impacts on adults.

- Soft shell clams' larval settlement behavior is influenced by the acidity of sediments. 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 (Green et al. 2009, 2013).

Local Remediation of Marine Acidification

Strategies for remediating coastal acidification are under investigation. Coastal vegetated habitats (salt marshes, mangroves, seagrass beds, and kelp forests) are significantly more efficient at capturing and storing carbon (C) via photosynthesis than terrestrial ecosystems like forests (Duarte et al. 2005, McLeod et al. 2011) and can thus help reduce OCA. Maine's Ocean Acidification Commission identified strategies worthy of more research to increase capacity to mitigate, remediate and adapt to the impacts of OCA, including depositing ground shells (as a source of carbonate) or using phytoremediation (C, N, and P uptake and O_2 release during photosynthesis) to reduce acidity in areas immediately adjacent to shellfish farms or areas of wild harvest. Depositing ground shells brings with it risks of spreading disease among cultured and wild stocks and the expense of accumulating, treating, grinding, and redistributing shells diminishes utility and cost-efficiency of this approach, among other concerns as to effectiveness or ecological compatibility. To date, direct buffering of intertidal sediments with ground soft-shell clam shells in 10-ft x 10-ft field plots (2014-2016; Freeport, Maine) has not resulted in an enhancement of young-of-the-year soft-shell clams or hard clams compare to controls (preliminary data, B. Beal). However, Green et al (2013) had shown earlier that an application of aragonite can raise Ω_{ar} such that the buffered sediment enhances the settlement of tiny (plantigrade stage) soft-shell clams.

Phytoremediation via kelp (the edible brown seaweeds) aquaculture could help to raise carbonate saturation (Ω), absorb shellfish nutrient waste, elevate oxygen (O2) concentration, and even act as a secondary food source for shellfish. These optimized conditions can enhance shellfish growth, increase survival of early life stages and overall yield, and reduce time to market size in the immediate vicinity of a kelp farm even in the face of OCA. The capacity for farmed kelp to generate O_2 and capture (e.g., momentarily uptake) and remove (e.g., when harvested and before being remineralized or respired) excess CO_2, N, and P has recently been demonstrated in today's oceans (preliminary data, N. Price). This capacity is also predicted to be quite high in a future warmer, more acidic ocean (McLeod et al. 2011, Duarte et al. 2013, Lavery et al. 2013) and ample to reduce acidity, eutrophication, and hypoxia in shallow, embayed coastal ecosystems (Chung et al. 2011, Sanderson et al. 2012, Hendriks et al. 2014).

Application of phytoremediation in an aquaculture setting will require an understanding of the minimum kelp biomass required to generate a 'halo', with respect to the size and distribution of the shellfish cultivation system. As an example, sugar kelp (*Saccharina latissima*) – the most commonly farmed sea vegetable in the U.S. to date – has been grown to biofilter N, thereby reducing localized (10s of meters) eutrophication that exacerbates acidification

(Marinho et al. 2015). Recent evidence suggests that sugar kelp respond positively to experimentally raised CO_2 (Longphuirt et al. 2013) (and N. Price preliminary data) and land-based culturing practices indicate that most seaweeds are more productive at low pH levels (Flavine et al. 2013, Price et al. 2014), so C, N, and P capture rates may actually increase in the next 100 years under OCA, making this mitigation strategy even more appealing.

Similarly, seagrass beds are another example of submerged aquatic vegetation that could be significant sinks for carbon (Duarte et al. 2010). Seagrass-dominated estuaries, like those dominated by eelgrass in Maine, are thought to be able to buffer against ocean acidification in the water column (Hendriks et al. 2014).

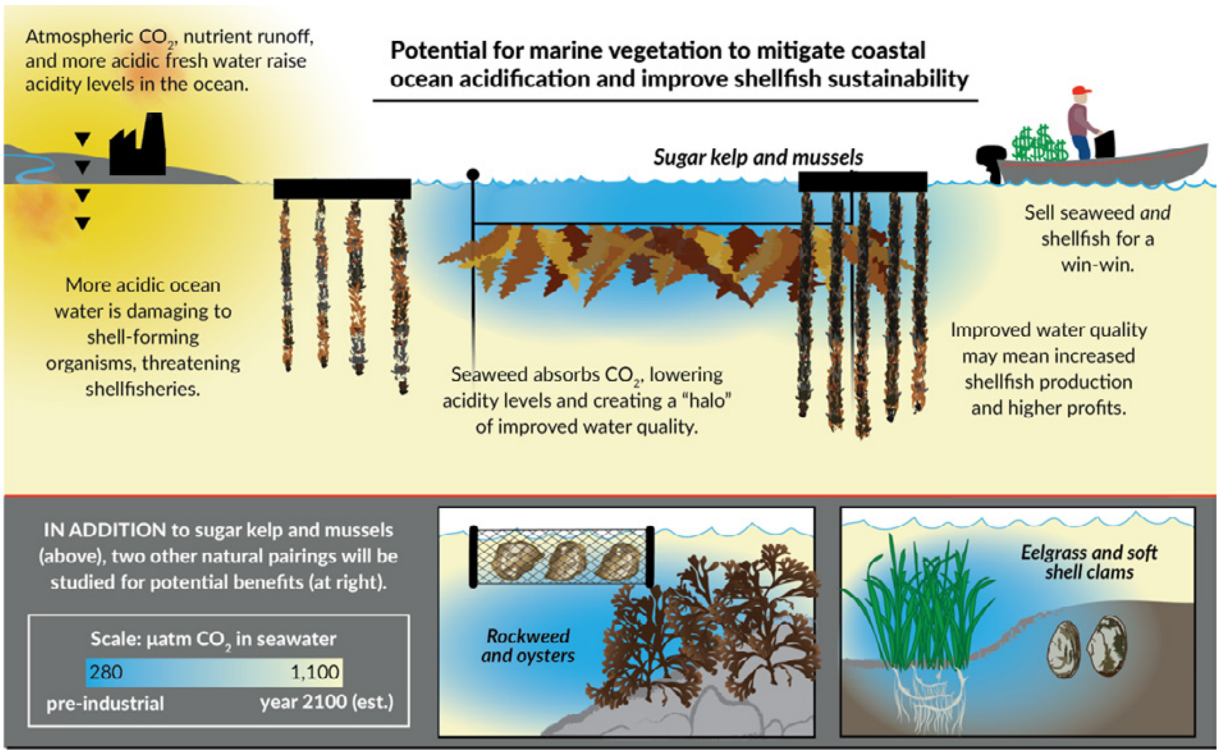


Figure 4. Conceptual diagram of phytoremediation. Diagram created by Island Institute and Bigelow Laboratory for Ocean Sciences.

Priority Information Needs

Research and Monitoring Needs-

- Monitor and establish decadal scale and longer-term trends in carbonate chemistry including hindcasting to the pre-industrial period, forecasting impending conditions at weekly to seasonal scales, and projecting long term changes in carbonate chemistry under IPCC scenarios. Ensure the use of a strategic monitoring design that permits quantifying net changes in the dominant forcing terms, including the boundary conditions (e.g., Scotian Shelf chemistry, upwelling waters, rivers). Take advantage of existing monitoring programs, establish sentinel sites with multiple carbonate chemistry parameters, including the addition of carbonate chemistry instruments on select NERACOOS buoys. When possible, pair chemical/physical monitoring alongside biological monitoring systems.

- Develop a regional scale model to feed into a finer scale, state level water quality model and use monitoring to validate the models

- Determine the relative contributions of drivers of ocean and coastal acidification in the Gulf of Maine (changing ocean circulation, air-sea exchange, river and stream discharge, upwelling, estuarine and oceanic processes including benthic exchanges, vertical mixing)

- Understand the response of critical marine species under multi-stressor (low pH, high temperature, low oxygen, limited food availability) and variable conditions (to more accurately reflect nature) and assess adaptive capacity to OCA through multi-generational studies to inform ecosystem management (see Breitburg et al. 2015)
- Determine impacts of OCA on larvae, especially for species of importance to fisheries and aquaculture to determine the developmental stage where there may be survival bottlenecks
- Study trophic interaction/indirect effects that consider how species' interactions with other species or with their environments may change as a result of OCA
- Assess OA impacts to communities and economies to incorporate OA into regional management plans and evaluate the cost and benefits of various mitigation and adaptation strategies (NOAA's New England research goal)
- Estimate biomass of sea grass, eel grass, and seaweeds in order to get a sense of blue carbon potential of the Maine Coast (funding needed for low altitude imagery used to map segments of coast for eel grass and potentially other species)
- Continue remediation research, building off of active research programs investigating potential applications of phytoremediation and buffering
- Improve our understanding of the sediment/water interface and how it impacts acidification. This is primary habitat for high value species (lobsters, scallops)
- Continued study to better understand algae blooms and their links to OCA
- Encourage the development of research hatcheries for rearing of more species and selective breeding for climate change tolerant strains
- Examine effects of OA on fecundity and reproductive success of adults of commercially-important bivalve mollusks and crustaceans

Requested Climate Council Actions-

- Establish a robust, long-term, coastal monitoring program that coordinates and supplements existing efforts. This will require reliable instrumentation and protocols, long-term funding, a data repository and management system, and the capacity to maintain and operate instrumentation and conduct meaningful data analysis. Continue to train and expand the capacity of the citizen scientist network.
- Recognize the critical roles that municipalities, fishermen, aquaculturists, and others are playing and will play to address ocean climate change, and ensure adequate opportunities to engage them in strategy development and action planning.
- Support advances in attribution science to link changes in carbonate chemistry in the Gulf of Maine to specific carbon emitters.
- Work with the Coastal and Marine Working Group and the Natural and Working Lands Working Group to develop policy recommendations to address land-based contributions to coastal acidification, including enforcing and strengthening existing regulatory tools to reduce nitrogen pollution, stormwater pollution, wastewater pollution, and other land-based inputs to ocean climate change. Existing laws and regulations should be reviewed to identify ways to reduce the causes and impacts of climate change, including introducing new laws

and regulations as needed. For example, excess nitrogen is delivered to our marine waters through stormwater runoff, point source discharges, and atmospheric deposition. Nitrogen pollution exacerbates coastal acidification and has other negative impacts on marine habitats and species. The State has existing regulatory tools that might be further employed to reduce nitrogen pollution, and those tools should be identified, amended where needed, and applied.

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APPENDIX 1

Key Resources:

- O'Chang Animated Comic on Ocean and Coastal Acidification in Maine- https://www.youtube.com/watch?v=ZimEBFw1Q7c
- Gulf of Maine 2050 Ocean and Coastal Acidification synthesis paper- https://www.gulfofmaine2050.org/wp-content/uploads/2019/11/Gulf-of-Maine-2050-Scientific-Scenario_Coastal-and-Ocean-Acidification.pdf
- Maine Ocean Acidification Commission Report- https://digitalmaine.com/opla_docs/145/
- Maine Ocean and Coastal Acidification Partnership (MOCA) report to the Maine Climate Council- https://seagrant.umaine.edu/wp-content/uploads/sites/467/2019/11/MOCA-Action-Plan-2019.pdf
- Supporting Materials for MOCA Action Plan (includes state of policy, outreach/education landscape)- https://seagrant.umaine.edu/wp-content/uploads/sites/467/2020/02/2020-moca-report.pdf
- The Northeast Coastal Acidification Network- www.NECAN.org
- Visualizing Ocean & Coastal Acidification Locally-http://www.vocalnewengland.info
- International Alliance to Combat Ocean Acidification- The State of Maine is a member- www.oaalliance.org

APPENDIX 2

Updated Organismal Responses

Tables adapted from Siedlecki, S. A., Salisbury, J. , Gledhill, D.K. , Bastidas, C., Meseck, S. , McGarry, K., Hunt, C. W., Alexander, M., Lavoie, D., Wang, Z. A., Scott, J., Brady, D. C., Milsna, I., Azetsu-Scott, K., Liberti, C. M., Melrose, D. C., White, M., Pershing, A., Vandemark, D., Townsend, D. W., Chen, C., Mook, W. & Morrison, R. (in review). Projecting ocean acidification impacts for the Gulf of Maine to 2050: New tools and expectations. *Elementa: Science of the Anthropocene*, ELEMENTA-D-20-00062

Common and Scientific Name	pCO_2 (ppm)	pH	ΩC, ΩA	Exposure Period	Life Stage	Results, Comments, Reference
American Lobster *Homarus americanus*	486	7.95	ΩA: 1.25	60 days	**Juveniles:** 50-65 mm Carapace Length, Sub adult females	↔ hemolymph total protein ↔ hemolymph calcium ↔ hemolymph ecdysterone (20E) ↓ L-lactate concentration ↓Total Hemocyte Counts ↓ Cardiac performance Harrington and Hamlin 2019
	850	7.6	0.63			
	400	7.92 ± 0.06 (2014); 8.02 ± 0.09 (2015	ΩC:3.15 ± 0.52; 2.66 ± 0.35	90- 120 days	**Juveniles:** 4 to 6 mo post hatch	↓ growth ↑ 1st intermolt time period ↑ 2nd and 3rd intermolt time period at medium CO_2 level ↑shell disease McLean et al., 2018
	1000	7.68 ± 0.08 7.64 ± 0.08	1.57 ± 0.30; 1.48 ± 0.29			
	2000	7.40 ± 0.17 7.40 ± 0.14	0.86 ± 0.47; 0.89 ± 0.30			
	380, 16 C	8.066	ΩA: 2.14	25 days up to 32	**Larvae:** Stage I-IV	↔ with CO_2 alone; with T increases: ↑feed-ing rates, swimming speeds, longer carapace lengths, greater dry mass and ↓ survival. Waller et al., 2017
	380, 19 C	8.091	2.65			
	750, 16 C	7.886	1.62			
	750, 19 C	7.836	1.67			
	400	7.97 ± 0.02	2.028 ± 0.009 ΩA	40 days	**Larvae:** Stage IV- V	↓ survival and slower development ↑aerobic capacity Menu-Courey et al., 2019
	600	7.89 ± 0.06	1.758 ± 0.018			
	800	7.8 ± 0.10	1.467 ± 0.024			
	1000	7.73 ± 0.10	1.268 ± 0.025			
	1200	7.67 ± 0.10	1.123 ± 0.023			
	2000	7.39 ± 0.12	0.609 ± 0.013			
	3000	7.17 ± 0.11	0.382 ± 0.011			

	RCP 4.5				**Adults**	Northward shift and ~71% ↓ suitable habitat by 2100 Boavida-Portugal et al. 2018
Sea Scallop *Placopecten magellanicus*	RCP 4.5				**Adults:** ↓ biomass, 13% by 2100	CO_2 emission scenarios were combined with management and impact scenarios for a total of 256 future scenarios Rheuban et al. 2018
	RCP 8.5				>50% by 2100	
	RCP8.5 MA	S: (8.05)-7.91	ΩC: 3.35-2.65	40 years	**Various:** Model assumes ↓ recruitment and growth due to OA, and ↑ growth due to warming	Projected pH for surface (S) and deep waters (D), with initial pH values in parentheses MA = Mid- Atlantic; GB = Georges Bank ↓ harvests by 2050 under RCP 8.5 CO_2 emissions and current harvest rules Cooley et al. 2015
	RCP8.5 GB	S: (8.08)- 7.94	3.23- 2.51			
	RCP8.5 MA	D: (8.05)- 7.85	2.64- 1.99			
	RCP8.5 GB	D: (8.05)-7.89	2.80- 2.11			
Eastern oyster *Crassostrea virginica*		7		3 and 5 weeks lab; 50 days field	**Adults:** 45-90 mm in length	↔ Shell length, width or weight ↓ parasite *Polydora websteri* Clements et al. 2017
		7.5				
		8				
	400	8.47		6 days	**Larvae:** early stages	↓ mean shell length, ↓ survival ↓↑ in expression levels of four calcium binding protein genes. Richards 2017
	1000	8.32				
	1000	7.64 ± 0.04	ΩA: 0.60 ± 0.06	10 days	**Adults:** 64.1–82.4mm shell height	↔gaping A 3-day heat shock (11 to 30°C) was applied after the CO_2 exposure to measure gaping Clements et al. 2018
	1500	7.44 ± 0.02	0.38 ± 0.02			
	2500	7.30 ± 0.02	0.28 ± 0.01			
	5500	6.91 ± 0.03	0.12 ± 0.01			
	8000	6.79 ± 0.06	0.09 ± 0.01			
	400	7.98 ± 0.01	ΩA: 1.91 ± 0.07	14 days	**Juveniles:** 2.45 ± 0.41 mm; and 24.92 ± 0.89 mm	↓ Shell growth rates ↓ Tissue growth rates Adding Ulva: ↑ bivalve performance Young and Gobler 2018
	1700	7.39 ± 0.01	0.59 ± 0.02			
Atlantic sea herring *Clupea harengus*	415, 6 C	8.15		27	**Larvae:** measured at hatch, from exposed eggs	Higher T: ↑energy demand; Higher T and CO_2: ↑ larval malformations Leo et al. 2018
	1101, 6 C	7.77		27		
	408, 10 C	8.17		16		
	1050, 10 C	7.79		16		
	403, 14 C	8.18		11		
	1050, 14 C	7.78		11		

	370	8.08		34 days	**Larvae:** 34 days post hatch	↔ Swim behavior, ↓ larval growth Measured pH Maneja et al. 2015
	1800	7.44				
	4200	7.08				
	380			113 days	**Larvae:** measured at hatch, from exposed eggs	↑ survival 19% Mesocosm experiment with sea herring larvae as top predator. Sswat et al. 2018a
	760					
	400, 10 C	8.11		32 days	**Larvae:** Post hatch until stage 2c	Higher T: ↑ swimming activity, ↓survival and growth rate Higher CO_2: ↔ Larval size, growth rate and swimming activity Higher CO_2, Lower T: ↓ larval weight Measured TA and DIC. Sswat et al. 2018b
	400, 12 C					
	900, 10 C	7.81				
	900, 12 C					
Soft-shell clam *Mya arenaria*	380,10-12C	8.076	ΩA: 2.298	13 days	**Juveniles:** 1.5–2.4 cm Shell Length	↑Steamer expression at low pH. Steamer is a retrotrasposon likely involved in dissem-inated neoplasia or hemocyte leukemia in the clam. TA and DIC measure-ments Lesser et al. 2019
	380,16-18 C	8.055	ΩA: 2.455			
	560,10-12 C	7.93	ΩA: 1.822			
	560,16-18 C	7.948	ΩA: 2.202			
		6.94 ± 0.04 lab sediment		20 min up to 7 days	**Juveniles**	↓burrowing ↓dispersal pattern Clements et al. 2016
		6.82 ± 0.03 field sediment				
	1284 ± 745	7.8	ΩC: 3.88 ± 1.47	30 days	**Juveniles:** 28.48 ± 4.41 mm	↓shell weight ↓responsiveness to predators Mesocosm: clam with blue crab; pH and TA measured and others calculated. Glaspie et al. 2017
	6464±1653	7.2	ΩC: 1.18 ± 0.41			
					Juveniles: < 6mm in length	↓Mean clam abundance with ↓sediment pH and ↓sediment grain size Clements and Hunt 2018

		6.18 to 8.34 in pore-water	ΩA: 0.30 to 3.52		**Larvae**: Settlement	pH and phosphate explained 44% of bivalve community composition (8 spp). *Mya arenaria and Nucula* spp. are dominant (83-100% abundance).TA 1635- 2808; DIC 1887-2439 µmol kg−1; TA, DIC: Near-shore < far-shore site Meseck et al. 2018

Table 1. Organismal responses of commercially important nearshore Gulf of Maine species to increased ocean and coastal acidification conditions. Species are listed in order of commercial importance ($ value for 2017 and 2018 in the US alone). This is a subset of all studies performed on species from the Gulf of Maine region since the review by Gledhill et al. 2015. Responses are indicated in relation to comparisons with the lowest pCO_2 treatment condition, unless otherwise noted. Symbols and abbreviations: ↑ = Significant positive response to increased pCO_2; ↓= Significant negative response to increased pCO_2; = ↔ No significant response to increased pCO_2; ΩC = ΩCalcite; ΩA = ΩAragonite; T = Temperature; TA= Total Alkalinity; DIC = Dissolved Inorganic Carbon. Type of study: Lab Experiment (no shading), Field Experiment, Modeling. Table modified from Siedlecki et al. 2020.

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			# of studies		Life Stage			Response to Acidification			
Group	Common Name	Scientific name	OA	Multi-stressor	Egg/ Larvae	Juvenile	Adults	+	-	Ø	Reference
Crustaceans											
	Blue crab	*Callinectes sapidus*	1				1			1	(Glaspie et al. 2017)
	Green crab	*Carcinus maenas*	1				1			1	(Spangen-berg 2018)
	Artic copepod	*Calanus glacialis*	1		1					1	(Bailey et al. 2016)
	Copepod	*Calanus finmarchicus*		1	1					1	(Preziosi et al. 2017)
	Copepod	*Acartia tonsa*	1		1	1	1		1		(Cripps et al. 2014)
Mollusks											
	Blue mussel	*Mytilus edulis*	6	3	2	2	5	1	7	1	(Broszeit et al. 2016; Dickey et al. 2018; Fitzer et al. 2014a; Fitzer et al. 2014b; Fitzer et al. 2015; Lesser 2016; Ramesh et al. 2017; Ventura et al. 2016; Young & Gobler 2018)
	Hard clam	*Mercenaria mercenaria*		4	2	1	1	1	5		(Clements & Hunt 2017; Clements et al. 2016; Griffith & Gobler 2017; Miller & Waldbusser 2016; Young & Gobler 2018)
	Nut clam	*Nucula spp.*		1			1		1		(Meseck et al., 2018)
	Pteropod	*Limacina retroversa*	2	1	1		2		3		(Bergan et al. 2017; Thabet et al. 2015)
	Bay scallops	*Argopecten irradians*		2		1	1	1	1		(Griffith & Gobler 2017; Young & Gobler 2018)

Fish											
	Little skate	*Leucoraja erinacea*		3	2	1			3		(Di Santo 2015, 2016, 2019)
	Skate	*Rostroraja eglanteria*		1			1		1		(Schwieter-man et al. 2019)
	Thorny Skate	*Amblyraja radiata*		1			1		1		(Schwieter-man et al. 2019)
	Inland Silver-side	*Menidia beryllina*		1	1				1		(Gobler et al. 2018)
	Sheepshead minnow	*Cyprinodon variegatus*		1	1				1		(Gobler et al. 2018)
	Smooth dogfish	*Mustelus canis*	1				1		1		(Dixson et al. 2015)
	Scup	*Stenotomus chrysops*	1			1				1	(Perry et al. 2015)
Echinoderms											
	Seastar	*Asterias rubens*	1				1			1	(McCarthy et al. 2020)
Polychaetes											
	Worms	*Hediste diver-sicolor*	1	1			2		2		(Freitas et al. 2017; Freitas et al. 2016)
	Worm	*Alitta virens*		1						1	(Nielson et al. 2019)
	Worm	*Hydroides elegans*	1	1			2	1	1		(Li et al. 2016; Meng et al. 2019)
Macroalgae											
	Kelp	*Undaria pinnatifida*	1					1			(Leal et al. 2017)
	Sea lettuce	*Ulva spp.*		2				2			(Young & Gobler 2016, 2018)
		Ulva lactuca	1					1			(Chen et al. 2019)
		Gracilaria tikvahiae		1				1			(Young & Gobler 2016)
		Pyropia leucosticta	1					1			(Chen et al. 2019)
Coralline algae	Rhodophyta	*Lithotham-nion glaciale*	2				2		2		(Ragazzola et al. 2012; Ragazzola et al. 2016)
		Lithotham-nion coralli-oides		2			2		2		(Legrand et al. 2017, 2019)
Protists											
	Foraminifera	*Globobulimia turgida*		1						1	(Wit et al. 2016)

Phytoplankton											
	Coccolithophore	*Emiliania huxleyi*	1	1				2			(Jin et al. 2015; Schlüter 2016)
	Dinoflagellates	*Alexandrium catenella*		1					1		(Seto et al. 2019)
		Scrippsiella sp.		1				1			(Seto et al. 2019)
		Karenia mikimotoi		2						2	(Seto et al. 2019; Wang et al. 2019)
Mesocosms											
	Phytoplankton			1				1	1		(Schulz et al. 2017)
	Copepod			1					1		(Vehmaa et al. 2016)
Marine Ecosystem Models											
	Fish, Sharks, protected species, invertebrates, plankton		1						1		(Fay et al. 2017)
	Lobster, snow crabs, shrimp, scallops, clams, mussels, oysters		1						1		(Wilson et al. 2020)
	Harmful Algal Bloom			1				1			(Glibert 2020; Raven et al. 2020; Tester et al. 2020)
Evolutionary/Adaptive experiments											
	Blue mussel	*Mytilus edulis*	2		2			1	1		(Kong et al. 2019; Thomsen et al. 2017)
	Worm	*Hydroides elegans*	1				1			1	(Lane et al. 2015)
	Copepod	*Acartia tonsa*	2			2			1	1	(Aguilera et al. 2016; Langer et al. 2019)
	Seastar	*Asterias rubens*		1			1		1		(Hu et al. 2018)

Table 2. A review of the biological studies on organismal responses of other Gulf of Maine species to increased ocean and coastal acidification conditions since the review by Gledhill et al. 2015.

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MARINE ECOSYSTEMS

HIGHLIGHTS

Large areas of the Gulf of Maine are changing rapidly with respect to the assemblage of species. The trend appears to be going in a direction of more temperate and fewer subarctic species, which presents challenges and opportunities for marine resource management and ecosystem function.

Ocean warming has played a key role in distributions of commercial and noncommercial species shifting northwards along the Maine coast, as well as contributing to an ever-increasing suite of non-native species invading from the south that exacerbate losses of native marine organisms through predation, competition and other biotic factors.

Maine people depend on marine resources, ecotourism, and maritime industries, so changes cascade well beyond the limits of the high tide mark. Market analyses for the developing shellfish and seaweed aquaculture industries point to potential for market growth, with groups like FOCUS Maine predicting 5,800–17,400 new jobs and $230–$800M in additional net exports from the aquaculture sector alone by 2025. Besides an economic dependence, Maine's very identity is inexorably linked to its living shoreline.

Most climate impact studies have considered warming, ocean acidification, or sea level rise in isolation. The interactive effects of these processes on coastal ecosystems is not known and it is possible that they may interact in unexpected ways.

Climate-driven thermogeographic changes create challenges for traditional place-based and population equilibrium-based management of marine ecosystems, fisheries and aquaculture. Amid such rapidly changing conditions, marine species populations are unlikely to achieve equilibrium with the environment's carrying capacity, challenging the concept of maximum sustainable yield so central to fishery management.

Reducing greenhouse gas emissions associated with marine resource use and quantifying and enhancing "blue carbon" potential (from submerged aquatic vegetation like coastal wetlands, marshes, and seaweed beds and farms) and related volunteer carbon and nitrogen markets offer opportunities to reach carbon neutrality while maintaining social and economic resilience.

DISCUSSION

Maine's marine ecosystems may be particularly vulnerable to climate-driven change for at least two reasons. First, coastal Maine is one of the world's most species-poor marine ecosystems (Frank et al. 2007, Estes et al. 2013). Second, the bathymetrically isolated region is thermally, chemically, and physically unique, owing in large part to the confluence of the cold Labrador Current and warm Gulf Stream off over the broad shelf waters of the Gulf of Maine. The Gulf of Maine has a high annual range and relatively cold temperatures, low buffering capacity against changing acidity (Gledhill et al. 2015), and some of the most complex coastlines and watersheds in the US. The structure and functioning of Maine's marine ecosystem are becoming increasingly dynamic and unpredictable as a result of the direct and indirect effects of climate change.

Maine people depend on marine resources, ecotourism, and maritime industries, so changes cascade well beyond the limits of the high tide mark. An overview of the current fisheries, aquaculture, and maritime tourism markets is available in the Economy chapter. Market analyses for the developing shellfish (GMRI shellfish report, CEI sea scallop report) and edible seaweed aquaculture (Island Institute report) industries also point to potential for market growth, with groups like FOCUS Maine predicting 5,800–17,400 new jobs and $230–$800M in additional net exports from the aquaculture sector alone by 2025. Besides an economic dependence, Maine's very identity is inexorably linked to its living shoreline.

Maine people depend on marine resources, ecotourism, and maritime industries, so changes cascade well beyond the limits of the high tide mark.

Arguably, temperature is the single most important driver of the distribution, abundance and diversity of marine organisms (Hedgpeth 1957, Adey and Steneck 2001). Globally, warming oceans can have both direct effects on species physiology and indirect effects on the species assemblage, species interactions, and ecosystem function and services from marine systems (Dutkiewicz et al., 2013; Levin, 2018; Carozza et al., 2019). Rising seawater temperatures increase metabolism, with a cascade of effects on mortality, reproduction, growth rates (Lemoine and Burkepile, 2012) and distributions and abundance of larvae, juveniles, and adult organisms (Steneck and Wahle, 2013; MacKenzie and Tarnowski, 2018; Mao et al., 2019). As oceans warm, marine biogeographies shift poleward; however, local extinctions of some species may occur (Valentine 1968).

Climate warming affects the distribution and productivity of wild capture fisheries and is well-documented on a global scale (Pinsky et al. 2013, Hare et al. 2016, Free et al. 2019). As species keep pace with their moving thermal niche, sub-Arctic and boreal species are disappearing from the Gulf of Maine's traditional fishing grounds while temperate species from the south invade. Shifts and range extensions in species distributions can bring lucrative fisheries up the coastline, as has happened for Maine's American lobster (Steneck and Wahle 2013, Le Bris et al. 2018, Goode et al. 2019, see Appendix) (Fig. 1), or open the invasion windows (Stachowicz et al. 2002) of harmful species such as green crabs, Asian shore crabs, tunicates, and invasive seaweed (Compton et al. 2010, Stephenson et al. 2009, Newton et al. 2013, respectively; see Appendix). Climate-driven thermogeographic changes create challenges for traditional place-based and population equilibrium-based management of marine ecosystems, fisheries and aquaculture (Vannuccini et al. 2018). Amid such rapidly changing conditions, marine species populations are unlikely to achieve equilibrium with the environment's carrying capacity, challenging the concept of maximum sustainable yield so central to fishery management (Larkin 1977).

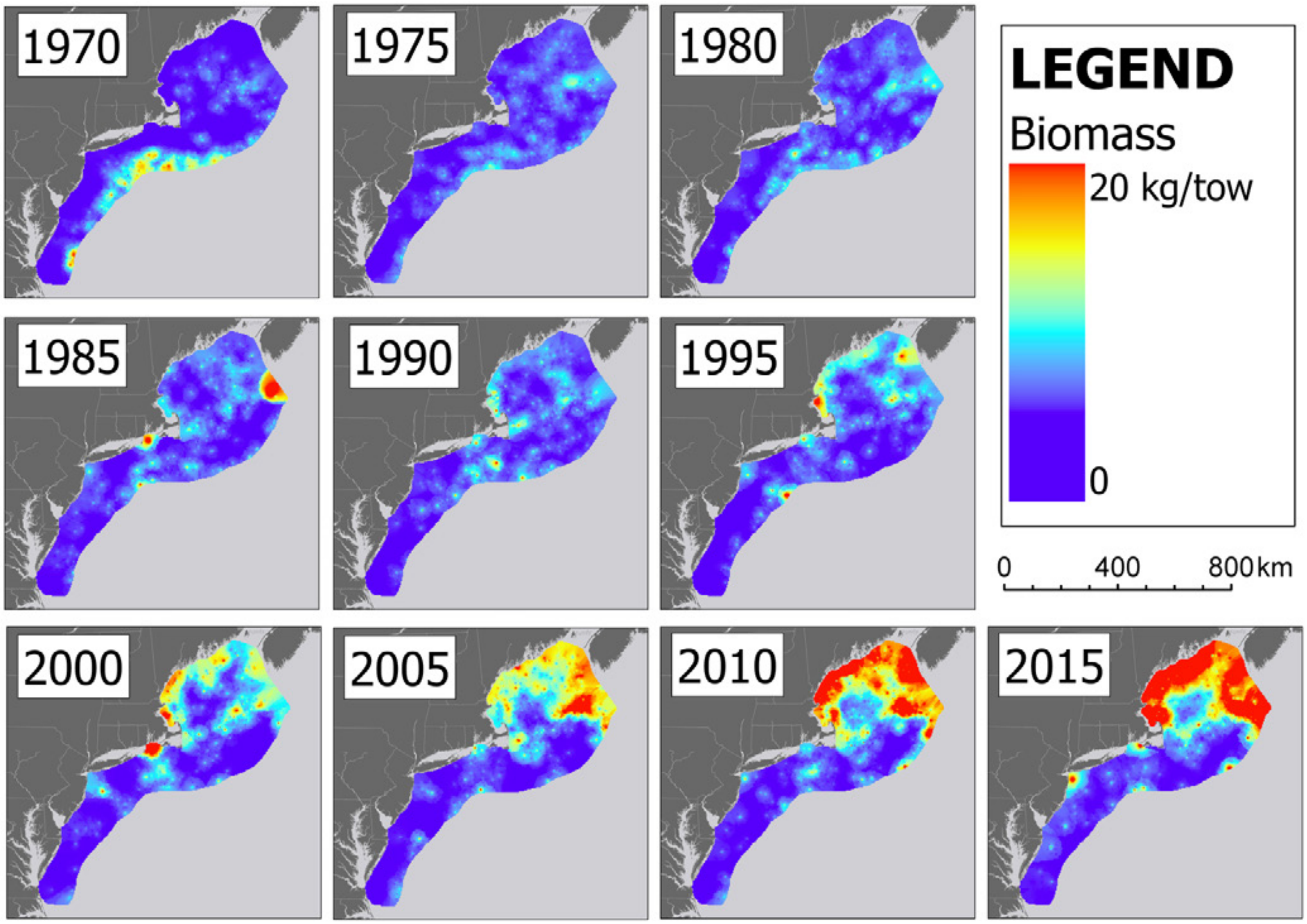

Figure 1. Changing fortunes of the American lobster, Homarus americanus, fishery. Decadal northward shift in the distribution of lobster in NOAA trawl surveys 1970-2015. Images courtesy M. Pinsky; NOAA OceanAdapt (2016). From Wahle et al. (2020). In a warming ocean the northward shift in lobster resulted from the collapse of populations in coastal southern New England due to thermally stressful summers and disease, just as historically cooler areas in the northeastern Gulf of Maine became more favorable to larval settlement. This led to a net boom in the lobster fishery that elevated it to its current status as the single most valuable fishery in the United States. The boom was likely reinforced by the depletion of predatory ground fish over the same period.

Aquaculture revenues have more than tripled in Maine (Maine Aquaculture Economic Impact Report) in the past decade. Aquaculture represents a viable and sustainable mechanism for diversification away from a single species wild-capture fishery for Maine. While land-based hatcheries and recirculating aquaculture systems are relatively protected from the vagaries of oceanic conditions (e.g., incoming seawater can be cooled, buffered against acidification, and filtered for harmful algae, microbes, or inadvertent nutrient loading), open ocean cultivation systems are not. Coastal and ocean acidification will continue to limit bivalve production, particularly for shellfish aquaculture that relies on wild 'seed sets', or natural recruitment of larval forms to establish the next generation (see the Ocean Acidification chapter in this report for more details).

Changing thermal regimes similary will impact aquaculture. Even for shellfish hatcheries where environmental conditions are highly regulated, the cooler wetter springs and late phytoplankton blooms Maine has experienced can delay the transport of juvenile stages to farms. Other seasonal events delayed by late spring warming or late fall cooling, such as the timing of reproduction in rockweed and kelp, also impacts the seaweed aquaculture and wild harvest industries as it does wild populations (Staudinger et al. 2019). Ice scouring can impact operations of over-wintering species (e.g., seaweeds, mussels, scallops).

Changing precipitation and storm patterns paired with nutrient run-off are the likely culprits behind toxic harmful algae blooms and cause shellfishery closures even if blooms are not occurring, thus impacting the aquaculture industry (see the Ocean Acidification chapter in this report for a case study of these impacts from Mook Sea Farms). Aquaculturists may find the need to invest in re-engineering rafting, caging, and long-line rearing techniques as the combination of sea level rise and more frequent, intense storms damage gear. However, some of the financial costs of investments in various climate change mitigation strategies may be initially offset by increased values of Maine shellfish and seaweed commodities as a result of southern states losing productivity at those species' southern range limits.

For more than two decades the scientific community has recognized the impact of ocean warming on the global increase in opportunistic marine diseases (Harvell et al. 1999, Tracy et al. 2019). More recently, it has been recognized that changes in seawater acidity and precipitation and storm patterns shift the host-pathogen-environment equilibrium (Burge et al. 2014). Stressful environmental conditions compromise the resistance of marine organisms to pathogens, and species range shifts can bring pathogens into contact with previously unexposed hosts. Because human activities can accelerate transport of pathogens to vulnerable host populations, it is especially important for Maine to take a vigilant stance to monitor the prevalence of marine diseases among its wild-caught, farmed, and native marine species.

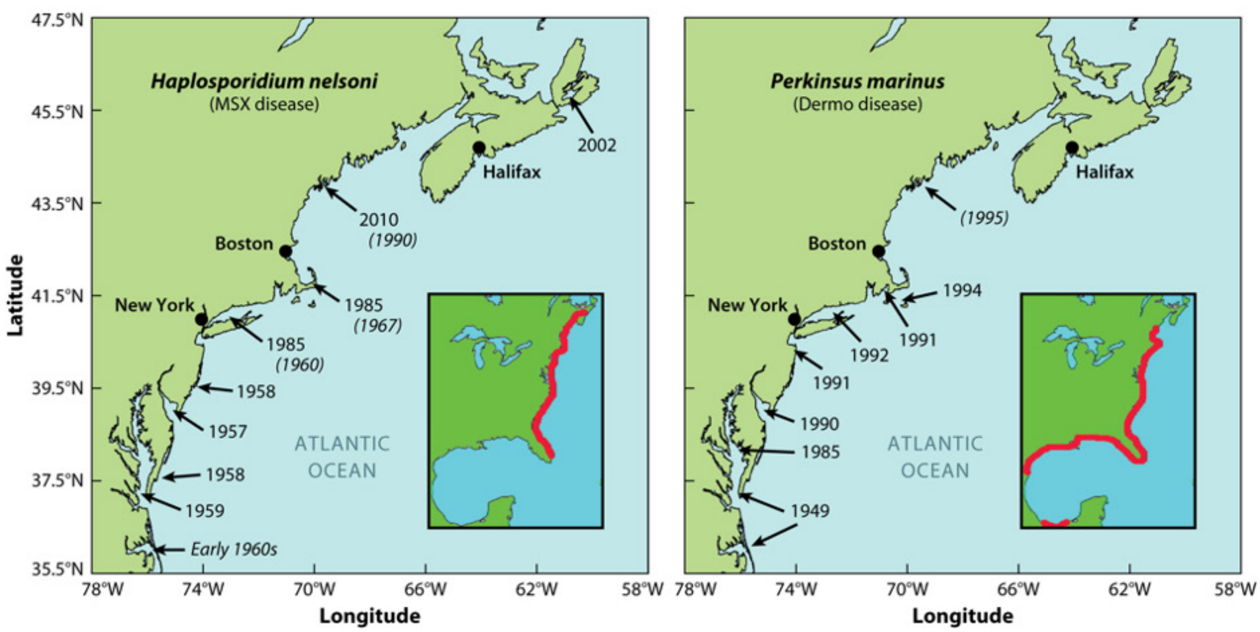

Figure 2. Range extension of oyster disease outbreaks in the northeastern United States and Canada. Years of first reported mortality are shown in roman type; when different, years in which the pathogen was first reported are shown in italic. No mortality has been associated with the northernmost report of *Perkinsus marinus* (in Maine, United States). The northward extension of P. marinus (Dermo disease) epizootics (outbreaks of animal disease) coincided with a pronounced winter warming period beginning in the mid-1980s, and range extension were especially pronounced between 1990 and 1992, when disease outbreaks occurred over a 500-km range from Delaware Bay, New Jersey, to southern Massachusetts. The period between 1989 and 1995 was also marked by consistently positive North Atlantic Oscillation anomalies. Insets show the parasites' entire ranges, including everywhere they have been reported. Figure from Burge et al. 2014

Documented epizootics (outbreaks of animal disease) in Maine and the Northeast region include lobster shell disease, a variety of bivalve diseases, and some marine mammal infections (Sanderson & Alexander 2020). Two diseases – MSX (*Haplosporidium nelsoni*) and Dermo (*Perkinsus marinus*) – that can cause mortality in oysters have become more prevalent in the Gulf of Maine as ocean temperatures have warmed (Marquis et al. 2015, Robledo et al. 2018). While oyster aquaculturists can use broodstock that is presumably resistant to disease, wild populations aren't protected. After more than 20 years of study, the lobster shell disease epizootic in New England remains a conundrum. While the relationship between shell disease and warmer temperatures is well documented and predictable, a full understanding of the epidemiology of the disease remains elusive (Glenn & Paugh. 2006, Castro et al. 2012). Initiated by a bacterial infection causing pitting of the surface of the exoskeleton, more severe cases are typically associated with secondary infections that interfere with the molt cycle, cause blindness, and eventual death (Cawthorn 2011). Since the late 1990s the disease has spread from south of Cape Cod into the southwestern Gulf of Maine and into Maine waters (Reardon et al. 2018). While some 30-40% of lobsters in southern New England are infected with the disease, to date Maine remains relatively unscathed with prevalence levels of only a few percent. Still, important questions remain about how contagious the disease is and how to prevent and treat it.

The majority of published climate change studies relevant to Maine's marine ecosystems focus on temperature effects. Fewer ocean acidification ("OA") or sea level rise studies have been conducted, but those that have found considerable variability in impacts that range from beneficial for some submerged aquatic vegetation to corrosive for certain marine 'calcifiers' (Gledhill et al. 2015; see Ocean Acidification chapter in this report for a more thorough review). Increases in the spring and fall precipitation (rain and snow) event frequency and intensity in Maine has also influenced functioning of the marine ecosystem. The freshening not only contributes to coastal acidification ("OCA") by lowering seawater pH, but also has demonstrably changed the distribution, abundance, and timing of algae blooms in the Gulf of Maine (Record et al. 2019), presumably by altering nutrient loading and turbidity along the coast through shifts in seasonality of export of dissolved organic carbon and matter from land to sea (Balch et al. 2016, Huntington et al. 2016). The consequences are overall reduced primary productivity in the water column (Balch et al. 2012) and the appearance of harmful algal species that may be toxic (e.g., *Karenia mikimotoi* and *Pseudo-nitzschia australis*, Clark et al. 2019) or a nuisance (macroalgae blooms in Casco Bay) in the last several years. Either impedes productivity and sales in the shellfish industry.

Changes at the base of the foodweb driven by these multiplicative factors telescope up to indirect effects on other marine species. Recent correlative research suggests climate related declines in the abundance of the energy rich, planktonic copepod *Calanus finmarchicus* may not only affect herring, sea birds, and right whales (Record et al. 2019), but may also explain recent declines in the survival and settlement of larval lobster to coastal nurseries (Carloni et al. 2018). Indeed, to truly understand the full impact of a changing climate on Maine's all-important lobster resource will require a comprehensive analysis starting at the base of the food web.

Description of Priority Information Needs

1. Food web structure and dynamics for Maine

    a. Monitor for invasive species that are detrimental to ecosystem function and/or have commercial potential

    b. Develop predictive models and warning systems for marine harmful algal blooms (HABs), thermal anomalies, and precipitation andacidification events that are accessible to resource managers and fisheries stakeholders

    c. Monitor water quality and manage, particularly in areas identified as vulnerable and/or that support wild capture and aquaculture fisheries

    d. Pair biological monitoring with physicochemical parameters at sentinel sites, particularly for the base of the food web that supports all fisheries

Sustainable fisheries management strategies need to reflect and react to the complexity and non-linearity of the marine ecosystem response to changing oceans and the rapid rate of warming in the Gulf of Maine. Traditional approaches of managing a particular fishery for maximal sustainable yield will become increasingly challenging as the population dynamics become less predictable and rates of emigration and immigration of competing, predatory, or pathogenic species also fluctuate. Ecosystem based management (EBM) practices rely on complex food web models that integrate these species interactions and feedback loops, capturing the inherent complexity of a dynamic marine system (Levin and Lubchenco 2008). EBM can be applied to both wild-capture and aquaculture fisheries, and objectives to strengthen ecosystem function to support surrounding wildlife can also be identified in the management plan (Ruckleshaus et al. 2008).

To facilitate and apply this management approach, Maine needs a robust and updated food-web model (Overholtz and Link 2009, Heymans et al. 2016) routinely validated with comprehensive biological monitoring, particularly for the base of the food web (e.g., Fig. 3). For example, an early mass-balanced Ecopath-foodweb model illustrated the positive impact of depleting predatory groundfish on the Gulf of Maine lobster stock over the two decades from the 1980s through the 1990s (Zhang and Chen 2007). Other machine-learning based modeling tools can incorporate these data sets with physico-chemical monitoring time series to develop predictions under various climate scenarios, giving the working waterfront practitioners decision tools about where and when to invest in an emergent fishery, to pull resources from a potentially floundering one, or to take action to avoid the economic hardship brought by harmful algal blooms (HABs) and disrupted production. Investment into water quality management programs could help mitigate coastal acidification and possibly HABs. But this approach will only be successful if current volunteer and civic science programs are augmented by cooperative testing programs and facilities across state programs, academic institutions, wastewater management facilities, and stakeholders.

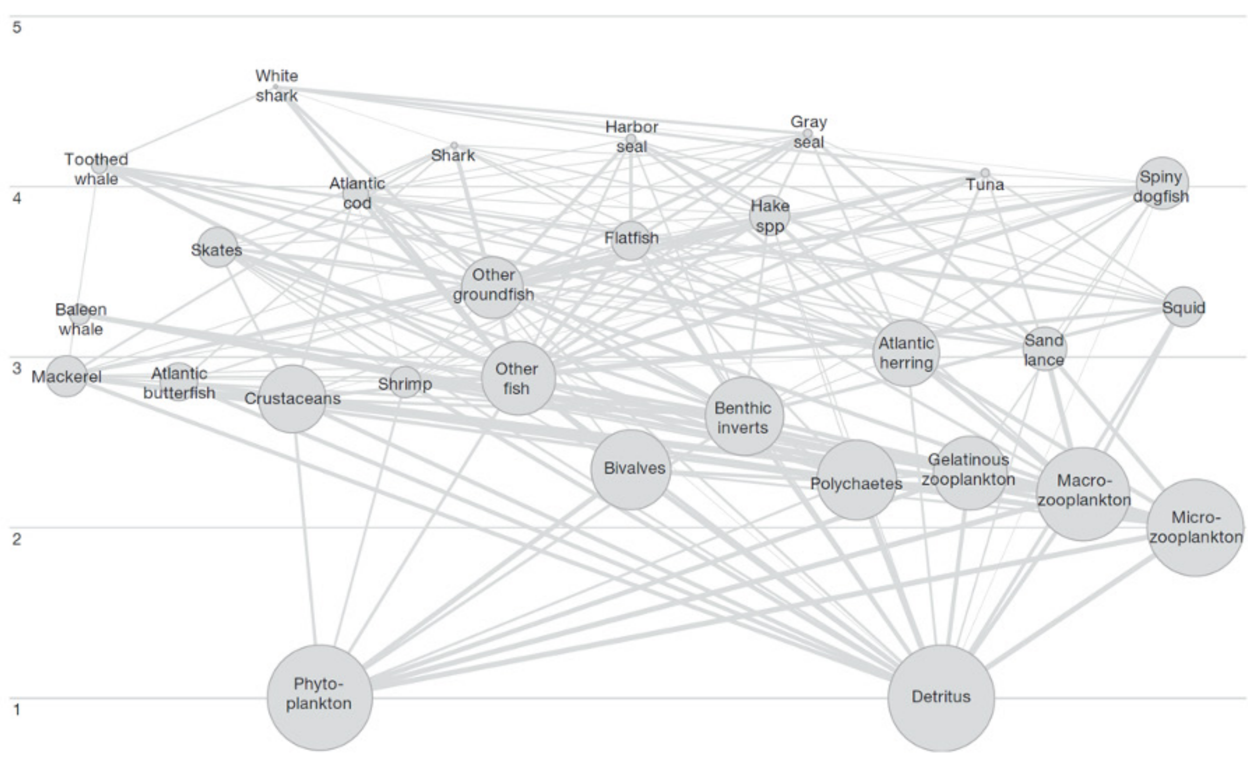

Figure 3 Gulf of Maine balanced 2014 baseline food web model. The size of nodes represents relative biomass of each species group. The thickness of lines represents relative flow of energy between species groups. All groups are arranged according to trophic level. Inverts: invertebrates. From Byron & Morgan 2016.

2. Understanding fisheries carbon footprint and potential for efficiencies in the supply chain lead to reductions in GHG emissions

    a. Conduct cradle to grave life cycle assessment for wild-capture and aquaculture fisheries including energy demands to harvest and distribute, process and package

    b. Compare fisheries footprint to other commodities and energy demands in Maine

    c. Identify socially and economically viable strategies to meaningfully reduced fisheries carbon footprint

Information needs for quantifying the carbon footprint of fisheries are vast and will continue to present challenges, particularly as the identity of species of interest will change along with climate. Further, as the recirculating land-based and coastal or offshore aquaculture industries develop and becomes more vertically integrated in Maine, production and processing fuel demands may also increase. Any proposed changes to reduce the carbon footprint of wild capture or cultivated fisheries should be balanced with the relative impact to Maine's carbon budget and the socioeconomic impact to the working waterfront.

3. Resource management to optimize the blue carbon potential of coastal Maine *and improve* CO_2 sequestration capacity in a changing ocean

    a. Develop ground-truthed carbon capture and storage rates for submerged aquatic vegetation including seagrasses, saltmarshes, and intertidal and subtidal macroalgae

    b. Monitor for baseline standing stock biomass assessment and annual change in submerged aquatic vegetation distribution and abundance (LD559)

    c. Develop best management practices for submerged aquatic vegetation (SAV)

        i. Understand species-specific carbon stocks and deposition rates for Gulf of Maine SAVs, including seaweeds

        ii. Determine which seaweed harvest and aquaculture practices best balance resource use with carbon sequestration strategies

        iii. Identify heritable traits through selective breeding programsto assist in adaptation to warming waters for marine aquatic vegetation (and other ecologically and commercially important cultivated marine species)

        iv. Develop fine-scale mapping of sea level rise, inundation frequencies to better identify where 'refugia' exist for saltmarsh migration inland

        v. Optimize restoration strategies for eelgrass beds compromised by green crabs

The capacity for particular species of submerged aquatic vegetation to capture (e.g., momentarily uptake carbon, which may eventually be remineralized or respired) and store (e.g., sequester into roots and rhizomes and more permanently bury 'blue' carbon in marine sediments) excess CO_2 is predicted to be quite high (McLeod et al. 2011; Duarte et al. 2013; Lavery et al. 2013) and ample to reflect meaningful slowing of emissions nationwide (Fargione et al. 2018) (Fig. 4).

The tidal coast of Maine is 3,478 miles long (50 miles longer than California), much of it suitable habitat for SAV. While limited data exist for distribution and abundance of eelgrass and rockweed species and more exist for saltmarshes, these systems are extremely dynamic and those datasets out-of-date (in some cases, four decades old). Further, carbon and nitrogen uptake and storage rates are also seasonally variable and species specific. In order to evaluate the feasibility of - and to implement certification processes for – volunteer carbon and nitrogen credit markets, validated methods for location and species-specific storage rates need to be established. By filling in these critical data gaps, resource managers in Maine will be better equipped to restore SAVs where they have been lost. Policy might also be developed to preserve SAVs in the face of sea level rise and ocean warming to maximize coastal carbon sequestration now and in the coming decades. For instance, shoreline development plans could account for marsh migration or permitting processes for aquaculture leases could consider benefits of blue carbon potential. For further discussion of the blue carbon potential for Maine, refer to Appendix 3 of this section.

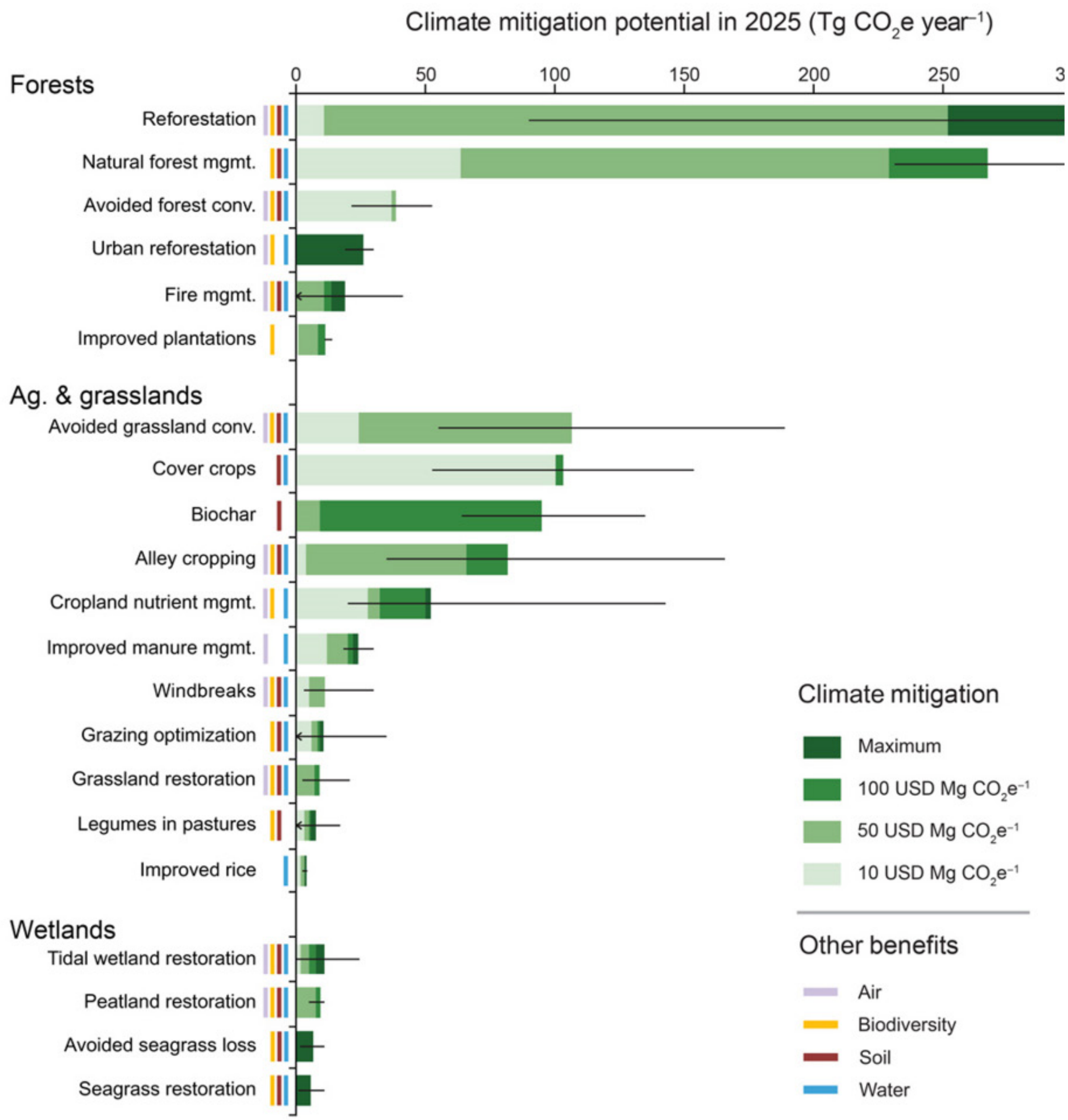

Figure 4. Climate mitigation potential of 21 natural carbon solutions (NCS) in the United States. Black lines indicate the 95% CI or reported range (see table S1). Ecosystem service benefits linked with each NCS are indicated by colored bars for air (filtration), biodiversity (habitat protection or restoration), soil (enrichment), and water (filtration and flood control). From Fargione et al. 2018.

APPENDIX 1:
The American lobster: Posterchild of a Changing Ecosystem

Climate warming affects the distribution and productivity of wild capture fisheries and is well documented on a global scale (Pinsky et al. 2013, Hare et al. 2016, Free et al. 2019). As species keep pace with their moving thermal niche in a warming ocean, many have disappeared or migrated from lower latitudes and advanced to higher latitudes, with net poleward shifts in their distribution. Rather than an outright migration, the demographic shifts represent a net spatial shift in dynamic balance of biological processes – reproduction, growth, mortality, as well as immigration and emigration (Pinsky et al. 2013, Mills et al. 2013, Caputi et al. 2013, de Lestang et al. 2015). Amid rapidly changing conditions, populations are unlikely to achieve equilibrium with the environment's carrying capacity, challenging the concept of maximum sustainable yield so central to fishery management (Larkin 1977).

In many ways, Maine's iconic American lobster, *Homarus americanus,* is a posterchild of our climate-driven marine ecosystem; however, unlike many marine fisheries that have suffered under increasing fishing pressure and ecosystem change, Maine's lobster population is one of the few that can claim to be more productive now than ever. Since the late 1980s, Maine's lobster harvest has increased six-fold from the very constant 10,000 metric tons per year landed at least as far back as the 1950s. As of 2018, 80% of the US catch came from Maine alone, and 90% from the Gulf of Maine. Together with the catch from other lobster-producing states over the past decade, the lobster fishery not only has gained status as Maine's number one export commodity, but it is also the single most valuable fishery species in the United States. It would seem that Maine's lobster fishery has benefitted dramatically from a warming climate, but that view would be short-sighted. The long-term implications of climate change for Maine's lobster industry become most evident from an ecosystem perspective encompassing its full geographic range in the western North Atlantic.

Since the late 1980s, seawater temperatures off New England and Atlantic Canada have been rising faster than most other parts of the world ocean (Pershing et al. 2015). Therefore, it is important to consider both the direct and indirect effects of warming on the biological aspects of our commercial fisheries. The American lobster thrives where summer seawater temperatures range between 12 and 20°C (Wahle et al. 2020REFs). Temperatures exceeding 20°C are physiologically stressful (Factor 1995), and those below about 12°C hamper larval development (MacKenzie 1988, Annis et al. 2007). Above and below those limits there is a critical drop in performance and survival, but within the optimum range, metabolic rates and function rise predictably with temperature. Warmer temperatures are associated with higher molting and growth rates, earlier onset of sexual maturity, and greater behavioral activity (Factor 1995), all of which have important implications for the productivity of the fishery. For example, extreme warming events like the unprecedented "ocean heatwave" of 2012 hastened the spring molt, sending a glut of newly caught lobsters from the United States to Canadian processors before the close of their own fishing season, and triggering a large price drop that caught the industry by surprise (Mills et al. 2013). Over the longer term, several decades of warming have led to measurable declines in female size at maturity in the Gulf of Maine that may have important implications for the reproductive performance of the population (Le Bris 2017).

Lobster populations in southern New England have been subject to an increasing frequency of physiologically stressful summers that have triggered mass die-offs. One such extreme event in 1999 caused a 75% collapse in Long Island Sound's lobster fishery from which it has not recovered (Pearce and Balcom 2005). Hypoxia was likely an aggravating factor in this case: just as metabolic processes demand more oxygen at warmer temperatures, seawater's capacity to hold oxygen declines, heightening the risk that lobsters will suffocate where summer temperatures become stressful.

Consequently, southern New England lobster broodstock and nurseries have largely receded from shallow embayments to cooler outer coastal and shelf waters (ASMFC 2015, Wahle et al. 2015). Recently, hypoxia events in Cape Cod Bay resulted in similar lobster mortalities. In contrast, as temperatures have more frequently risen above the 12°C barrier in the historically cooler eastern Gulf of Maine and Bay of Fundy, there have been dramatic increases in larval settlement to historically cool sectors of the coast that have translated into historic increases in the fishery landings (Maine DMR 2016, DFO Canada 2017, Goode et al. 2019, Oppenheim et al. 2019).

The more indirect effects of warming on lobster relate to how varying temperature affects the prevalence of pathogens, predators and other stressors. The sudden onset and persistence of a shell disease epizootic off coastal Rhode Island followed a series of years with above average temperatures in the late 1990s. Shell disease exacerbated the already adverse effects of warmer summers by elevating natural mortality (Glenn and Pugh 2006, Wahle et al. 2009, Le Bris et al. 2018, Reardon et al. 2018). The disease has spread northward into the Gulf of Maine with diminishing prevalence toward the cooler waters of eastern Maine, and is being monitored closely by Maine Department of Marine Resources.

Predatory fishes that consume juvenile lobster also diminish in diversity and abundance in a northward direction in parallel with declining temperatures (Wahle et al. 2013). However, as temperatures warm, southern predatory species, such as black sea bass (*Centropristis striata*) and tautog (*Tautoga onitis*), have become increasingly abundant posing both a potential risk to the lobster fishery and potential new fishing opportunities (McMahan 2017). At the same time, the northward shift of cool water predators living at the southern extreme of their range in the Gulf of Maine, such as the Atlantic cod (*Gadus morhua*), may eventually be replaced as southern species become established (Pershing et al. 2015).

Fishing down predatory groundfish has reinforced the positive effects of warming temperatures on the lobster fishery in the Gulf of Maine and Atlantic Canada. The expansion of American lobster populations is linked to the selective removal of large, predatory Atlantic cod and other members of the associated groundfish assemblage (Fig. 1; Steneck 1997, Jackson et al. 2001, Worm and Myers 2003, Steneck and Wahle 2013, Wahle et al. 2013, Boudreau et al. 2015). Archeological evidence from shell middens in coastal Maine suggests the depletion of these top predators began with the indigenous human populations over 4000 years ago, with the most precipitous declines beginning shortly after European colonization in the 1600s (Jackson et al. 2001, Bourque et al. 2008). Ecopath mass-balanced food web modeling comparing the Gulf of Maine of the 1980s to that of the 1990s, detected a shift in the trophic regime from one dominated by high-trophic-level groundfish in the 1980s, to a lower trophic level crustacean-dominated system only a decade later (Zhang and Chen 2007). In another analysis, the surge in lobster abundance in the Gulf of Maine was found to be more strongly correlated with the decline in mean predator body size than to predator biomass across several species of groundfish, underscoring the importance of predator-prey size ratio to lobster population dynamics (Wahle et al. 2013).

Although it is difficult to quantify the relative contribution of ocean warming and predator release to Maine's lobster boom over the past decades, the net effect has been a northward shift of the center of American lobster abundance by an estimated 2.5° in latitude since 1968 (Fig. 2; Pinsky et al. 2013, Le Bris et al. 2018). Scientific consensus has gathered around the hypothesis that although ocean warming is having strong adverse effects at the warmer southern end of the species' range, the same warming has had a strongly positive effect in historically cooler parts of the range (Steneck and Wahle 2013). Furthermore, recent decadal scale models suggest that Maine's long-standing enforcement of strict conservation measures protecting broodstock enabled it to capitalize on the positive demographic effects of warming climate (Le Bris et al. 2018).

By 2018, lobster comprised more than three-quarters of Maine's total fishery value, whereas the once diverse and abundant groundfish resource represents one percent (Fig. 3). Maine fishermen are now perilously dependent on the singular lobster fishery. Harvesters who have become complacent with several decades of a growing lobster fishery risk falling into a "gilded trap" (Steneck et al. 2011) in which the value of this lucrative monoculture masks the risks of depending on a single species. The resulting over capitalization in this single fishery with over-sized vessels and debt are unsustainable if the harvest falls off.

The future of Maine's lobster fishery is uncertain, as not all indicators of future trends are pointing in the same direction. Nonetheless, forecast models and landings trends to date suggest that with the possible exception of eastern Maine, the wave of highest productivity may have crested in the Gulf of Maine and is heading toward Canada (Le Bris et al. 2018, Oppenheim et al. 2019). Apart from the effects of ocean warming, the implications of ocean acidification (OA) for the lobster are also unclear and still emerging (Whiteley 2011, Gledhill et al. 2015). Recent research suggests larvae and juveniles possess a capacity to offset physiologically the challenges of high pCO_2 levels (Ries 2009, Waller et al. 2016, Niemisto 2019), but no long-term or multigenerational exposure experiments have been conducted to fully understand the long-term impact of acidification on lobster.

Maine's fisheries are now dominated by marine calcifiers – crustaceans and mollusks (Fig. 3), some of which are known to be more vulnerable to OA than others (Gledhill et al. 2015). Another poorly understood aspect of climate change on the lobster includes how climate driven changes in the planktonic food web may impact larval survival and recruitment. Recent correlative research suggests climate related declines in the abundance of the energy rich, planktonic copepod *Calanus finmarchicus* may not only affect herring, sea birds, and right whales (REFs), but may also explain recent declines in the survival and settlement of larval lobster to coastal nurseries (Carloni et al. 2018). To truly understand the full impact of a changing climate on Maine's all-important lobster resource will require a comprehensive analysis starting at the base of the food web.

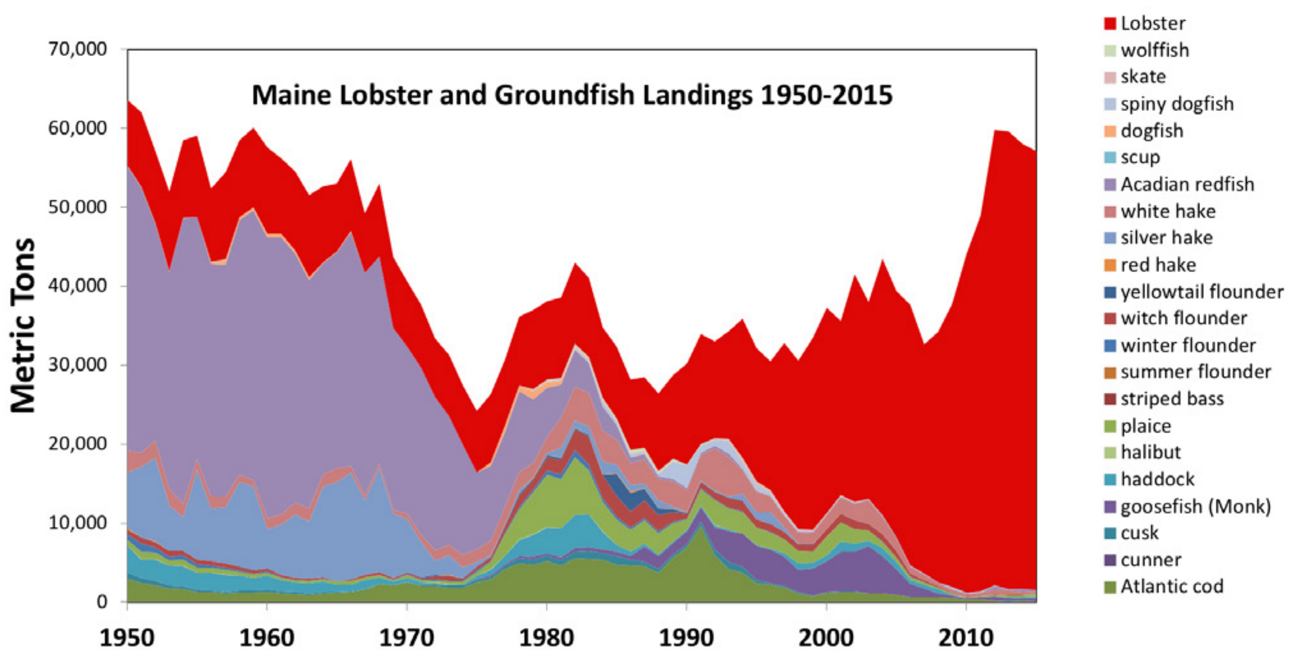

Figure 5. The growing dominance of the American lobster (red) in the wake of an increasingly depleted groundfish fishery (muted colors) in Maine, USA, from 1950 to 2015. Data from Maine Department of Marine Resources. (Figure from Wahle et al. in press).

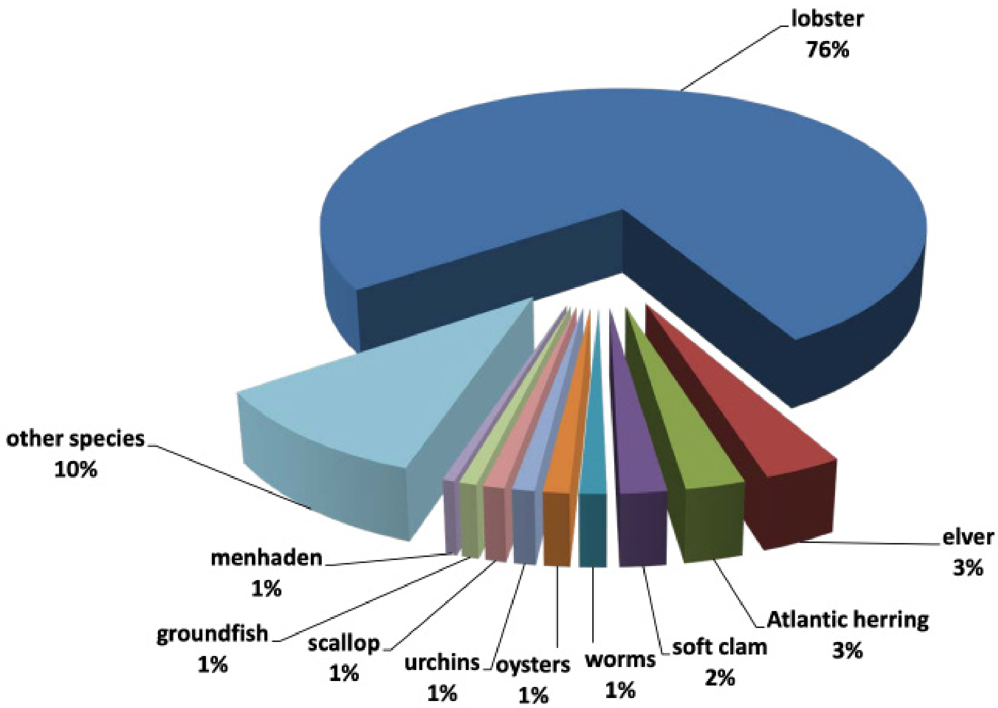

Figure 6. Maine commercial landings by ex-vessel value in 2018. Total value $637M.

APPENDIX 2:

Telescoping impacts of a climate-driven species invasion: the green crab and soft-shell clam story

Ocean warming may also increase ecosystem susceptibility to invasion among thermally-limited non-native species (e.g., Asian shore crabs in Maine, Stephenson et al., 2009). Further, Maine's low species diversity lowers "biotic resistance from native species" (Mahanes and Sorte, 2019). These and other biodiversity effects interplay at high latitudes (Goldsmit et al., 2017; Mahanes and Sorte, 2019) contributing to explosive population growth among non-native species that have already established themselves in Maine's marine ecosystems and likely will continue to play disproportionately greater roles in population and community dynamics (Ricciardi et al., 2013; Denley et al., 2019). Below, we illustrate important ecological and economic indirect effects resulting from the introduction of and climate change-driven population growth of green crabs on the coast of Maine.

Green crabs, *Carcinus maenas*, were first discovered in North America in Long Island Sound, NY in 1817 (Say, 1817), and in Maine (Casco Bay) in 1905 (Rathbun, 1905). Here, coastal commerce associated with moving live lobsters up-and-down the coast in smacks contributed to its northeastward expansion and range extension until it had colonized both hard and soft-bottom intertidal environments as far east as Lubec by 1951. During the period between 1950 and 1954, a warming anomaly in the Gulf of Maine (Fig. 1) resulted in a dramatic increase in sea surface temperature that coincided with a population explosion of green crabs. For example, during the 5-yr period from 1945-1949, winter (Jan-Mar) seawater temperatures recorded at the Bureau of Commercial Fisheries Biological Laboratory in West Boothbay Harbor averaged $1.9 \pm 0.12^{o}C$ vs. $4.8 \pm 0.11^{o}C$ from 1950-1954, nearly a 150% increase. Green crabs prefer bivalve mollusks, especially blue mussels, *Mytilus edulis*, and softshell clams, *Mya arenaria* (Ropes, 1968), and from 1950-1954, clam abundance along the coast decreased 50% compared to the previous five years.

Green crabs were abundant coastwide, but especially in Jonesport (eastern Maine) where lobster trap-sized crab traps yielded daily average catches of 400-500 individuals (Welch, 1968). In Sagadahoc Bay on Georgetown Island (midcoast Maine), population surveys of softshell clams were conducted from 1949-1953 (Glude, 1955). Typically, young-of-the-year clams were observed at densities between 10-100 ind. ft^{-2} each spring, but by the next fall, nearly all clams had disappeared. In areas where green crab foraging was deterred with fencing or screening, clam survival and growth were deemed excellent (Glude, 1955). At that time, the commercial softshell clam fishery nearly collapsed. During the period from 1945 to 1949, clam landings in Maine averaged 40.3 million pounds per year, but fell by 75% to an historic low, averaging 9.7 million pounds per year from 1955-1959. Glude (1955) commented that the future of Maine's clam industry was "... very dark. Production may continue to drop, as it did in Massachusetts, if the weather remains mild." Seawater temperatures during the 1960's and 1970's returned to pre-1950 levels (Fig. 1), green crabs became scarce along the entire coast (Welch, 1968), and, by 1977, commercial landings of softshell clams had rebounded to 38.3 million pounds, a level not seen since 1949. Today, green crab populations are undergoing similar increases as Gulf of Maine seawater temperatures have risen to levels that were observed in the early 1950s (Pershing et al., 2015). While recruitment rates today in many areas are similar to those observed in Sagadahoc Bay in the early 1950s, mortality rates on softshell clam juveniles exceed 99% due primarily to green crab attack (Beal et al., 2018). In 2017, commercial clam landings were the lowest in over 80 years (6.8 million pounds).

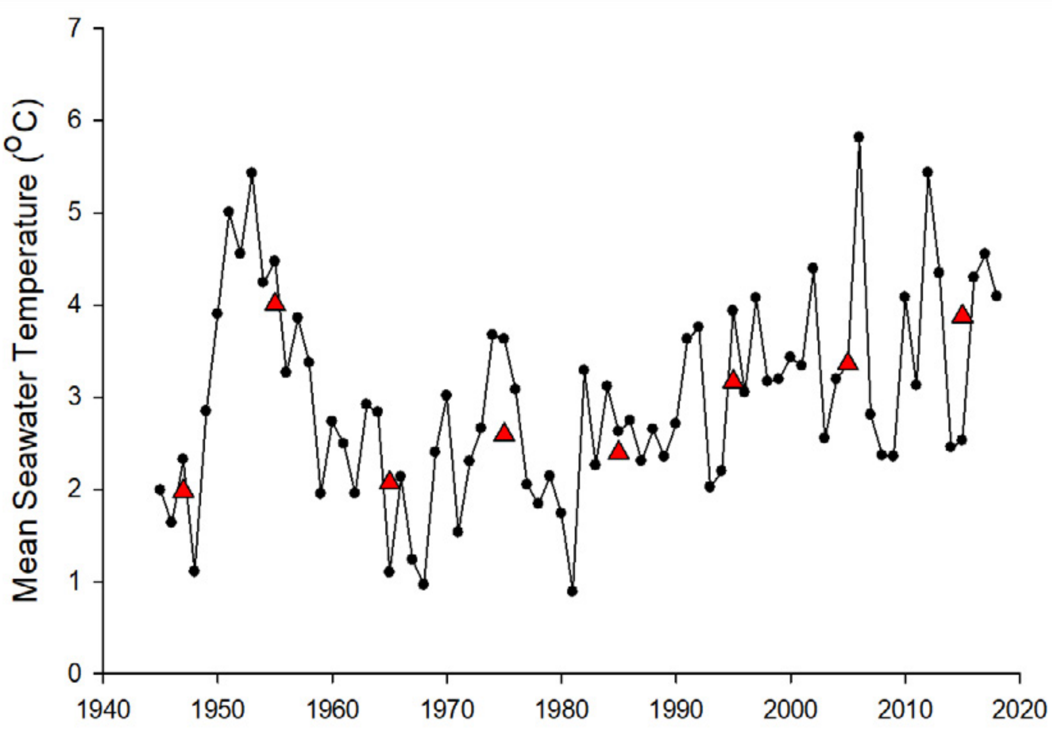

Figure 7. Mean seawater surface temperature at West Boothbay Harbor, Maine for 1 January to 31 March from 1945-2018 (black circles) and decadal means (red triangles). Data from https://www.maine.gov/dmr/science-research/weather-tides/bbhenv.html.

Of course, softshell clams are not the only species affected by high population densities of predatory green crabs (Elner, 1978; Grosholz and Ruiz, 1996). Notably, the blue mussel (*Mytilus edulis*) declined markedly following the 2012 ocean heat-wave (Mills et al., 2013). The intertidal mussel zone has largely disappeared in years since 2013 (Sorte et al., 2017 Steneck, unpublished data). No similar decline was observed for blue mussels growing on suspended ropes or on the bottom of working floats out of the reach of green crabs. Declines in the seagrass, *Zostera marina* (Davis et al., 1998; Neckles, 2015), and invertebrates including sea stars are attributed to green crab predation.

APPENDIX 3:

Maine's hidden carbon capture tool along our complex coastline: the blue carbon potential from submerged aquatic vegetation

Carbon capture rates in temperate kelp beds (1300-1800 g C $m^{-2}y^{-1}$; Mann 2000) are higher than that of seagrass beds (300-1500 g C $m^{-2}y^{-1}$; Duarte 1989). Aquaculture of kelp (brown seaweed) may be quite efficient at momentary carbon (C) uptake surrounding seaweed farms. Longer, more lasting effects of phytoremediation will require C removal from seawater at sufficient rates, via harvest of farmed or wild seaweed biomass, to prevent remineralization of C and eventual oxygen (O_2) depletion from seaweed tissue decomposition (Tang et al. 2011).

Carbon storage is a slower process, but C burial in sediments can affect the global ocean carbon cycle and thus mitigate OA on a much broader scale. Carbon burial is relatively high in seagrass beds and saltmarshes because significant biomass is allocated to roots and rhizomes in the underlying anoxic sediments which decompose relatively slowly (Duarte et al. 2010; Duarte et al. 2011), and because the grasses are effective at trapping particulate matter in the water column. Average global total carbon sequestration in seagrass beds approximates 83 g C $m^{-2}y^{-1}$ (Duarte et al. 2005), 40 to 60% of which is derived from seagrass biomass (Kennedy et al. 2010). Average global total carbon sequestration in salt marshes approximates57 g C m^{-2} yr^{-1} (recalculated from Chmura et al. 2003 and Drake et al. 2015). The remaining carbon stored in seagrass beds and saltmarshes is derived from other remote sources, some of which could have seaweed origins. Storage by seaweeds was once presumed to be negligible due to the lack of biomass in the holdfasts. However, on average 16% of seaweed biomass (that which sloughs off as the blade grows) is buried prior to remineralization (Krause-Jensen and Duarte 2016) and contributes to the total sedimentary organic pool in coastal and deep ocean systems, thereby contributing to long term carbon storage.

Most rocky shores are dominated by Maine's brown intertidal seaweeds commonly called rockweeds and bladderwracks. Subtidally kelp, red seaweeds like *Chondrus,* and filamentous species dominate the rocky bottom. Topinka et al. (1981) suggest 15 to 63 kg of rockweeds occupy each meter of coastline and productivity is estimated to be up to 7,100 kg C yr^{1} km^{-1}. There are 8,047 km of coast in Maine yielding 120,000 to over 500,000 metric tons of seaweed and 5.71 x 10^{7} kg C yr^{1} taken up. If 16% of this mass is indeed transported to and buried in the seafloor, this represents sequestration of 9.14 x 10^{6} kg C yr^{1} or ~33.5 $MtCO_2eq$ yr^{1} for the coast of Maine, which is a CO_2-sink not currently accounted for in our state's carbon budget – just by these specific intertidal brown seaweeds. Similar estimates could be done for the subtidal kelp and other seaweed, eelgrasses, and saltmarshes. For instance, Beal et al. (2004) estimate that total (intertidal and subtidal) aboveground eelgrass production in Cobscook Bay ranges from 3.3-5.3 x 10^{8} g C yr^{1}. These conservative estimates of coastal blue carbon sinks are likely an underestimate of the full potential for Maine's coast to store carbon.

Much like capture rates, carbon storage in seagrass and macroalgae beds is expected to increase under increased atmospheric CO_2 growth conditions (Jiang et al. 2010; Campbell & Fourqurean 2013; summarized in Koch et al. 2013 and Garrard & Beaumont 2014), suggesting that the phytoremediation strategy will improve in the future. However, salt marshes may become less productive (Chmura 2003) and may migrate inland as a consequence of sea level rise (see the Sea Level Rise chapter in this report).

Currently, management of marine vegetation is predicated on protecting endangered species that reside therein and critical or important habitats, but not built around maximizing blue carbon potential. Management strategies such as restoration or prevented loss of eelgrass beds and coastal development programs that leave space for migrating saltmarshes are presented by Fargione et al. (2018). Additional resource management programs that carefully assess the impact of wild-harvest of seaweed and shellfish on stimulation of primary productivity of intertidal brown seaweeds and other macroalgae could be necessary to track blue carbon. For instance, permitted wild shellfish harvest practices can negatively impact the surrounding vegetation (Neckles et al. 2005). Intertidal seaweed harvesting regulation challenging to enforce and done only with consideration of habitat conservation, not considering other ecosystem services such as net primary productivity. Marine preserves and protected areas are not currently designed to facilitate blue carbon maximization. The aquaculture permitting process does not value or reward phytoremediation services. Thus, even if phytoremediation is found to be an effective GHG mitigation strategy, venues for implementation within existing regulatory structures are scarce and require increased willingness of aquaculture business owners and policy-makers to incorporate. Geraldi et al. (2019) present myriad tools used to measure to blue carbon sequestration and voluntary markets for blue carbon that have already been developed in the European Union.

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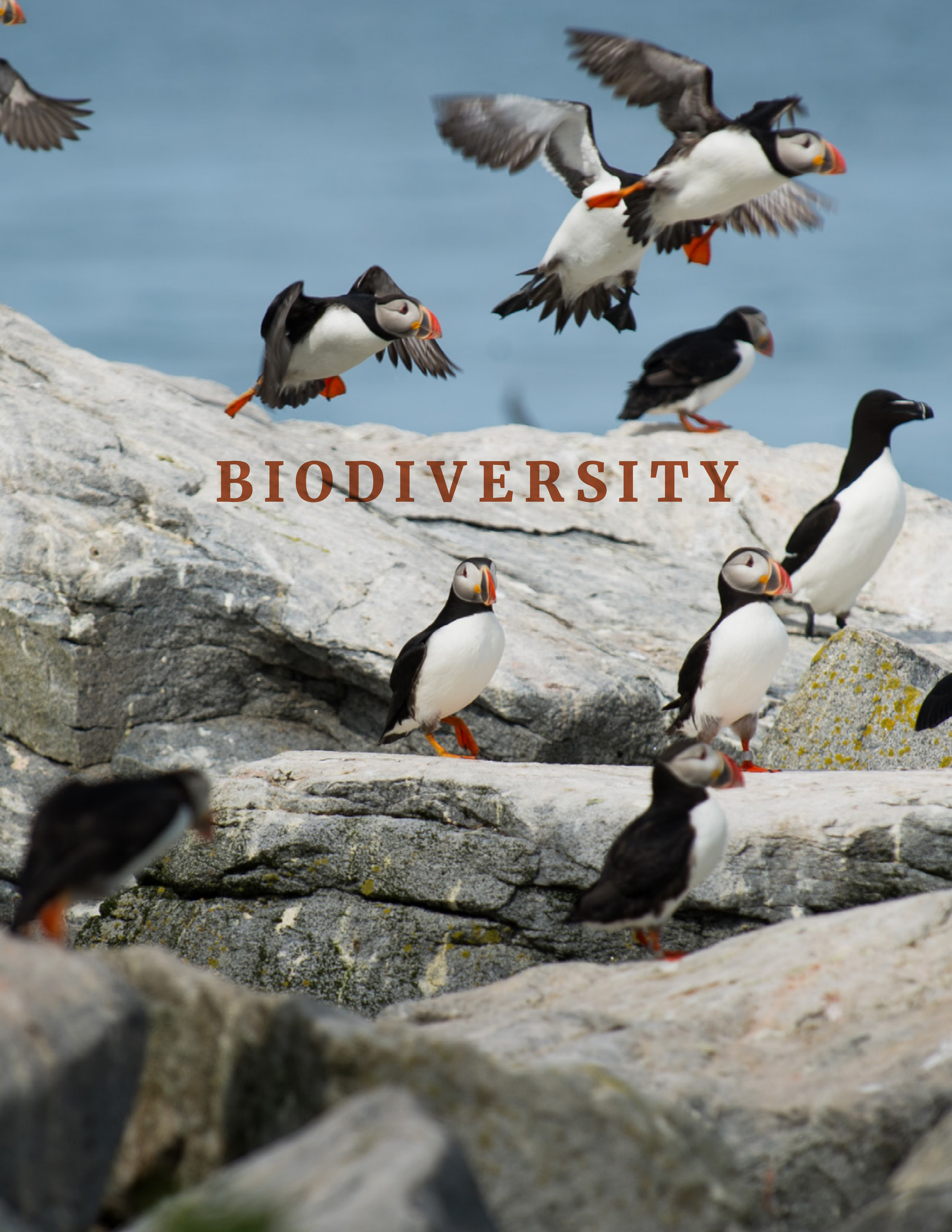
BIODIVERSITY



HIGHLIGHTS

Maine is a biodiverse ecological transition area, where temperate ecosystems characteristic of southern New England give way to northern boreal systems often associated with southern Canada. Climate change is already having dramatic effects on this biodiversity, and those impacts will likely escalate in the future.

What We Already Know

- Approximately one-third of the 442 plants and animals, 21 habitats, and Species of Greatest Conservation Need found in the state are affected by climate-change related threats, including habitat shifts and alterations, droughts, temperature extremes, and storms and flooding, and are therefore highly vulnerable to climate change. Another one-third are moderately vulnerable.

- Iconic Maine species such as furbish lousewort, moose, Canada lynx, loons, boreal chickadees, eastern brook trout, and Atlantic puffins are experiencing multiple threats as a result of climate change, including shifting winter ice cover and scouring regimes; shorter winters with less deep snow cover (resulting in mismatch of fur color and ground cover); a rapid expansion of pests (e.g., winter ticks); parasites previously only seen further south; heat stress; lack of cold water refugia; more frequent and higher flooding of tidal marshes; and changes in available prey species. Many other lesser known species face additional threats.

- Some species have already started shifting ranges north in Maine, including for example, red-bellied woodpeckers, tufted titmice, opossum, gray fox, and arctic fritillary.

What the Future Holds

- Scientists predict that 34%–58% of species will go extinct given current climate change scenarios if they are unable to disperse to new locations, while 11–33% will still go extinct even if they can disperse to future areas that are within their current climatic niche.

- The best way to maintain biodiversity is to ensure a network of biologically and geographically diverse lands that are well connected so that plants and animals can move across the landscape to find the places they need for breeding, feeding, resting, and raising their young. The specific species and habitats will change over time, with some adapting and moving more quickly than others.

- In fragmented landscapes and for species with limited mobility (for example, many lichens, wildflowers, salamanders, turtles, fish, and invertebrates), additional conservation measures may be needed to maintain species viability in a changing climate.

DISCUSSION

Maine's 2015 State Wildlife Action Plan identifies and prescribes conservation actions for Maine's 378 most at-risk fish and wildlife species (Species of Greatest Conservation Need or SGCN). Nearly one-third of these species are predicted to be affected by climate-change related threats, including habitat shifts and alterations, droughts, temperature extremes, and storms and flooding. Climate change is among the top three most ubiquitous threats across all SGCN taxonomic groups, from freshwater snails, such as the six-whorl vertigo, to marine mammals, such as the humpback whale (Appendix A). The 2015 SWAP recommends nearly 50 conservation actions to directly address climate threats to SGCN and habitats, including a statewide focus on resilient and connected landscapes to support species' opportunities to shift and adapt to a changing climate. These actions will also have other benefits such as flood control, clean drinking water, and outdoor recreation for local communities.

The 2015 SGCN list was informed, in part, by a 2014 study titled 'Climate Change and Biodiversity in Maine: Vulnerability of Habitats and Priority Species', which found 7 (or 33%) of 21 habitats and 168 (or 37%) of 442 plant and animal species are highly vulnerable to climate change (Whitman et al. 2013a) (Appendix B). An additional 171 (or 38%) plant and animal species are moderately vulnerable to impacts from climate change. Half of all SGCN mammals and state-listed Threatened or Endangered plant species are highly vulnerable to climate change. While highly vulnerable species occur in all major taxonomic groups, some of the better known of the 55 vulnerable vertebrate species include moose, Canada lynx, gray jay, Northern parula warbler, Atlantic puffin, and Eastern brook trout. These species are vulnerable to climate change because they:

- Occur at their southern range limit in Maine (e.g., Canada lynx)·
- Depend on coldwater (e.g. Eastern brook trout, brook floater) or boreal habitats (e.g., boreal chickadee)
- Breed in wetlands that are vulnerable to fluctuating water levels during nesting periods (e.g., yellow rail, least bittern)
- Are coastal or marine species affected by sea level rise, altered ocean chemistry, or changes in marine food webs (e.g., saltmarsh sparrow, Atlantic puffin, Arctic tern)
- Inhabit naturally fragmented habitats that limit dispersal (e.g., Blanding's turtle)
- Have narrow habitat requirements (e.g., Katahdin arctic butterfly)

The most vulnerable habitats include alpine and montane forest systems, peatlands, northern river shores, spruce flats and cedar lowlands. Coastal and aquatic systems are moderately vulnerable, although this is difficult to predict because of the many uncertainties surrounding changing precipitation regimes, hydrology, and potential movement of salt marshes and estuaries.

Many scientists have predicted dire declines and/or extinctions for many species around the globe. In fact, significant declines or extinctions attributed to climate change have already been documented for some species in other parts of the world such as tree frogs from the cloud forests of Costa Rica, Edith checkerspot butterfly from the Bay Area (California), American pika from the Great Basin (Western USA), and polar bears in the Arctic (Cahill et al. 2013).

Many wildlife species that are already facing steep declines face additional threats from a warming climate thus compounding other threats. Recent reports detailing dramatic declines in birds and insects attracted a lot of media attention in 2019. Rosenberg et al. (2019) documented declines in bird populations across North America — on average by 29%, or one in every four birds — across all taxonomic groups and biomes since 1970. Even greater declines are being seen in certain groups, including 74% of all grassland species, 68% percent of shorebird species, 73% of species that eat aerial insects, 64% of all eastern forest bird species, and 50% of all boreal forest species. National Audubon (Wilsey et al.,2019) predicts 64 species in Maine are highly or moderately vulnerable at 1.5°C warming, 84 species at 2.0°C, and 106 species at 3.0°C. Hallmann et al. (2017) documented a decline greater than 75% over 27 years in total flying insect biomass, with samples taken in *protected* areas (not in areas subject to direct habitat loss or significant land use changes). Lister and Garcia (2018) found declines in insect populations linked to parallel declines in insectivorous lizards, frogs, and birds in a tropical rainforest. Moose are a prominent species illustrating the compounding effects of climate change on pre-existing species threats. Like many moose populations at the southern edge of their range in North America, moose populations in western Maine and northern New Hampshire have declined over the last 5-10 years due to increased winter tick outbreaks. With increasingly warmer winters, sustained winter tick outbreaks are expected to expand northward. Reptiles and amphibian species may also suffer from compounding climate stressors. For example, wood turtles, whose habitats are already impacted by habitat fragmentation, may face additional threats to stream-side nesting areas from increased flooding and storm events.

Across all species, Cardinale et al. (2019) notes that other authors projected 34%–58% (minimum 0.8-1.7C to maximum >2.0C emissions scenarios) of species are expected to go extinct by 2050 if they are unable to disperse to new locations. Even for species that can disperse within their current climate niche, these authors predict 11-33% may still go extinct. They further note that climate-driven changes in species distributions have already begun to alter ecosystem services that impact human well-being, ecosystem health, and feedbacks that reinforce the rate of climate change. These changes include shifts in human disease, emergence of pest species of agriculture and forested ecosystems, and changes in species that are vital to food security.

Additional details from the examples above, plus case studies detailing climate change impacts on some of Maine's most iconic species (e.g., moose, Canada lynx, forest songbirds, amphibians, Atlantic puffins, and island-nesting seabirds), are provided in the Biodiversity in Maine: Additional Information section below. Examples are organized into the following ecosystems: coastal and marine habitats; freshwater wetlands; streams, rivers, and lakes; northern forests; and high elevation systems. In addition, Appendix A provides detailed reports for four climate stressors (habitat shifting and alteration, droughts, temperature extremes, and storms and flooding) on Maine's most at-risk species and habitats; Appendix B includes lists of Maine's most vulnerable plants, animals, and habitats to climate change; Appendix C describes national trends in shifting bird ranges; and, Appendix D details the impacts of climate change on the St. John River Valley ecosystem.

Tribal Considerations

While implications of biodiversity changes to Maine's tribes are not within the scope of this report, we recommend the Maine Climate Council incorporate tribal perspectives, data, and knowledge to fully inform this topic.

Description of Priority Information Needs

The following section presents several priority research, monitoring, policy, and adaptation needs compiled from Maine's 2015 State Wildlife Action Plan, other reports and studies included in the Appendices, and multiple subject experts. This is not an exhaustive list of recommendations but is intended to inform the Maine Climate Council as they identify and prioritize mitigation and adaptation strategies that also conserve our state's biodiversity. Recommendations are largely limited to non-commercial species, as commercial species are addressed by other STS reports.

Recommendations: Priority Research and Monitoring

In order to further understand climate change impacts to Maine's species and habitats, we recommend continued support for and expansion of (where necessary) the following:

- Monitor winter tick impacts on moose population dynamics and identify strategies to reduce the winter tick population through targeted moose harvests in heavily infested areas and habitat management strategies
- Investigate changing winter impacts (particularly reductions in average snowpack depth) on snow-dependent species and habitats including, but not limited to, Canada lynx and snowshoe hare population dynamics, vernal pool hydrology and synchronicity with amphibian life cycles, and overwintering success of multiple taxa
- Monitor impacts of early spring precipitation on song- and game bird fledgling success
- Implement food-web level studies on the impacts of invasive plant species on trophic cascades
- Document changes in species abundance, distribution, and diversity of key taxonomic groups (e.g., birds, insects)
- Monitor changing food web dynamics for cetaceans (whales, dolphins, and porpoises) across their feeding and breeding ranges
- Compile historical trends in Maine wetland species relevant to climate change from existing data sources (government agencies, universities, non-governmental organizations, etc.) and identify data gaps and research needs.
- Model and determine impacts of climate change on wetland, river, and stream species; utilize the Maine Department of Environmental Protection's (DEP) Biological Monitoring Program, which conducts sampling for aquatic macroinvertebrates and epiphytic algae and phytoplankton in emergent marsh and aquatic bed habitats, including shallow vegetated areas within low gradient streams, lakes and ponds.
- Support the Maine Stream Temperature Workgroup and participation in the Spatial Hydro-Ecological Decision System (SHEDS) to identify refugia for brook trout and Atlantic salmon.
- Publish results from Maine DEP's computed provisional thermal tolerances of stream fish, algae, and macroinvertebrates.

Recommendations: Priority Policies and Adaptation Strategies

Based on the best available science and professional expertise and judgment incorporated into Maine's 2015-2025 State Wildlife Action Plan, the following policies and adaptation methods would help conserve Maine's biodiversity in a changing climate but also produce multiple co-benefits for infrastructure resiliency, carbon sequestration and storage, and human communities:

- Conserve climate resilient landscapes and strongholds, biogeographically diverse landscapes, wetlands, streams and riparian areas, and the connections among these areas so that species can move unimpeded across the landscape; in particular:
    - » Downscale currently available regional climate refugia and habitat connectivity models to scales useful for local planning and decision making
    - » Conserve and enhance riparian habitats (85% of Maine's vertebrates use riparian habitat sometime during their annual life cycle)

- Protect functioning road-crossing infrastructure and replace failing structures, using Stream Smart practices for freshwater bridges and culverts and the CoastWise Approach for tidal crossings
- Conserve land adjacent to tidal marshes to allow for marshes to move inland with sea level rise
- Support conservation and technological strategies to reduce impervious surfaces (thereby reducing run-off and effluents into waterbodies)
- Promote Smart Growth and Beginning with Habitat approaches to land use planning to encourage development in compatible areas and away from sensitive wildlife habitats
- Promote local habitat protection and water quality through community conservation programs such as Bringing Nature Home, LakeSmart, and Bayscaping
- Integrate social, economic, and ecological values into vulnerability assessments to generate ecosystem and lake-level management strategies for addressing climate change (Tingley et al. 2019)

- Promote habitat connectivity in state planning efforts, as outlined in the New England Governor's-Eastern Canadian Premiers Resolution 40-3 on Ecological Connectivity, Adaptation to Climate Change, and Biodiversity Conservation and through practices identified by the Staying Connected Initiative
- Provide incentives to promote mature forest stands; these areas contain more habitat features for a wide array of species and individuals, maintain healthier soils, store more carbon, and are more resilient to changes in species composition, disease and pests than younger stands.
- Manage thermal discharges and other activities that may further stress aquatic organisms to the extent required by statute and rule.

ADDITIONAL INFORMATION ON BIODIVERSITY IN MAINE

Maine is a biodiverse ecological transition area, where temperate ecosystems characteristic of southern New England give way to northern boreal systems often associated with southern Canada. Forests cover nearly 85% of Maine's land area, shifting from deciduous and mixed forests in southern, western and central Maine to boreal conifer forests in northern, eastern, and higher elevation regions (MDIFW State Wildlife Action Plan 2015; referred to hereafter as MDIFW SWAP 2015). Surface waters cover almost 13% of the state, with coldwater lakes, rivers and streams in northern and western Maine and warmer waters in southwestern parts of the state. Maine's complex coastline totals almost 3,500 miles, and the Gulf of Maine itself transitions into cooler waters along a west-to-east gradient due to tidal mixing with the North Atlantic's Labrador Current (MDIFW SWAP 2015).

Distribution of Maine's approximate 33,000 wildlife and 1500 vascular plant species reflect these diverse ecosystems and transition zones, with many of the state's species at the northern or southern limits of their ranges. Examples of northern fauna at the southernmost range limits include Canada lynx, Arctic charr, mink frog, and Atlantic puffin. Southern fauna that are near the northern edge of their range in Maine include New England cottontail, roseate tern, black racer, loggerhead sea turtle, and monarch butterfly (MDIFW SWAP 2015).

With its abundance of edge-of-range species, Maine provides a unique laboratory to document the effects of climate change on biodiversity. In general, species at the northern edge of their ranges may be able to expand northward throughout the state, while those at the southern edge of their ranges will likely shift farther north or to higher elevations (Jacobson et al. 2009). Iconic Maine species, such as moose and Canada lynx, may become less prevalent in the state while more southern species, such as red-bellied woodpeckers and Virginia opossums, are already expanding their ranges. By maintaining and restoring connected terrestrial and aquatic landscapes, mobile species may successfully adjust their ranges in response to a changing climate. However, in fragmented landscapes and for species with limited mobility (such as many plants), additional conservation measures (e.g., assisted migration) may be needed to maintain these species in a warmer climate.

General Trends for Climate Change and Global Biodiversity

Much of the research documenting specific impacts of climate change on wildlife and biodiversity have occurred in areas outside Maine. While these studies cannot necessarily be applied to or used to predict what will happen in Maine, they are instructive in setting the stage for understanding the extent of change already occurring and likely to occur in the foreseeable future. Below we summarize information on extinction rates and range shifts from around the globe.

Extinction Rates

Numerous scientists have predicted widespread declines and/or extinctions for many species around the globe (Urban 2015). In fact, significant declines or extinctions attributed to climate change have already been documented for some species in other parts of the world such as tree frogs from the cloud forests of Costa Rica, Edith checkerspot butterfly from the Bay Area of California, American pika from the Great Basin in the western U.S., and polar bears in the Arctic. Although data is limited for species declines in Maine that are directly attributed to climate change, the decline and loss of species will detrimentally affect ecosystem functions and the ability to provide the ecosystem services upon which people depend (Mooney et al. 2009). Below, we provide global examples to bring greater context to trends being observed in Maine.

species	location	hypothesized proximate cause of local extinction	reference
American pika (*Ochotona princeps*)	Great Basin region, USA	limited tolerance to temperature extremes (both high and low)	[25,63]
planarian (*Crenobia alpina*)	Wales, UK	loss of prey as result of increasing stream temperatures	[35]
desert bighorn sheep (*Ovis canadensis*)	California, USA	decrease in precipitation leading to altered plant community (food)	[64]
checkerspot butterfly (*Euphydryas editha bayensis*)	San Francisco Bay area, CA, USA	increase in variability of precipitation corresponding with reduction of temporal overlap between larvae and host plants	[66]
fish (*Gobiodon* sp. A)	New Britain, Papua New Guinea	destruction of obligate coral habitat due to coral bleaching caused by increasing water temperatures	[36]
48 lizard species (genus *Sceloporus*)	Mexico	increased maximum air temperature approaches physiological limit, seemingly causing decreased surface activity during the reproductive season	[23]
Adrar Mountain fish species	Mauritania	loss of water bodies due to drought	[30]

Table 1: Examples of climate-induced local extinctions (from Cahill et al. 2013).

Cahill et al. (2013) lists examples of seven different species from around the globe that have become locally extinct most likely due to a changing climate (Table 1).

Cardinale et al. (2019) reviewed and modeled species extinctions and rates around the globe:

> "*While few species have yet to be driven globally extinct, the biotic signatures of anthropogenic climate change are pervasive. Population decay caused by climate change has led to a higher number of threatened species than was predicted by models. Species on land and in the oceans have exhibited rapid range shifts toward the poles and upward in elevation. Phenological shifts have led to population asynchronies that have reduced the fitness of interacting species, and entire biomes have exhibited regime shifts to alternative states.*
>
> *Climate-driven changes in species distributions have already begun to alter ecosystem services that impact human well-being, ecosystem health, and feedbacks that reinforce the rate of climate change. These changes include shifts in human disease, emergence of pest species of agriculture and forested ecosystems, and changes in species that are vital to food security" (p. 401).*

Authors "used range comparisons, species-area relationships (SARs), and International Union for the Conservation of Nature (IUCN) Red List criteria to forecast species extinctions. Based on their modeling efforts, **the authors projected that 34%–58% (minimum 0.8-1.7C to maximum >2.0C scenarios) of species are committed to extinction by 2050 for the given climate change scenarios if they are unable to disperse to new locations**, while 11–33% are committed to extinction even if they can disperse to future areas that are within their current climatic niche. For certain groups of organisms, the predicted estimates of extinction were exceptionally high, such as the projected 87% of Amazonian plants, or 48% of European birds projected to go extinct under scenarios of maximum climate change" (p. 379).

Range Shifts

The Union of Concerned Scientists (2003) summarized the following trends in range shifts from around the globe: "Range shifts in areas with regional warming trends have been reported in alpine plants (Grabherr et al., 1994), butterflies (Parmesan, 1996; Parmesan et al., 1999), birds (Thomas and Lennon, 1999), marine invertebrates (Barry et al., 1995), and mosquitoes (Epstein et al, 1998). Two of those studies (Thomas and Lennon, 1999; Parmesan et al., 1999) evaluated changes at both southern and northern margins. In a sample of 35 European non-migratory butterfly species, 63% had ranges that shifted to the north by 35-240 km during the past century, and only 3% shifted to the south (Parmesan et al., 1999). The range shift parallels a 0.8°C warming over Europe during the last century, which has shifted the climatic isotherms northwards by an average of 120 km (Beniston and Tol., 1998)."

They further state that "factors other than climate may limit the extent to which organisms can shift their ranges. Physical barriers such as mountain ranges or extensive human settlement may prevent some species from shifting to more suitable habitat. In the case of isolated mountain top species, there may be no new habitat at higher elevation to colonize. Even in cases where no barriers are present, other limiting factors such as nutrient or food availability, soil type, and the presence of adequate breeding sites may prevent a range shift. Although tree line will probably increase in elevation as climate warms, for example, soils at higher elevations are often thin and of poor quality and could be inadequate to sustain species from lower elevation sites. In coastal areas, the loss of wetlands and beaches due to sea level rise could destroy sites used by turtles, birds, and marine mammals for breeding and raising young. It should be noted that given all these potential difficulties, it is encouraging that a few species have apparently been able to shift their ranges in response to climate, as described in the studies listed below. However, the long-term impacts of these shifts on the populations and species as a whole, and the extent to which other species can adapt to changing climate, are difficult to assess at this time."

General Trends for Climate Change and Maine's Biodiversity

Habitat Shifts Expected in Maine

Whitman et al. (2013b) notes that we can expect to see numerous habitat shifts in Maine over the next 100 years, with many species shifting north or to higher elevations, but also in ways that are unpredictable, creating new assemblages. The authors further state that species in northern Maine may have an easier time moving further north or upslope than those moving into Maine from southern states, where more extensive development and habitat fragmentation could seriously impede their ability to move in step with changes. More mobile animals (such as birds) are expected to have an easier time moving to new habitats and ranges than animals with smaller ranges and mobility (such as amphibians, many invertebrates) and most plants. Nonetheless, Malcolm and Markham (2000) predict over 44% of Maine's landscape will shift to other habitats over the next 100 years, which is the highest percentage of area vulnerable to climate change of any state in the U.S.

Climate Change Impacts on Vulnerable Habitats and Priority Species

Whitman et al. (2014) concluded that 7 of 21 habitats evaluated in Maine are highly vulnerable to climate change. Of the 442 plant and animal species assessed for vulnerability, 168 (or 37%) are highly vulnerable and 171 (or 38%) are moderately vulnerable to impacts from climate change. All species groups contained species highly vulnerable to climate change, and 50% of at-risk Species of Greatest Conservation Need mammals and state-listed Threatened or Endangered plant species were ranked highly vulnerable to climate change.

Highly vulnerable species include 55 vertebrate species that are vulnerable because they:

- Occur at their southern range limit in Maine (e.g. Canada lynx)
- Depend on coldwater (e.g. brook trout) or other "cold" habitats such as boreal forests (e.g. boreal chickadee)

- Breed in wetlands that are vulnerable to fluctuating water levels during nesting periods (e.g. yellow rail, least bittern)
- Use coastal or marine habitats affected by sea level rise, altered ocean chemistry, or changes in marine food webs (e.g. saltmarsh sparrow, Atlantic puffin, Arctic tern)
- Inhabit naturally fragmented habitats that limit dispersal (e.g. Blanding's turtle)
- Have narrow habitat requirements

The most vulnerable habitats include alpine and montane forest systems, peatlands, northern river shores, spruce flats and cedar lowlands. Coastal and aquatic systems are moderately vulnerable, although this is difficult to predict because of the many uncertainties surrounding changing precipitation regimes, hydrology, and potential movement of salt marshes and estuaries.

Detailed lists of the most vulnerable plant and animal species and habitats, taken from Whitman et al. (2013a), can be found in Appendix B.

Climate Change Impacts on Maine's Species of Greatest Conservation Need

Maine's 2015 State Wildlife Action Plan (MDIFW SWAP 2015) identifies and prescribes conservation actions for Maine's 378 most at-risk species (Species of Greatest Conservation Need or SGCN). Nearly one-third of these species are affected by climate-change related threats including habitat shifts and alterations, droughts, temperature extremes, and storms and flooding. Climate change is among the top three most ubiquitous threats across all SGCN taxonomic groups, from freshwater snails, such as the six-whorl vertigo, to marine mammals, such as the humpback whale (Appendix A). The 2015 SWAP includes nearly 50 conservation actions to directly address climate threats to SGCN and habitats, including a statewide focus on resilient and connected landscapes to support species' opportunities to shift and adapt to a chance climate.

Climate Change Impacts on Federally Threatened and Endangered Species

Several federally listed or proposed threatened or endangered species are exhibiting declines and/or threats related to climate change. Explained in more detail in three different extensive species status assessments, the U.S. Fish and Wildlife Service found interesting examples of how climate change affects species: diminishing spruce-fir forest habitat (Bicknell's thrush); changing ice regime and flooding in the St. John River (Furbish lousewort); diminishing snow quality, quantity, and duration (Canada lynx); pelage (seasonal color) change mismatch for snowshoe hare (Canada lynx), and competition from bobcats expanding their range northward (Canada lynx) (M. McCollough, U.S. Fish and Wildlife Service, personal communication, December 2019).

Figure 1: North American bird declines since 1970 (from Rosenberg et al. 2019).

Climate Change Impacts on Birds

Population Declines

Rosenberg et al. (2019) documented dramatic declines in bird populations across North America — on average by 29%, or one in every four birds —

across all taxonomic groups and biomes since 1970 (Figure 1). Even greater declines are being seen in certain groups, including 74% of all grassland species, 68% percent of shorebird species, 73% of species that eat aerial insects, and 64% of all eastern forest bird species, and 50 percent of all boreal forest species. That translates to a loss of 167 million eastern forest birds and a loss of 501 million boreal forest species in North America alone.

That means nearly one in four of all Eastern forest birds and one in three of all boreal forest birds that were coloring the forest with their flashy feathers and cheerful songs in 1970 are no longer with us. The only bird group with increasing numbers are wetland birds, which is driven by increased numbers of ducks and geese thanks to concerted conservation and advocacy efforts (see https://www.maineaudubon.org/news/bird-numbers-declining-by-the-billions/ and https://www.pressherald.com/2019/10/03/maine-voices-our-states-actions-are-key-toreversing-trend-of-bird-population-decline/ for summary of the study by Sally Stockwell, Maine Audubon).

Almost three billion birds have been lost since 1970, according to Rosenberg et al. (2019). The numbers are based on data from a variety of sources, including nearly 50 years of North American Breeding Bird Surveys, Audubon Christmas Bird Counts, and Partners in Flight Population Estimates, plus Shorebird Migration Studies and USFWS Breeding Waterfowl Surveys. Radar studies from across the continent have also documented a dramatic decline of around 13% in the total biomass of birds passing overhead during migration during just the past 10 years.

National Audubon reported in *Survival by Degrees: 389 Birds on the Brink* in 2019 that based on models of current species ranges, vegetation, surface water, human land use, habitat characteristics, and climate projections, that 64% (389 of 604) bird species across North America are at risk of extinction if the climate warms 3.0°C. They suggest if we act now to limit temperature rise to 1.5°C, we will reduce the risk for 76% of the 389 vulnerable species (Wilsey et al., 2019).

In Maine, National Audubon predicts 64 species are highly or moderately vulnerable at 1.5°C, 84 at 2.0°C, and 106 at 3.0°C of warming over preindustrial temperatures. The list of Maine vulnerable species at 2.0°C includes species from almost every bird group (such as waterfowl), but especially raptors, flycatchers, sparrows, thrushes, and warblers (16 species). Across North America, the most vulnerable groups based on habitats include Arctic, Eastern Forest, Grassland, and Marsh birds (Wilsey et al., 2019).

Shifts in Bird Ranges - Maine

In addition to declining population, bird ranges have been shifting throughout North America. In Maine, we have some very specific examples. Some species that are not common now in Maine, could become more common with rising temperatures. Based on National Audubon's report (Wilsey et al., 2019), this includes species such as American oystercatcher, great blue heron, eastern screech owl, red-bellied woodpeckers, eastern kingbird, yellow-throated vireos, tufted titmice, Carolina wren, eastern bluebirds, house finch, Louisiana waterthrush, hooded warbler, and indigo bunting. In fact, we are already seeing several of these species more commonly in Maine than we did 20 years ago. Here are a few examples:

More bluebirds have been seen each year during the Maine's Christmas Bird Count since 2006; they are spreading from the southern-most counts and the number of counts being reported is also increasing (D. Hitchcox, Maine Audubon, personal communication, December 2019; Figure 2). The southern counts are reporting higher numbers consistently each year, and the reach of smaller (approximately <25 individuals) wintering populations is continuing north-northeast (Hitchcox 2019; see https://www.maineaudubon.org/news/bluebirds-in-winter/ for an animated graphic)

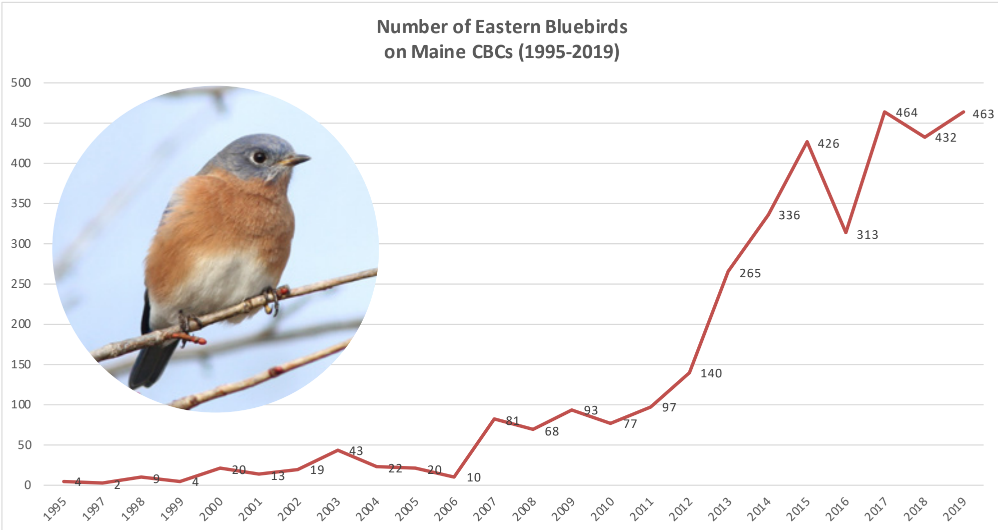


Figure 2: Numbers of Eastern bluebirds reported in Maine's Christmas Bird Count (CBC) 1995-2019 (from Maine Audobon 2019).

Likewise, red-bellied woodpeckers are moving north. Red-bellied woodpeckers have been going through a steady range expansion for a few decades. It was during 2004-2005 that these birds erupted into Maine in larger numbers than had been seen before and have since become resident breeders. Based on reports to eBird, an especially dramatic change is noted from a frequency high of 4% in 2010 to 14% in 2014. Christmas Bird Counts also show a steady increase from 1990 to 2014 (Figure 3; see Doug Hitchcox January 20, 2015 blogpost here: https://www.maineaudubon.org/?s=red-bellied+woodpeckers+on+the+rise)

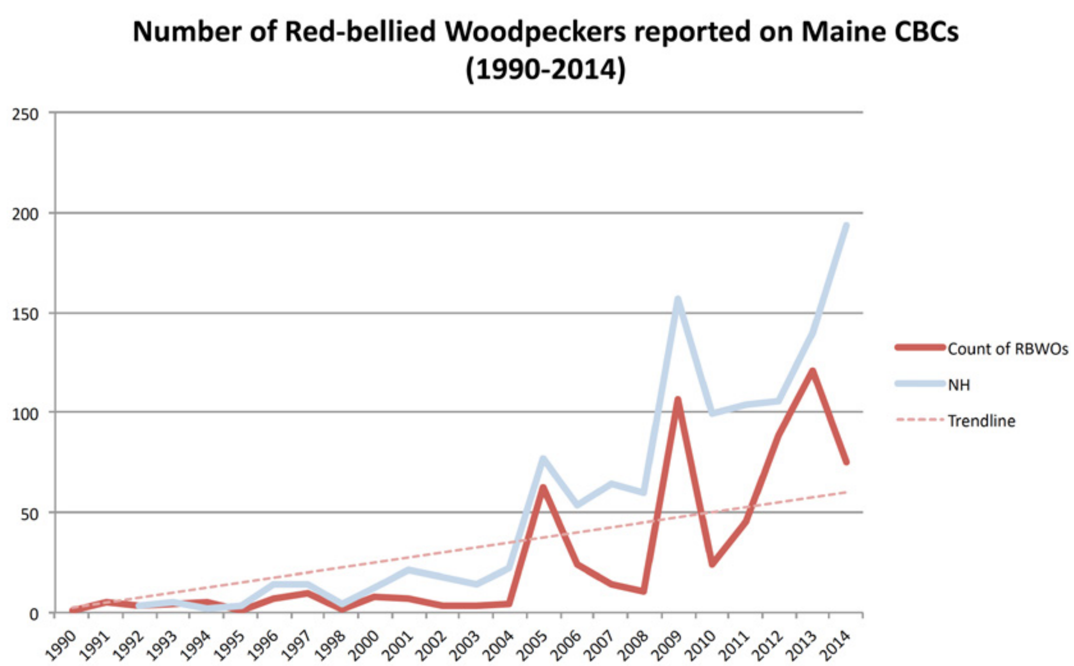


Figure 3: Numbers of red-bellied woodpeckers reported in Maine's Christmas Bird Count (CBC) 1993-2014; data is also shown for New Hampshire (NH) (from Maine Audobon 2020).

Climate Change Impacts on Invertebrates and Associated Biodiversity

Several studies in recent years have documented significant declines in insect populations in various parts of the world, particularly when coupled with other human-induced stressors. Hallmann et al. (2017) documented a decline greater than 75% over 27 years in total flying insect biomass, with samples taken in *protected* areas not in areas subject to direct habitat loss or significant land use changes (Figure 4). Lister and Garcia (2018) found declines in insect populations linked to parallel declines in insectivorous lizards, frogs, and birds in a tropical rainforest. Sanchez-Bayo and Wyckhuys (2019) conducted a meta-analysis of existing literature and identified climate change (among other human-induced factors such as habitat loss, pollution, and introduced species) as a major driver of insect declines.

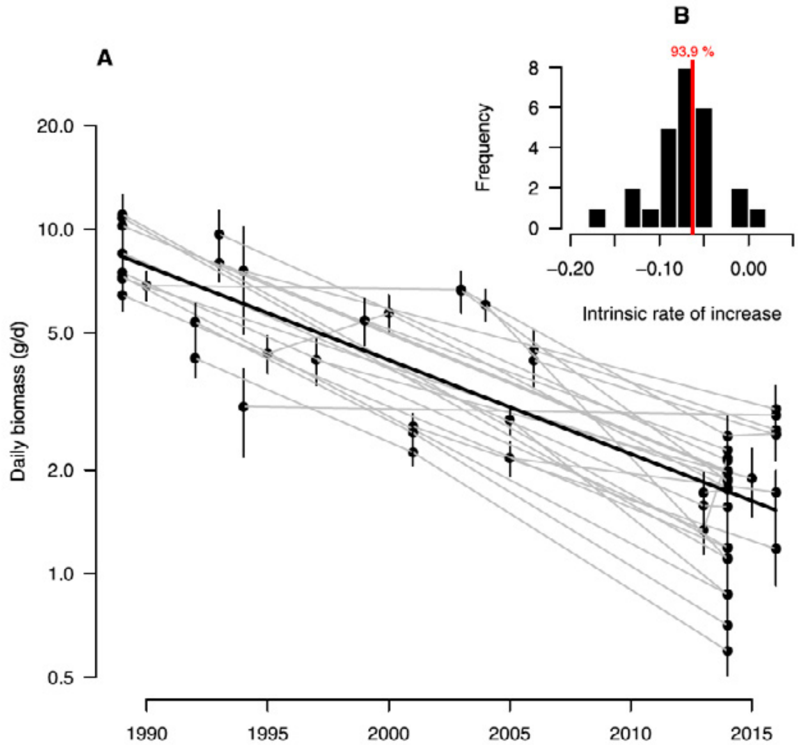


Figure 4: A) daily insect biomass (mean ±1 se) across 26 global locations during 1990-2015, and (B) distribution of mean annual rate of decline across sites (From Hallmann et al. 2017).

In addition to these insect-specific studies, other recent reports document global declines in species in all taxonomic groups occurring at an alarming rate, with climate change exacerbating and compounding other threats. For instance, the United Nations' Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services estimates that approximately one million animal and plant species are threatened with extinction (IPBES 2019), more than ever before in human history. Similar reports of declines in amphibians, reptiles, birds, and pollinators have captured the attention of the media and the general public increasingly over the last decade.

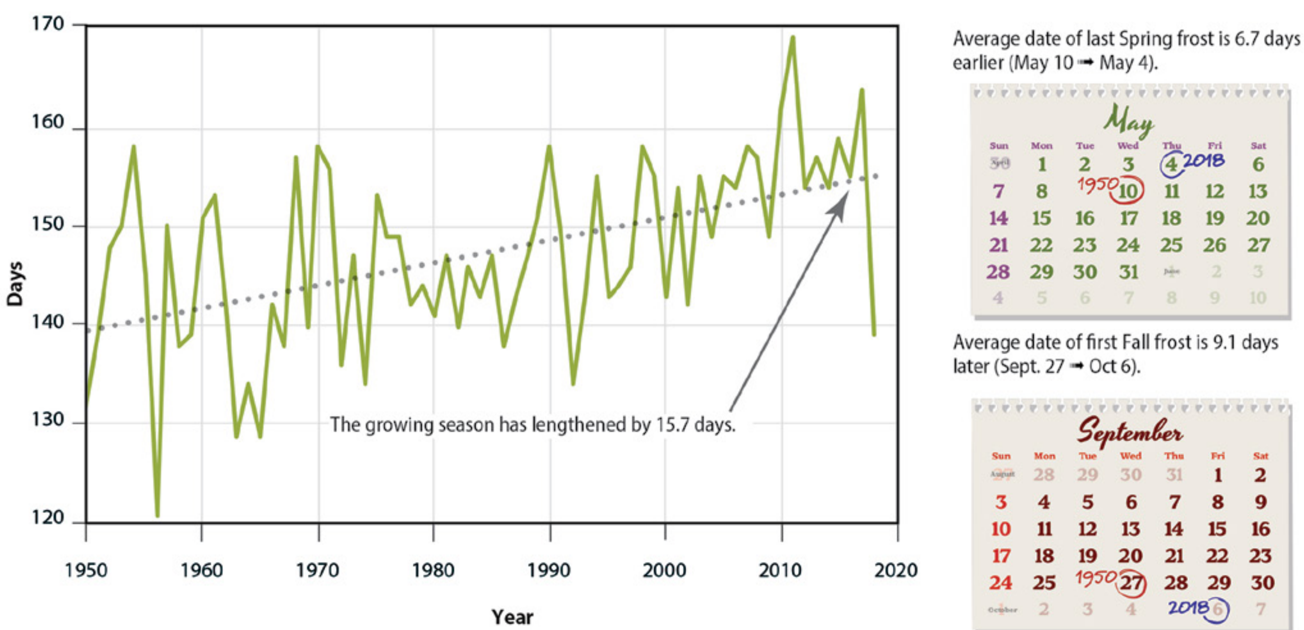
Climate Impacts on Spring and Flower Phenology

On average, the start of spring has occurred earlier in the contiguous United States since 1984 (U.S. Global Climate Research Program). These observations at a national level are mirrored by warming winter temperatures, earlier spring runoff and ice-out in Maine, and longer growing seasons (Figure 5; see also the Climate and Hydrology chapters in this report).

Recent research from Acadia National Park also confirmed this national trend: MacKenzie et al. (2019a) found that plants are flowering and leafing out earlier in the spring in the park. Comparing the data to southern New England, the researchers found that the shift in earlier phenology is occurring at a slower rate in Maine. Researches from Acadia National Park state: "In four years of intensive monitoring of transects on three mountains, we found large variability in spring temperatures across the mountains, but consistent patterns of advancing flower and leaf phenology in warmer microclimates. …The plants in Acadia responded to warming spring temperatures by shifting leaf and flower phenology in the same direction (earlier), but at a reduced rate (as measured in days/°C), in comparison with plants in southern New England (e.g., Concord, Massachusetts, USA)."

The re-discovery of a phenology journal from a naturalist in Aroostook county has shed light on patterns between spring temperature and flowering. When spring temperatures are higher, plants flower sooner (D. Cameron, Maine Natural Areas Program, personal communication, December 2019). Here is a summary of some of the most revealing information from those journals, taken from the University of Maine's *Maine Climate News:*

> *"A phenology journal for the Oxbow region in Aroostook county (about 60 km southwest of Presque Isle), created by a mid-20th century hunting guide named L.S. Quackenbush, was recently re-discovered, revealing a valuable set of records that have been integral to Dr. Caitlin McDonough's research, allowing her to compare the northern Maine region with historical and current records for the coastal Acadia region. A rich and detailed log of the seasons, Quackenbush recorded daily natural history observations and later indexed his own entries into lists of first flowering, leaf out, and migratory arrival dates……. So far, researchers have found Quackenbush's leaf out and flowering phenology observations are closely tied to spring temperatures and match the direction, though not the magnitude, of changes found in Southern New England plant communities as a result of climate change." (McDonough, undated. https://extension.umaine.edu/maineclimatenews/archives/uncovering-the-past-through-maines-historic-phenology-data/) (see also MacKenzie et al. 2019b)*



The Importance of Resilient Connected Landscapes for Conserving Biodiversity

Species distributions and abundances are already shifting in response to climate change, and our land use patterns can help facilitate or impede these movements. Anderson and Ferree (2010) determined that species diversity in the eastern U.S. and Canada is strongly predicted by four geophysical factors: the number of geological classes, latitude, elevation range, and the amount of calcareous bedrock. Within these landscapes, temperature and humidity microclimates further diversify ranges available to species. Anderson and Ferree (2010) propose conserving a diversity of these underlying geological 'stages' and the connections among them so that plant and animal 'actors' can move among the stages as needed to occupy suitable habitat.

Much of Maine is already characterized as a relatively resilient and connected landscape compared to other areas of the northeast (Anderson et al. 2016). However, much of southern Maine, where many of our at-risk species occur, is more highly developed and fragmented, and therefore less amenable to species movements and range shifts.

Conserving remaining unfragmented landscapes, restoring habitats, and enhancing habitat connectivity using approaches detailed by the Beginning with Habitat Program, the Staying Connected Initiative, Stream Smart, and other programs will be essential to conserving Maine's 'stage'. Because species move across political boundaries, coordination among state and international jurisdictions will be essential to conserve movement corridors. These approaches are outlined in the New England Governors-Eastern Canadian Premiers Resolution 40-3 on Ecological Connectivity, Adaptation to Climate Change, and Biodiversity Conservation (NEG-ECP Resolution 40-3 2016).

Ecosystem-Based Case Studies

The impacts of climate change on Maine's biodiversity is an incredibly diverse and broad topic. Below we highlight general trends and species examples for five major ecosystem groupings: coastal and marine; streams, rivers, and lakes; freshwater wetlands; northern forests; and high elevation areas. Where Maine-specific primary literature and reports were unavailable, we included regional references and expert input. This is not an exhaustive list of topics or a review of all taxonomic or habitat groups, but rather a presentation of a few examples to help illustrate the extent and complexity of the challenges climate change presents to our plants, animals, and ecosystems. A more detailed analysis of the risks Maine plant and animal species and habitats face from climate change is available in Whitman et al. (2013b), and we encourage anyone interested in this topic to carefully read that report.

Additional information is available from state and federal natural resource agencies including the U.S. Fish and Wildlife Service and the Maine Departments of Environmental Protection (DEP); Inland Fisheries and Wildlife (MDIFW); Agriculture, Conservation and Forestry (DACF); and Marine Resources (DMR).

Coastal and Marine Ecosystems

The Gulf of Maine is warming 99% faster than the global ocean (Pershing et al. 2015) and sea level rise impacts are already being observed in coastal Maine (see the Sea Level Rise chapter of this report). Recent reports suggest that 89% of the predicted tide levels for Maine in 2019 were exceeded, and October 2019 had the highest historical mean tide for any October (see the Sea Level Rise chapter of this report). Increased sea levels are starting to impact the upper edges of tidal marshes in Maine causing tree mortality but observations are still largely anecdotal. More significantly from an ecological perspective, high marsh areas are becoming flooded much more frequently than in the past, changing the cycle of sediment deposition in the upper marsh, accelerating decomposition in the marsh, changing the make-up of the saltmarsh grasses, and making it nearly impossible for marsh nesting birds (e.g., salt-marsh sparrows) to nest successfully. More extreme storms and storm surges are impacting shorelines - especially sandy beaches, dunes, and bluffs, causing flooding of beach-nesting birds, homes, and stormwater systems. Other impacts to water quality and influx of invasive and traditionally more southern species into the Gulf of Maine are outlined in the Marine Ecosystems chapter of this report.

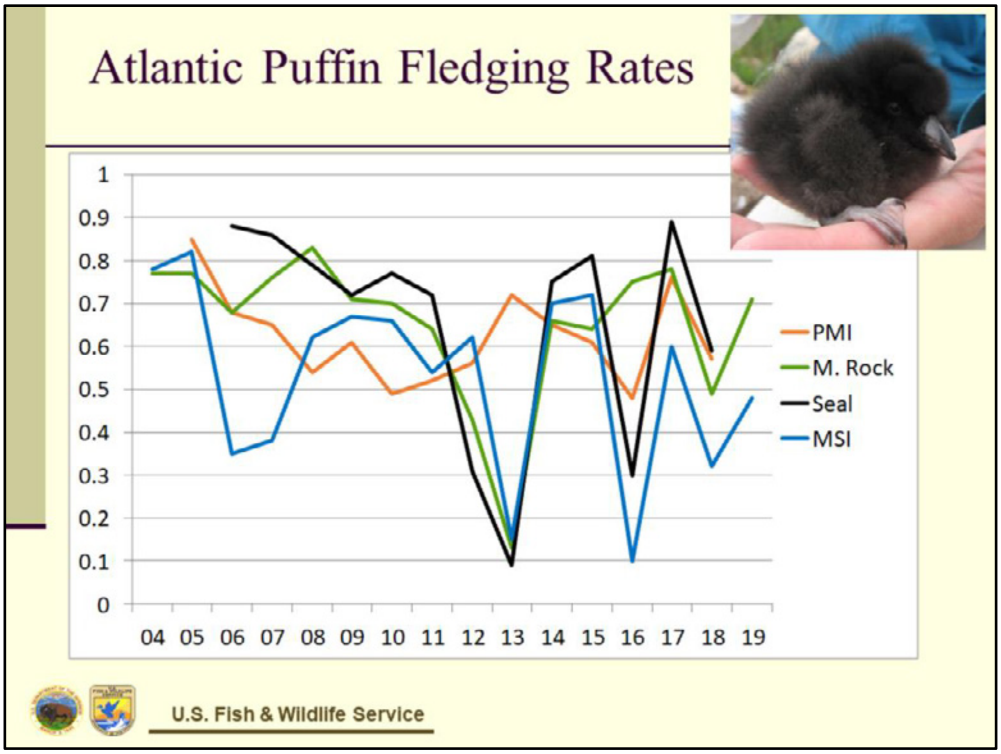


Figure 6: Atlantic puffin fledgling rates from four Gulf of Maine locations from 2004-2019. Year is shown on the x-axis and fledgling rate is shown on the y-axis. Fledgling rates crashed in 2013 and 2016 in relation to high sea surface temperature (USFWS data, unpublished).

Atlantic Puffins

Atlantic Puffin productivity crashed in 2013 and 2016 in relation to high sea surface temperatures. According to U.S. Fish and Wildlife Service (Welch 2018), in 2018 there was an Ocean Heat Wave in late July/early August (Figure 6). Due to this heat wave, puffin chicks stopped growing for about a month. The adults began feeding the chicks again in late August when the sea surface temperature dropped. It then took the chicks about one month longer than average to fledge. Kress et al. (2016) also discussed the increased vulnerability of puffin chicks due to the fact puffin chicks are not fed post-fledging from their parents (Figure 7). This is important as "chicks with lower weight/wing chord ratios are less likely to survive…" (p.39). In addition, Kress et al. (2016) writes that puffins in Maine "are especially vulnerable to changes in ocean warming as they are nesting at the southern limit of the species range and are thus most vulnerable to variation in water temperature and other climate change mechanisms" (p. 28).

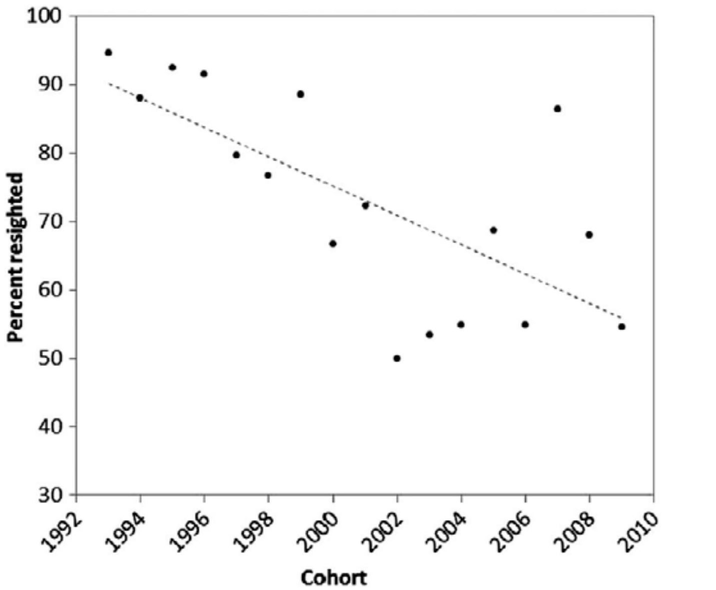


Figure 7: Percent of each Matinicus Rock puffin cohort resighted demonstrates the trend of reduced juvenile survival of Matinicus Rock puffins since 1993. The percentage resighted is, on average, decreasing by 2.525 percentage points per year (From Kress et al. 2016).

Seabirds

Puffins are just one species affected by climate change. Casualties include (but are not limited to) razorbills, terns, cormorants, and gulls. Historically, terns nested on 80-90 islands on the Maine coast. Now, the majority of terns are limited to only 10 managed colonies. This clumping places them at a higher risk for predation, disease, and events like oil spills. Impacts to one colony represent a significant percentage of the population. Puffins and razorbills are also grouped on a small number of islands, making them highly susceptible to these risks as well.

There are a multitude of ongoing climate change threats to seabirds, including increasing sea surface temperatures, declining ocean productivity, and increasing frequency and intensity of storms (Welch 2018). There has been a sharp increase in sea surface temperatures in Maine since 2004 (see the Ocean Temperature chapter of this report), affecting the amount and distribution of the available fish prey sources. Zooplankton and lipid-rich prey levels have also decreased, causing more issues for marine species and their predators. Storms create a range of problems for seabirds, and the increasing frequency of storms means there is less time for populations to recover. Wind, flooding, and subsequent storm runoff destroys eggs, kills chicks, and demolishes nests.

Cetaceans and Pinnipeds

Marine mammals are being impacted by climate change largely in relation to changes in prey and habitat availability (E. Summers, Maine Department of Marine Resources, personal communication, January 2020). The Gulf of Maine is an important feeding habitat for many kinds of cetacean species, including large, filter feeding whales and smaller toothed whales, dolphins, and porpoises. Changes already being documented to the temperature and circulation patterns within the Gulf of Maine are affecting the timing, density, and availability of prey for these species (Sorochan et al. 2019). Cetaceans, such as the endangered North Atlantic right whale, may change distribution and residency patterns in search of preferred prey items that have shifted or decreased in abundance (Record et al. 2019; Plourde et al. 2019). Shifts in prey availability for right and fin whales has been documented to be linked with decreased body condition and reproductive rates (MeyerGutbrod and Greene 2014; Williams et al. 2013). Related changes in habitat use and distribution has had a negative effect on right whales that have had to search for food in previously undocumented habitats, resulting in mortality events when overlapping with areas not previously protected for encounters with fishing gear and vessel strikes (Canadian Science Advisory Secretariat Science Advisory Report 2019/028). Additionally, smaller cetaceans with high metabolic rates, such as the harbor porpoise, will be sensitive to shifts in prey availability or other disturbances that disrupt feeding (Wisniewska et al. 2016).

Pinnipeds are also likely to be affected by climate change (E. Summers, Maine Department of Marine Resources, personal communication, January 2020). These species have a varied diet, so are less susceptible to shifts in prey species assemblages. However, species such as the harbor seal are susceptible to disease with changing population dynamics. Ice seals, such as harp and hooded seals found seasonally in Maine, are affected by the availability of winter ice for pupping (Johnston et al. 2012).

Shorebird, Beach, and Dune Habitats

Beaches are by nature very dynamic systems. Beach-nesting birds such as piping plovers and least terns are adapted to changes wrought by winter storms, exceptionally high tides, and periodic storm surges by searching for the best nesting sites each year, placing nests as high above the average high tide line as practical, and re-nesting if a nest or eggs are flooded or washed away. However, sea level rise and increasingly intense storms that cause exceptionally high storm surges and erode sand away and drench incubating adults and young chicks pose serious threats to the future of these already endangered birds. In an analysis of sea level rise impacts on nesting piping plovers on barrier islands in New York, Seavey et al. (2011) found that in places where beaches can migrate upslope and inland, breeding areas may actually increase, but in places where breeding habitat cannot migrate, sea level rise is likely to reduce breeding areas. In addition, the authors note when sea level rise and coastal storms converge, breeding areas are at higher risk. For example, they estimated a large hurricane could flood up to 95% of plover habitat. Some piping plover nesting areas in Maine may similarly be at risk due to sea level rise (see the Sea Level Rise chapter of this report for more information).

Saltmarsh Sparrows

Saltmarsh sparrows, listed as vulnerable by the IUCN, are limited in their breeding and nesting range, making them especially vulnerable to climate change and subsequent effects. Shriver et al. (2015), analyzed data from 2000-2013 and found saltmarsh sparrow populations within the Rachel Carson Wildlife Refuge had declined, writing, "Breeding season precipitation negatively influenced population trends for Saltmarsh and Nelson's Sparrows and mean sea level had a negative effect on Saltmarsh Sparrow population trends" (p. 2). In addition to these factors, the increase in the presence of invasive species, such as green crab, as well as the "increasing intensity of summer rain storms" (MDIFW SWAP 2015) affect already particularly vulnerable species, like the saltmarsh sparrow. Rising sea levels alter the patterns and intensities of flooding, which then affects the survival rate of both adults and their nests (Gjerdrum et al 2005). Further research is needed throughout the saltmarsh sparrow range, but studies in Maine demonstrate a clear connection between climate change and negative impacts to nesting marsh birds.

Salt Marsh Tiger Beetle

The Salt Marsh Tiger Beetle is a rare beetle that occurs in only 12 sites in 10 river-marsh systems in coastal southern and midcoast Maine (Ward and Mays 2014). This species' narrow coastal distribution and habitat specialization make it particularly vulnerable to development, oil spills, and climate change impacts. Rising sea levels and intensifying coastal storms could significantly damage or destroy marshes occupied by salt marsh tiger beetles (MDIFW SWAP 2015).

Tidal Marshes and Sea Level Rise

There is extensive documentation that sea levels are rising along the coast of Maine as they are all over the eastern sea board (D. Cameron, Maine Natural Areas Program, personal communication, December 2019). The most recent data shows that 89% of the predicted tide levels for Maine in 2019 were exceeded, and that October 2019 had the highest all time means for high tide for any October ever recorded (see the Sea Level Rise chapter of this report for more information).

Figure 8: Woody vegetation dying on the edge of the Scarborough Marsh due to increasing exposure to sea water (Maine Natural Areas Program photo).

Increased sea levels are starting to impact the upper edges of tidal marshes in Maine causing tree mortality but observations are still largely anecdotal (Figure 8). News reports from New Jersey and other areas along the east coast indicate more severe impacts are occurring at some locations causing what is now referred to as "Ghost Forests". Based on current sea level rise trends, it is only a matter of time before we will see more obvious impacts to the lowest lying areas along Maine's coast, where we can expect widespread decline of freshwater wetland plant communities as salt water flows into these areas with increasing frequency.

A recent 5-year study (Burdick et al. 2020) conducted across marshes in New England via the National Estuary Research Reserve System found that over the study time period low marsh (which is characterized by high dominance of *Spartina alterniflora* grass), had a decrease in *S. alterniflora* cover and an increase in bare mud and detritus, and high marsh saw a decrease in the characteristic *S. patens* and *Distichilis spicata* grasses and an increase in *S. alterniflora* as well as unvegetated area. This pattern is indicative of a progressive shift of low marsh into the more elevated high marsh areas, which is predicted to occur as sea levels rise and inundation time and frequency increase in high marsh areas (Burdick et al. 2020).

Marine and Commercial Species

We direct readers to other Maine Climate Council Science and Technical Subcommittee chapters for more information on climate change effects on marine and commercial species, particularly the Marine Ecosystems and Maine's Economy chapters.

Stream, River, and Lake Ecosystems

The abiotic and biotic characteristics of stream, river, and lake ecosystems may be significantly altered by climate change, although specific impacts are difficult to predict because of uncertainties around precipitation changes (see the Climate and Hydrology chapters in this report for more information). Limited precipitation in summer may cause wetlands such as vernal pools and peatlands to dry early, interfering with amphibian life cycles; excess runoff from extreme rain events may flush out aquatic insects, limiting available food for fish and other aquatic life; and open water may suffer from lower water levels and warm prematurely, creating challenges for many species that live in or near these waters (Whitman et al. 2013b). Changes in ice cover duration also may affect pond and lake communities and lead to increased algal blooms. See the Freshwater Quality chapter of this report for more information on this topic.

With Maine as the last stronghold for wild Eastern brook trout and Atlantic salmon populations in the U.S., maintaining cool and connected habitat refugia for these and other coldwater-dependent species will have important ecological, social, and economic importance. Furthermore, actions to conserve freshwater habitats for fish and wildlife species also have numerous co-benefits for protecting drinking water sources and other ecosystem services.

Abiotic Impacts and Monitoring

Maine has already documented changes in abiotic aquatic features (such as water chemistry and temperature) with corresponding impacts to invertebrate and vertebrate fauna.

Baseflow in urban and urbanizing streams in Maine has been noticeably lower in the last five years with particularly dry summers (J. Dennis, Maine Department of Environmental Protection, personal communication, January 2020). In many of these streams it is becoming a limiting factor for the macroinvertebrates that require water with at least some velocity to survive. Not only is the availability of flowing water in riffles compromised, or in some cases, eliminated, but the wetted area in pools and runs gets very low, thus also limiting available habitat for species that do not require running water. This may be particularly pronounced in watersheds with limited groundwater storage, such as those with shallow to bedrock and marine clay soils.

In first and second order streams with significant commercial, office, institutional and multi-unit residential development as well as interstate exchanges, chloride toxicity during periods of extended baseflow is a dominant threat on the impaired macroinvertebrate community (J. Dennis, Maine Department of Environmental Protection, personal communication, January 2020; see also the Freshwater Quality chapter of this report). During baseflow, when most of the water in these headwater streams comes from local groundwater, chloride concentrations are well above the 230 mg/l threshold for chronic toxicity. Surprisingly, in many of these streams, invertebrates are less stressed during and shortly after a runoff event when chloride levels are diluted. Longer intervals between rainfalls exacerbates chronic toxicity. Logger data shows specific conductance in these streams steadily rising until the next rain, and the Maine Department of Environmental Protection reports two to three-week periods when the chronic toxicity threshold is exceeded each summer (J. Dennis, Maine Department of Environmental Protection, personal communication, January 2020). With increasing frequency and duration of drought periods coupled with increased use of deicers to address winter icing events, chloride toxicity is becoming Maine's most challenging urban stream issue because there are no Best Management Practices (BMPs) that can remove chloride from the stormwater or the groundwater. Low Impact Development BMPs that promote infiltration and are effective against other urban pollutants are not an option for treating chloride toxicity. Instead, salt laden stormwater must be treated in lined BMP structures and delivered in secure pipes or lined ditches to avoid contaminating local aquatic environments.

Maine's Water Quality Standards (WQS) for rivers and streams and a subset of lakes and ponds can be used to track changes in water quality (such as dissolved oxygen and temperature) over time (http://www.mainelegislature.org/legis/statutes/38/title38sec465.html). Because state records indicate that coldwater fish, brook trout and/or Atlantic salmon are or were present in essentially all rivers and streams in Maine at some time in the year, Maine DEP applies temperature and dissolved oxygen criteria for coldwater fish to all rivers and streams in Maine (J. Dennis, Maine Department of Environmental Protection, personal communication, January 2020).

General Effects on Stream Biota

There is limited information regarding historical trends of the effects of climate change on the aquatic life communities of Maine's streams and rivers. However, the Maine Department of Environmental Protection collects data for aquatic macroinvertebrates (1980s to present) and started collecting stream algae data in 2000. The aquatic life communities (including algae, fish, macroinvertebrate, and plant assemblages) of streams, rivers, and riverine impoundments will likely be affected as climate change affects the temperature, chemistry, and other characteristics of aquatic ecosystems (T. Danielson, Maine Department of Environmental Protection, January 2020).

Compounding threats, such as habitat fragmentation and development, may exacerbate these effects, while relatively intact watersheds may be more resilient in recovering from the effects of climate change. For example, macroinvertebrates in a Catskill Mountain river in New York experienced a large decrease in abundance following floods associated with Tropical Storms Irene and Lee (Smith et al. 2019). The macroinvertebrate community recovered during the next year, which may have been facilitated by having a relatively undisturbed watershed. Already stressed streams, such as those in urban and urbanizing areas, are likely less able to recover.

The following characteristics of streams could be altered by climate change, which could subsequentially impact aquatic life:

- Increased water temperature could lead to extirpation of certain aquatic species from some stream or river segments.
- Alteration of magnitude, duration, and seasonality of flood and drought events could alter geomorphology of streams, rivers, and floodplains. These changes to hydrology and geomorphology could reduce habitat quality for aquatic life.

- Seasonal changes in stream flow and water temperature could disrupt the timing of reproduction and growth of certain aquatic species with specific environmental requirements.

- Increased water temperature and changes in stream hydrogeomorphology as a result of changes in stream flow and access to floodplains could negatively impact endangered and threatened species, such as the Tomah Mayfly and Roaring Brook Mayfly.

- Prolonged periods or increased frequency of drought could harm aquatic life communities of headwater streams. Long-lived species, such as freshwater mussels, could be extirpated from streams and sections of rivers if they dry often.

- Shifts in hydrology and water temperature could promote blooms of phytoplankton or benthic algae and subsequently alter dissolved oxygen concentrations and pH.

- Changes in food sources could alter the relative abundance of macroinvertebrates with different eating habits (*e.g.*, shredders, collector-filterers, predators, scrapers) (Jourdan et al. 2018).

- Alteration of fish assemblages could impact mussels that require certain species of fish as hosts for their larval stages (glochidia).

The thermal tolerances of fish and some macroinvertebrates are already available in the scientific literature, and the Maine Department of Environmental Protection has computed (but not yet published) additional provisional thermal tolerances of stream fish, algae, and macroinvertebrates in Maine. These data can be used to create multi-species indexes that could quantify the overall thermal preference of an assemblage of organisms collected at a site (T. Danielson, Maine Department of Environmental Protection, January 2020).

Fisheries

Climate change is altering the abundance, growth, and recruitment of some North American inland fishes, particularly coldwater species (Lynch et al. 2016). These impacts occur largely through physiological changes in neuroendocrine, cardiorespiratory, immune, osmoregulatory, and reproductive systems of freshwater and diadromous fishes (Whitney et al. 2016). Climate-induced fish declines are often coupled with anthropogenic threats. A recent assessment of 136 studies suggests that species interactions are often the immediate cause of localized extinctions due to climate change (Lipton et al 2018). However, vulnerability to climate change is variable due to a species level of exposure, sensitivity to change and adaptive capacity.

Migratory and riverine Salmonid species throughout North America also are being affected by decreased snowpack, decreasing summer stream flow, higher storm intensity and flooding, physiological and behavioral sensitivity, and increasing mortality due to warmer stream and ocean temperatures (Lipton et al 2018). Warmer summer air temperatures lead to increased stream temperatures and reduced suitable habitat available for trout (Rummel 2017). Increased storm activities cause erosion and an increase in sedimentation, thus reducing food sources and limiting trout movements.

Maine's Eastern brook trout population is especially important for long-term biodiversity conservation because they are especially adaptable to temperature increases as high as 6°C (J. Reardon, Trout Unlimited, personal communication, December 2019). Reestablishing stream connectivity or assisting migration in fragmented systems is an important strategy to allow trout access to suitable conditions and thermal refugia during stressful events or seasons

(M. Gallagher, Maine Department of Inland Fisheries and Wildlife, personal communication, January 2020) Similarly, for coldwater species that primarily live in lakes and ponds (such as Arctic charr, lake whitefish, and lake trout), the ability to evade stressful conditions or recolonize evacuated habitats is severely compromised when coupled with other anthropogenic threats such as invasive or competing species, pollution, or degraded habitat conditions.

Climate change will affect Atlantic salmon, whose southern limit occurs in Maine (E. Zimmerman, Maine Department of Environmental Protection). The Gulf of Maine distinct population segment was listed as endangered in 2000, with an expanded listing in 2009 due to further population declines (USFWS-NMFS 2018). The most sensitive life stages of Atlantic salmon occur during the freshwater period of their life cycle (eggs, yolk-sac fry) and as they transition to saltwater as smolts (Elliot and Elliot 2010). The abundance of Atlantic salmon across the species' range has decreased over the past 20-30 years by 88%, with populations at the southern edge being the most impacted (Chaput 2012, ICES 2017). Spring stream flows are occurring 4-8 days earlier over the 1913-2002 time period (Hodgkins and Dudley 2006). High winter flows can disrupt ice formation, create ice jams, and cause flooding which can damage in-stream salmon habitat. Stream temperatures across Maine are already exceeding stress thresholds for optimum salmon growth (USFWS-NMFS 2018). Migrations of smolts are occurring 2.5 days earlier per decade, corresponding with increases in spring stream temperatures (ICES 2017, Otero et al. 2013).

The Northeast is expected to experience increased temperatures and increased variability in precipitation, which increases the risk of floods and droughts, and reduces water quality (IPCC 2014). Some salmon populations risk significant reductions in abundance, or possibly even extinction at the southern edge of their range (ICES 2017). Increasing temperatures can lead to increased growth, as long as temperatures remain below lethal or stressful thresholds (ICES 2017). However, increasing temperatures can also alter the timing of spawning, egg hatching and emergence of larvae, which could lead to a mismatch with optimal food availability both in freshwater habitats and in the ocean (ICES 2017, Jonsson and Jonsson 2009). Increasing temperature can also increase susceptibility to disease (Jonsson and Jonsson 2009). Changes in hydrologic regimes, especially extremes in water flow, can decrease recruitment and survival of salmon due to a lack of water or flood damage (ICES 2017).

Common Loons

Climate change may be affecting loon behavior and exposure to infectious diseases. Hanson (2016) found that an increase in temperature inversely correlated to the success and viability of nests and their chicks because "As temperatures rise, adults spend more time off the nest to cool off, leaving the eggs prone to predators." National Audubon Society's report, Survival by Degrees, published findings (Wilsey et al., 2019) showing that a 5.4°F (3°C) temperature increase over pre-industrial temperatures could cause one fourth of the loon's breeding range to become unusable for the birds. In addition, the Loon Preservation Society found a strong negative correlation between hotter temperatures and successful nests (Vogel et al. 2019).

Another issue climate change brings is the northward migration of infectious diseases found in birds, which has already seen among loons. Prior to the last few years, these diseases were primarily noted in southern, warmer climates of the United States (Associated Press 2016). Pokras (2018) wrote that the instances of avian malarial parasites in New England loons has increased significantly in recent years, and at least one death from the parasite has been documented. Mortalities of avian malaria have also been documented in New Hampshire in 2019 but may have been occurring since 2011 (M. Pokras, personal communication). In addition to malaria, West Nile virus, Type E botulism, and Avian Pox have been recorded in northern New England (McCarthy 2010).

Mink Frogs

Mink frogs (Figure 9) are a coldwater adapted species occurring at the southern edge of their range in Maine and other northern U.S. states. This species is associated with well-oxygenated ponds and wetlands but is often undetected throughout its range due to late-night peak calling times outside of typical call surveys (Shearin et al. 2012) and cryptic egg masses (Patrick et al. 2012). With warming temperatures leading to lower dissolved oxygen in breeding wetlands, suitable mink frog habitat may shift northward and lead to local extirpations (Popescu and Gibbs 2009; Patrick et al. 2012; MDIFW SWAP 2015).

Figure 9: Mink frogs are a Species of Greatest Conservation Need in Maine due to their dependence on cold water, well-oxygenated breeding wetlands that are vulnerable to warming temperatures (Photo credit: Jonathan Mays, MDIFW).

Wood Turtles

Wood turtles are at risk throughout their range from habitat loss and fragmentation, illicit collection for the pet trade, and direct mortality from farm machinery and vehicles at road crossings (Figure 10).

Because these turtles make use of uplands several hundred meters and even up to a kilometer from the sandy river and stream shores they nest along, they are more at risk of road kill than many other turtles. Similarly, to tiger beetles (described below), the free movement and reworking of sediment in tributary and mainstem floodplains is crucial to forming and maintaining nesting beaches and bars and structurally complex habitats for this species. Increased flooding frequency and intensity may damage or destroy these nesting habitats, thus further compounding other species threats (MDIFW SWAP 2015).

Figure 10: Due to compounding threats from climate change, habitat fragmentation, and poaching, wood turtles are a Species of Greatest Conservation Need in Maine (Photo credit: Jonathan Mays, MDIFW).

Tiger Beetles

Maine's streams and rivers provide habitat to two extremely rare species of tiger beetle: the cobblestone tiger beetle (discovered in Maine in 2014 in only one location) and the White Mountain tiger beetle (found in seven river sites statewide) (Figure 11). Rivershore tiger beetles require well-sorted gravel to cobble substrate that remains free of vegetation.

Increased storm magnitudes may open and sort gravel bars regularly, but disturbances that are too frequent or intense could strongly impact breeding and larval stages when stable substrate is needed. Severe floods could damage or destroy the few locations these species are found and potentially extirpate these species from Maine (MDIFW SWAP 2015).

Figure 11: The cobblestone tiger beetle is found in only one location in Maine, where its riverside habitat is vulnerable to increasingly severe storms and flooding (Photo credit: Jonathan Mays, MDIFW).

Furbish's Lousewort

The St. John River is unique in Maine and the eastern U.S. in having its ecology driven in part by the behavior of ice scour (Appendix D). When the ice goes out on the river at the spring thaw it often severely scrapes and gouges the banks, with the net effect that taller woody vegetation (trees and shrubs) cannot persist and therefore other low growing shrubs and herbs can form unique plant communities. These habitats are considered rare in Maine and support numerous rare plant species including Furbish's lousewort, which grows nowhere else in the world (D. Cameron, Maine Natural Areas Program, personal communication, December 2019).

The Furbish lousewort is uniquely vulnerable to the changing climate, not only due to the very small number of populations in the world (limited to Saint John River in Maine and a couple subpopulations in New Brunswick, Canada) but also due to its dependence on precise ice scour conditions that needs to be "not too frequent or too infrequent and not too severe" (McCollough 2018). The warming climate is starting to affect this system by increasing the frequency and severity of ice events causing both direct impacts to the vegetation as well as erosion of the riverbank. Studies by Baltaos et al. (2002) have shown that the number of days above freezing during the coldest months (January and February) on northern points of the river is increasing, and that this warming trend is correlated with mid-winter rains and subsequent mid-winter ice break-up. Subsequently the river freezes again, often with jumbled blocks of ice, that can make the eventual spring ice-out event more severe. This increased frequency of ice-out events appears to increase the impacts to the river bank including preventing heavily scraped or unstable bank areas from being successfully recolonized by plants, which then increases the banks vulnerability to continued erosion and instability.

Long term monitoring of Furbish's lousewort has shown the decline of the species at a number of sites where repeated disturbances to the river bank promote erosion and prevent the recolonization of vegetation. Several populations already have reduced resiliency due to highly unfavorable ice scour events. The composition and the extent of river ice is changing; freeze up areas are occurring higher than normal and the ice cover thickness is increasing. McCollough (2018) writes that in the worst-case scenario (a warming of 4.5 °C by the year 2060), "the Furbish lousewort may still occur at a few upriver subpopulations but the subpopulations will not be resilient and the metapopulation may not be viable" (p. 58).

Freshwater Wetlands

Maine is covered in over two million hectares of freshwater wetlands, from small emergent wetlands to large peatlands. Maine wetlands represent close to 25% of the state's land area (including 64,000 hectares of coastal wetlands), which is four times the wetland areas of the other five New England States combined (Maine DEP 2003). Biological communities and ecosystem services in both inland and coastal wetlands may be profoundly affected by climate change-induced threats including increased temperature, sea level rise, changes in frequency, duration and magnitude of precipitation, drought, snowmelt, altered water levels and flow regimes, and increased contaminated runoff (e.g. excess nutrients, sediment, toxics) (ASWM 2015).

Impacts on Ecosystem Services

Wetland ecosystem services including flood protection, carbon sequestration, water quality protection (i.e. nutrient, sediment and toxic contaminant retention), stream flow maintenance, groundwater recharge/discharge, shoreline stabilization, aquatic life and wildlife habitat, recreational uses, and economic benefits may be severely impacted by climate change induced changes in temperature, precipitation, extreme weather events, contaminated runoff, and sea level rise (Moomaw et al. 2018). Results from EPA's 2011 National Wetlands Condition Assessment, including Maine data, indicate that freshwater inland wetlands collectively hold nearly ten-fold more carbon than tidal saltwater sites and are therefore vital to regional carbon storage (Nahlik and Fennessy 2016; J. DiFranco, Maine Department of Environmental Projection, personal communication, January 2020).

Impacts on Biological Communities

Climate change may cause loss of wetland habitat and/or major changes in structure due to changing hydrology (i.e., conversion to a different wetland type), alteration of biological community composition, nutrient enrichment and toxic effects to organisms, loss of populations or shifts in range, disruption of reproductive and migration cycles, reduction or loss of rare/threatened species, and increased threats from invasive species (Shorta et al. 2016; J. DiFranco, Maine Department of Environmental Projection, personal communication, January 2020)

Impacts on Aquatic Invasive Species

A warming climate and associated increases in lake water temperature and shortening of annual ice cover duration will result in longer in-water growing seasons that will likely benefit all aquatic macrophytes (John McPhedran, Maine Department of Environmental Protection, personal communication, January 2020). There is some evidence, however, that warmer temperatures will differentially benefit invasive aquatic flora. A study using mesocosms suggests that warmer lake water temperatures due to climate change favors growth of a non-native milfoil species over a native milfoil species (Patrick et al. 2012). Invasive aquatic species have spread to new waters and much of the dispersal has been human mediated. But it is also likely that warming temperatures have made conditions more favorable for invasive aquatic species to become established in new areas. Further warming will only expand the range for invasive aquatic species.

A meta-analysis of non-native species performance in terrestrial and aquatic ecosystems suggests that aquatic systems are more vulnerable to climate change. Primarily in studies of aquatic animal systems, increases in CO_2 and temperature largely inhibited native species while there was a stronger positive response among non-native species (Sorte et al. 2013). Climate change will influence the likelihood of new invasive aquatic species establishing themselves by eliminating cold conditions that currently prevent survival of certain species (Rahel and Olden 2008).

Improved growing conditions for invasive aquatic macrophytes in Maine lakes from climate change will have significant socio-economic impacts. Research in New England has shown declines in property values due to infestations of invasive aquatic plants. In Maine, property valuations were reduced on Lake Arrowhead (Limerick and Waterboro) due to invasive aquatic plant infestation. Apart from socio-economic effects, there may be far-reaching impacts on lake habitats. Additional significant impacts to lake habitats may result from other invasive aquatic taxa.

Waterbirds

Marsh nesting birds, such as bitterns, rails, common gallinules, and black terns are all vulnerable to flash flooding that may result from intense rainstorms, which have been increasing in Maine in recent decades (see Climate chapter in this report). Rapidly increasing water levels can cause nest failure. While some species and individuals may be able to adjust and respond to water level fluctuations to varying degrees depending on site-specific situations, species with small populations in Maine such as the black tern or least bittern may be more severely affected. (MDIFW SWAP 2015; D. D'Auria, Maine Department of Inland Fisheries and Wildlife, personal communication, January 2020).

Peatlands

Drying of peatlands also accelerates carbon release, which may be of concern for Maine if we experience longer drought periods (D. Cameron, Maine Natural Areas Program, personal communication, December 2019). Lower water tables and drier peatlands may also lead to increased colonization of open peat areas by forest, but there appears to be no conclusive information on how peatlands may change in Maine as the climate warms.

Forests

Maine is approximately 90% forested, from scrub oak-pitch pine ecosystems in southern Maine to spruce-fir boreal forests in the north. Maine is the most heavily forested state in the lower 48 United States, and our economy and culture are tied closely to our forests (see the Forestry chapter in this report for more information). Forest ecosystems are covered in greater detail in other Maine Climate Council Science and Technical Subcommittee chapters; however, we describe below several key forest ecosystem dynamics and iconic species likely to be affected by climate change.

Forest Composition

Bose et al. (2017) assessed how the occurrence and abundance of American beech, sugar maple, red maple, and birch has changed between 1983 and 2014 across four northeastern states (Maine, New Hampshire, Vermont, and New York). Their analysis revealed that American Beech occurrence and abundance has increased while the occurrence of the other three study species declined throughout nearly all the study region (including all of Maine). Bose et al. (2017) found that increases in beech occurrence and abundance was primarily linked to higher temperatures and precipitation, although past management practices also likely play a role.

Invasive Pests

Below, we provide two examples of forest insect pests whose impacts in Maine will likely be exacerbated by climate change.

Hemlock Woolly Adelgid

Warming temperatures are one reason the hemlock woolly adelgid is successfully expanding in Maine, though that process has been assisted by the spread of infected nursery stock (and probably low levels of detection when it first became established in some areas). Persistent hemlock woolly adelgid infestations are devastating to hemlock trees. Mature healthy trees survive longer than younger or stressed trees, but still succumb within about 10 years. Loss of hemlock will drastically alter the character of forests where hemlock is a common component. Some sites on north facing slopes or in cool coves and incised drainages in Maine are heavily dominated by hemlock. These sites will be completely transformed if the trees are killed by hemlock woolly adelgid (McAvoy et al. 2017). As hemlocks along streams decline, the forest canopy opens and light levels increase, leading to greater variability in water temperature (Webster et al. 2012) and less desirable conditions for cool-water species such as Eastern brook trout.

Southern Pine Beetle

The Southern pine beetle will likely impact Maine's pine forests as higher temperatures facilitate its continued spread northward. Although New York and Connecticut mark the nearest detections to Maine, the latitude of the northernmost Southern pine beetle sighting has drifted north by 0.8° latitude (~85 km) per decade since 2002 (Lesk et al. 2017). By 2050, climate conditions under all emissions scenarios will be suitable for Southern pine beetles to exist from southern Maine to Ohio (Lesk et al. 2017). While it is unknown when Southern pine beetles will arrive in Maine, they are likely to cause significant damage and eventually death to Maine's native pine species, especially along the coast. White pine and pitch pine are significant components of a variety of forest and woodland types in southern Maine. Decline in these species may cause substantial changes to these forest ecosystems and the local economies dependent on them.

Changes to Snow Pack and Ecological Implications

The ecological impacts of loss of seasonal snow cover and increasing winter and spring air temperatures have been documented both within Maine (e.g., Richardson et al., 2009; Auclair et al., 2010; Patel et al., 2018) and within the New England region (e.g., Comerford et al., 2013; Bergeron and Perkins., 2014; Campbell et al., 2014; Crossman et al., 2016; Lesk et al., 2017). These include changes to beneath-snow soil biological processes, above- and belowground tree health and productivity, and wildlife foraging, nesting, and herbivory (Contosta et al., 2019 and references therein).

Snow acts as an insulator such that a decline in snow depth and duration exposes soils to air temperatures. Loss of snow plus the trend toward warmer winter and spring air temperatures might accelerate rates of soil organic matter and soil nutrient cycling, leading to consequences for forest productivity and water quality that are not fully understood. At the same time, periodic cold snaps that occur in the absence of snow cover can freeze both soils and fine roots (Tierney et al., 2001; Tatariw et al., 2017), resulting in fine root mortality and nutrient leaching (Cleavitt et al., 2008; Campbell et al., 2014), and decreasing forest growth in the following year (Borque et al., 2005; Reinmann and Templer, 2016; Reinman et al.,2019). Warming winters may also impact forest health and productivity by enabling the proliferation of forest insect pests such as the hemlock wooly adelgid and the southern pine beetle. Both these insects die at extreme cold temperatures (between -20 and -30 °C) that have become increasingly rare as winters warm.

Reduced snow cover that accompanies warming temperatures also carries consequences for wildlife, though the effects of changing snow depth, duration, and snow physical characteristics can vary among species and across the winter season (A. Contasta, University of New Hampshire, personal communication, January 2020). For example, larger mammals such as moose may benefit from shallower snow packs that expose more vegetation to browsing. At the same time, later onset of the snowpack and earlier snowmelt can expose moose to winter ticks that are leading to high rates of moose mortality (Dunfey-Ball 2017).

Moose

Moose are a prominent example illustrating the compounding effects of climate change on pre-existing species threats. Maine is home to the largest moose population in the lower 48 United States (MDIFW 2020). However, like many moose populations at the southern edge of their range in North America, moose populations in western Maine and northern New Hampshire have declined over the last decade. While multiple natural and anthropogenic factors affect moose population dynamics (Van Ballenberghe and Ballard 2007), a warming climate is likely exacerbating lethal regional outbreaks of the epizootic winter tick. Winter ticks occur throughout Maine and are a one-host species found primarily on moose and other ungulates (Figure 12).

Figure 12: Moose exhibiting hair loss from abundant winter tick feeding. Photo credit: Sharon Fiedler.

Larvae hatch in late summer, quest for hosts during fall, then feed throughout the winter until molting into adults in the spring (University of Maine Cooperative Extension Tick Lab 2020). Winter tick outbreaks historically caused local declines in moose (Samuel 2004), but the increasing frequency of warmer and shorter winters has led to increased winter tick abundance and more sustained negative impacts across the moose's southern range (Jones et al. 2019). High densities (up to 70,000 ticks per individual) of winter ticks on 9 to 12 month old calves induce an estimated loss of 64%-149% of total blood volume, thus leading to emaciation, severe metabolic imbalance from blood loss, and eventual death (Jones et al. 2019; Table 2). Recent studies in western Maine and New Hampshire indicate winter tick outbreaks caused 70% calf mortalities during 2014-2016 (Jones et al. 2019).

Winter ticks also may affect reproductive success of adult cow moose by draining stored nutrients during the last three months of pregnancy when fetal development requires additional nutrients (especially protein) supplied by the cow's fat reserves (L. Kantar, Maine Department of Inland Fisheries and Wildlife, personal communication, January 2020). Without green nutrient-rich vegetation to eat in winter and faced with constant blood loss from winter ticks, cows become protein deficient and suffer reduced body condition, weight loss, and possible loss of appetite. Heavily infested moose exhibit restlessness and may spend less time feeding and more time grooming. As a result, cows may give birth to underweight calves and may produce less and lower quality milk resulting in reduced calf survival within the first three weeks of life. With poorer body condition in late spring/early summer, cows may also have difficulties defending and caring for calves (Jones et al. 2019). Where historic winter tick outbreaks may have been localized and persisted for 1-2 years, climate change has resulted in region-wide outbreaks in five of the last 10 years in southern-range moose. With increasingly warmer winters, these sustained winter tick outbreaks are expected to expand northward.

	n	NH	*n*	ME	*n*	Combined
Mortality period	53	3 February – 1 May	57	27 February – 2 May	110	3 February – 2 May
Mean (±SD) body mass	35	129±29 kg	37	139±16 kg	72	136±17 kg
% FMF	30	12%	—	—	30	12%
Visual estimate of % FMF	52	<20%	56	26%	108	<25%
Mean (±SD) liver iron concentration	26	97±53 ppm	54	75±37 ppm	80	82±44 ppm
Hair-loss rating		*n* = 53		*n* = 52		*n* = 105
None		11%		16%		14%
Light		28%		46%		37%
Moderate		33%		38%		35%
Severe		26%				13%
Worst case		2%				1%
Lungworm infestation		*n* = 51		*n* = 25		*n* = 76
None		18%		4%		13%
Light (<20)		41%		20%		34%
Moderate (20–50)		27%		32%		29%
Heavy (>50)		14%		44%		24%

Note: FMF is femur marrow fat. Hair-loss rating is based on Samuel (2004).

Table 2: Moose calf mortalities associated with high winter tick infestations in New Hampshire and western Maine in 2014-2016 (from Jones et al. 2019).

Canada Lynx

Like moose, Canada lynx are adapted to cold weather and snow. While stomach contents indicate lynx consume a variety of rodents, their preference for snowshoe hare could further limit their ability to adapt to changing conditions within their environment. The lower 48 marks the southern range limit for Canada lynx with resident lynx populations found in Maine, Minnesota, Montana, Washington and Colorado. Maine's extensive boreal forested habitat and abundant prey supports the largest lynx population in the lower U.S. 48 states. In the future, climate warming is expected to diminish boreal forest habitats and snow conditions at the southern edge of the lynx range. This is especially concerning for areas where habitat is patchily-distributed and perhaps only marginally capable of supporting resident lynx (USFWS 2017a; page 68). The U.S. Fish and Wildlife Service noted that the "observed impacts attributable to climate change that may affect lynx habitats and populations include upslope and northward shifts in species distributions across multiple taxa, decreases in snow cover and duration, and increased wildfire and insect activity in boreal and subarctic conifer forests of Canada and the western United States" (USFWS 2017a, p. 67). Furthermore, climate changes may affect the lynx's ability to traverse habitats, potentially reducing gene flow if population become more segregated. As snow depth and duration declines with climate warming, habitat conditions that provide lynx with a competitive advantage in the northeastern U.S. will likely decline (Siren et al. 2019). However, the timing, rate, and extent of habitat decline due to projected climate warming and corresponding effects to lynx populations is highly uncertain (USFWS 2017a; page 10). And like moose, birds, and other wildlife, the introduction of new and exacerbation of existing parasites and diseases due to warming temperatures may also affect lynx populations.

Marten

Siren et al. (2019) writes: "Based on an extensive, multi-species camera trapping study in Vermont and New Hampshire, researchers determined the probability of occurrence for American marten was positively and strongly associated with both an increase in maximum snow depth and boreal forest biomass. Predicted occurrence was near zero until maximum snow depth reached 120 cm, and increased exponentially between 120 and 190 cm." As with lynx, negative effects of climate warming on snow depth and duration may reduce suitable habitat conditions for marten in the northeast U.S. In Maine, Krohn et al. (2005) predicted that marten would decline with decreased snow pack due to increased competition with fisher.

Songbirds

Eastern forest songbirds, one of our most vulnerable groups, have shown dramatic declines over the past 40-50 years as documented by the Breeding Bird Survey. These declines cannot all be attributed to climate change, but it is very likely climate change is exacerbating declines for some species, and will increase threats to many others, making recovery more difficult.

More than 90 bird species breed in the Maine woods, but the number of species recorded on Breeding Bird survey routes in Maine has

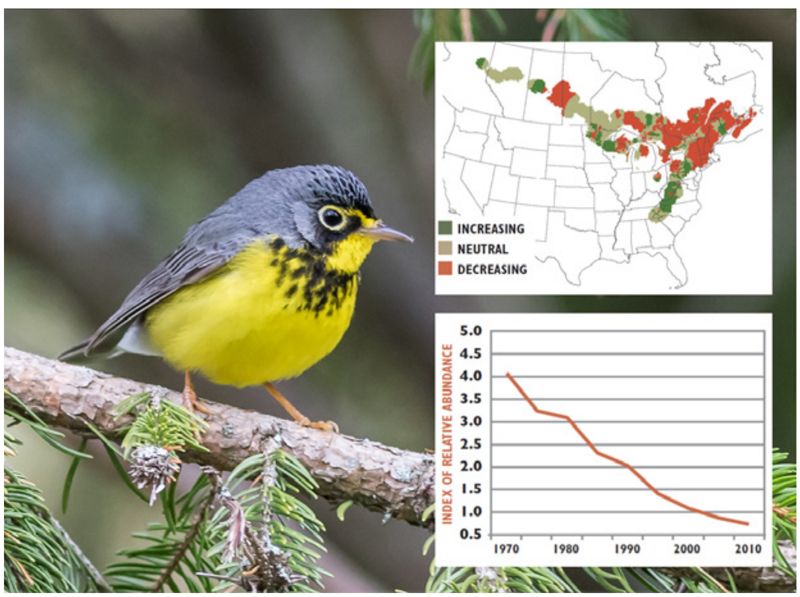


Figure 13: Declines in Canada warbler across North America from 1970 to 2010 based on USFWS Breeding Bird Survey data (From Maine Audobon 2020).

dropped 10-20% in recent years compared to the earliest surveys in the later 1960s and 70s (U.S. Geological Survey, personal communication 2019).

Canada warblers are one of the most at-risk forest songbirds, showing dramatic declines over most of its range, including Maine (Figure 13). While this decline is not necessarily due to climate change, the Canada warbler was ranked as moderately vulnerable by Whitman et al. 2013a) and highly vulnerable by the National Audubon study (Wilsey et al. 2019). This is an example of how already declining species are especially vulnerable to additional threats from a changing climate.

Vernal Pools and Their Organisms

Vernal pools are ephemeral wetlands characterized by a temporary hydroperiod. Spring rainfall and melting snow fill pools in the spring, and evapotranspiration from surrounding vegetative growth draws down pool water in the late spring and summer. While pools may not completely dry every year, they do so periodically enough to prevent successful colonization and reproduction by fish and other organisms requiring a permanent hydroperiod (such as green frog and bull frog larvae). The resulting fish-free environment is critical for successful reproduction by three Maine amphibian species (blue-spotted salamanders, spotted salamanders, and wood frogs) and several species of fairy shrimp.

Life cycles of vernal pool organisms are timed closely with pool hydrology, with breeding and egg-laying associated with spring filling and metamorphosis and dispersal timed with pool drying. Under climate-change predictions of more episodic precipitation and increased evapotranspiration, vernal pools may dry earlier before vernal pool organisms have successfully metamorphosed from aquatic to terrestrial life stages. These changes would adversely affect the successful reproduction of pool-breeding amphibians (Brooks 2004). Also, where vernal pool amphibians exist as metapopulations with regular gene flow among pool complexes, climate change coupled with increased habitat fragmentation may isolate remaining productive pools. Furthermore, changes to winter temperature and precipitation patterns may detrimentally affect hibernacula (overwintering habitat) quality and reduce survival of vernal pool organisms overwintering under the snowpack (Groff et al. 2016).

High Elevation Ecosystems

Montane Species

Montane systems in the northeast United States appear to be relatively stable, but climate change-induced shifts are likely to become more pronounced within this century. According to Wason et al. (2017), due to the warming since the 1960s and continued expected warming, "...the temperature regimes characteristic of the lower range margin of spruce-fir forests are unlikely to be present on many mountains in the region by 2100" (p. 272). While large shifts may not be apparent currently, "The large magnitude of expected warming and associated elevational shifts in climate envelopes are likely to limit the ability of mountains in the northeastern United States to act as refugia for spruce-fir forest species under long-term global warming" (p. 279).

Climate warming is likely responsible for declines of red spruce and paper birch in the northern hardwood-boreal forest ecotone (Beckage et al. 2007), but it is worth noting that this study has been criticized for failing to include a few key aspects, including expected changes post-logging as well. In addition, the "ebb and flow of some alpine species over time, meaning differences between just two samples over time must be interpreted with caution" (K. Kimball, Appalachian Mountain Club, personal communication, December 2019). However, Kimball notes that

"Though the Northeast alpine-forest ecotone boundary has shown to be relatively stable over long periods of time, current climatic changes and nitrogen deposition are now exceeding ranges going back to the last glacial period (K. Kimball, Appalachian Mountain Club, personal communication, December 2019). Sarah Nelson, Director of Research at Appalachian Mountain Club, may summarize this best: "More research is needed to better define the pattern of warming across elevation, but no matter how you slice it, overall both alpine and lower-elevation sites are warming" (S. Nelson, Appalachian Mountain Club, personal communication, December 2019).

Alpine Habitats

In 2016, alpine plots established in 1993 along 26 permanent transects (796 plots) on Franconia Ridge in the White Mountains in New Hampshire were resampled, and the results indicate an increase in shrubby heath vegetation (cranberry, bilberry) in some areas of formerly dominated alpine meadow (sedge cover), and a minor expansion of krummholz cover (Cogbill 2017). While this ecosystem is dynamic and observed vegetation shifts may not be directly linked to climate change (Cogbill 2017), these are the type of initial shifts in vegetation cover expected in alpine areas under warming climate scenarios (D. Cameron, Maine Natural Areas Program, personal communication, December 2019).

Bicknell's Thrush

Climate change will likely negatively affect Bicknell's thrush, a declining species associated with dense montane forests in Maine. The northwest region of the U.S. Fish and Wildlife Service published a Biological Species Report in 2017 highlighting the expected outcomes of climate change, which include: an increase in competition between Bicknell's thrush and Swainson's thrush (which will favor the Swainson's thrush), a significant reduction in the amount of spruce-fir habitat (Bicknell's thrush's breeding grounds), and substantial decrease in wet montane habitats (areas vital to the Bicknell's thrush survival; USFWS 2017b).

Climate change will also exacerbate additional threats to Bicknell's thrush, such as an increased vulnerability to diseases and parasites. Insect infestations from the balsam woolly adelgid, as well as the spruce budworm and the hemlock looper, all have the potential to drastically alter forest environments as they tend to thrive in warmer temperatures (USFWS 2017b). While the Bicknell's thrush may benefit in the short run from forest disturbances, like that of a budworm outbreak (the budworm attacks high spruce and fir, creating younger, denser habitats where Bicknell's thrush may initially thrive), the devastation of repeated outbreaks has the potential to support the potential elimination of the Bicknell's thrush from its current range (USFWS 2017b).

Katahdin Arctic

The Katahdin Arctic is a subspecies of Arctic butterfly found only on the summit of Katahdin in Baxter State Park. This species inhabits the sedges and grasses of Katahdin's tundra-like Tableland along with other alpine species such as the American pipit and northern bog lemming (MDIFW 2003). While the Katahdin Arctic is primarily at risk due to off-trail recreational activities on Katahdin's summit, its tundra habitat is limited and will likely shrink with climate change (MDIFW SWAP 2015). Unless other Katahdin Arctic populations are documented elsewhere, it is possible this subspecies could be completely lost from Maine.

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ADDITIONAL RESOURCES

EPA Plant and Animal Impacts Bibliography This site offers an extensive listing of scientific articles about the impacts of climate change on wildlife. http://www.epa.gov/globalwarming/impacts/imp_blio.html

World Wildlife Fund Climate Change Campaign This site is a gateway to several WWF online reports on the impacts of climate change on wildlife and protected areas. http://www.panda.org/climate/impact.shtml

FORESTRY AND FOREST ECOSYSTEMS

HIGHLIGHTS

Forests currently cover nearly 89% of Maine's area and sequester over 60% of the state's annual carbon emissions, while the forest industry sector is statewide, multi-faceted, and provides between $8-10B in direct economic impact. However, both the natural forest and industry expect significant challenges in the decades to come. For example, the state has some of the highest densities of non-native forest pests in the US, linked to changes in both climate and human behavior, which are expected to continue to increase in the coming decade.

In addition, Maine's forest is a transitional ecotone with a broad mixture of species, which means that changing climatic conditions create significant stress as most species are either at their northern or southern limit. This stress has become even more evident as precipitation events have become more extreme and snowpack has become less continuous as well as more variable, which has significant implications for trees, the broader forest ecosystem, and forest management.

Currently, temperatures in Maine are warming much faster than other areas in the contiguous US, and should increase by 5.4°F (3°C) by 2030 compared to the 3.6°F (2°C) rise globally. All of these factors create high uncertainty for the forest industry as they could influence wood supply, harvesting, and transportation as well as the future composition and structure of Maine's forest. In addition, exotic pests like Emerald ash borer threaten key cultural aspects.

- Forest productivity will likely be more variable with some portions of the state seeing greater growth due to a longer growing season and more favorable climate, while other areas will decline due to the increased occurrence of drought. In short, the forest response to climate change will be complex and difficult to predict given the range of conditions and species present in Maine's current forest as well as variation in future management practices.

- The spruce-fir forest type will likely decline as a result of less snow and warmer winter temperatures, but some supplementary suitable habitat along the southern edge of species' ranges will generally persist. Hardwoods, particularly paper/yellow birch, red maple, and red oak are expected to displace spruce-fir with a much greater fraction of the landscape considered as a mixed forest type.

- Policy recommendations based on Maine's forest carbon cycle require adequate measurements and monitoring of all carbon pools and fluxes. While some of those pools and fluxes are regularly measured in Maine, many are not, leaving considerations of offsets a challenge. A recent analysis estimated that ≈50-60% of Maine's greenhouse gas emissions are offset by forest growth, and ≈75% are offset by forest growth and durable products. Note that this estimate is also intended as a first approximation that both provides insights on Maine's dynamic carbon cycle, but also highlights the challenge and complexity of the task that will require research and monitoring to improve carbon cycling calculations and tracking over time.

- Primary recommendations include: (1) improved monitoring of key forest attributes like species composition, health, growth, and carbon; (2) revised projection models that cover a broader array of potential future scenarios; (3) improved tools to help with decision-support and forest management planning; (4) a greater number of studies that evaluate and assess the human behavior component of forest management; and (5) increased linkages between forest researchers, land managers, and policymakers to ensure long-term sustainability.

DISCUSSION

Maine Forest's Importance to State's Annual Carbon Budget

Carbon Pool	% of State's Annual Fossil Fuel Emission
Forest carbon uptake as net annual growth	60.03%
Durable Forest products	15.39%
Total forestry sector	75.43%
Net Land Sink	78.15%

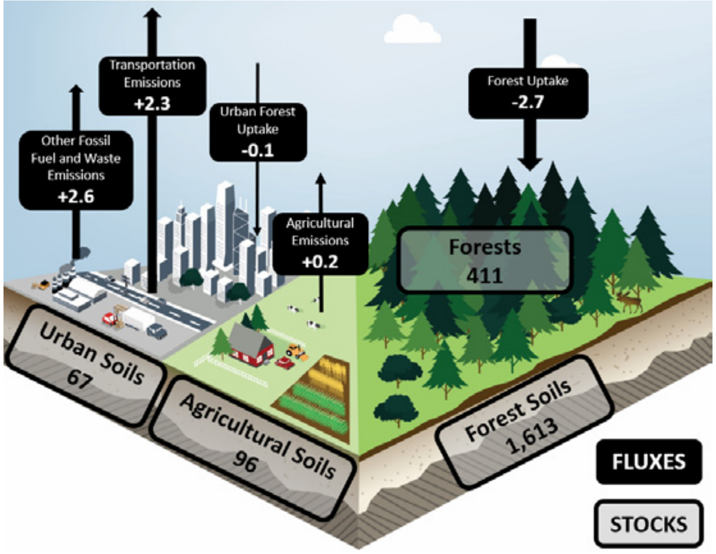

Figure 1. Estimates of Maine's forest sequestration as a fraction of the state's annual fossil fuel emissions and annual fluxes as well as stocks for forests and other land uses in Maine between 2006 and 2016. More information, including data sources and references, can be found online by visiting the University of Maine's Forest Climate Change Initiative URL: crsf.umaine.edu/forest-climate-change-initiative/carbon-budget.

With nearly 89% of Maine's landscape in forests (Figure 2), Maine forests remain a central focus in considering both the impacts of climate change, as well as the contributions of forests in providing an array of ecosystem services, including forest contributions to reducing greenhouse gas concentrations in the atmosphere (as in, carbon sequestration).

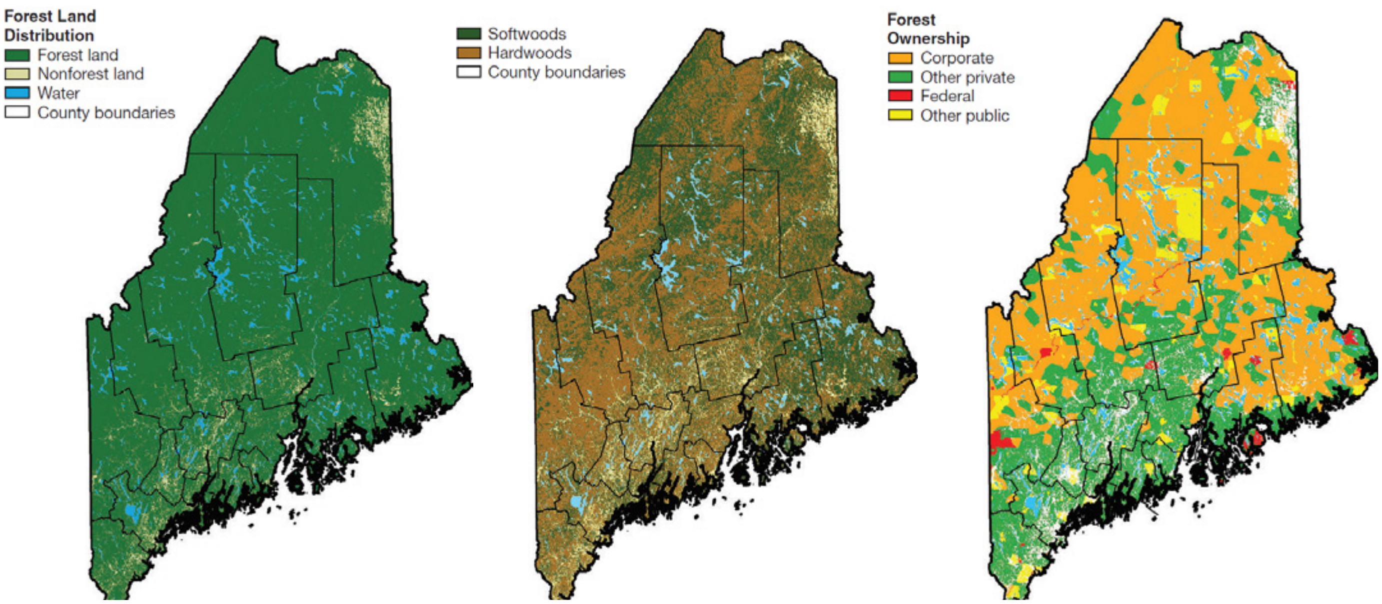

Figure 2 - Characteristics of Maine Forests, 2103 (from McCaskill et al. 2016).

The impacts of climate change on Maine forests encompass operational concerns about harvesting on frozen soils as we see evidence of a declining winter, washed out roads from intense rain storms, to the impacts of health risks from vector-borne diseases on people working and recreating in the Maine Woods. However, the first thing many people think of with regards to the effects of climate change on Maine forests is that some species will be lost, while more southerly tree species will gain prominence in the landscape. Changes in forests will reflect complex interactions that can occur with the simultaneous changes in temperature, precipitation, atmospheric concentrations of CO2, and other air pollutants like acid rain and ozone.

Maine's forest composition has shifted in response to a changing climate over millennia (Jacobson et al., 2009). Today's spruce-fir forests are relatively recent, with their populations having expanded southward in the past 500-1,000 years. Maine will continue to have abundant forests, but the composition of the forest and the way trees grow in the future will be different from today. Warmer temperatures and the potential fertilization effects of CO2 and nitrogen may promote accelerated tree growth. Increased disease, insect infestations, and forest fires threaten to temper predicted increases in fiber production. Forest management will play a critical role in maximizing forest utilization opportunities and resilience, while maintaining forest sustainability and enhancing carbon storage.

Anticipating Maine's Future Forests

A useful resource to learn about the current extent of individual tree species in the Northeast and anticipated extent under different future climate scenarios is the USDA Forest Service Climate Change Tree Atlas (Prasad et al. 2014). This resource predicts future environmental conditions and therefore the suitability for individual species, not the presence or absence of the trees themselves. More recently, Janowiak et al. (2018) carried out a comprehensive vulnerability assessment for forests in the Northeast. In their work, model projections suggested that many northern and boreal species, including balsam fir, red spruce, and black spruce, may fare worse under future conditions, but other species may benefit from projected changes in climate. Their vulnerability assessment included published literature on climate impacts related to wildfire, invasive species, and forest pests and diseases in the overall determination of climate change vulnerability. Montane spruce-fir, low-elevation spruce-fir, and lowland mixed conifer forests were determined to be the most vulnerable communities. Central hardwoods, transition hardwoods, and pitch pine-scrub oak forests were perceived as having lower vulnerability to projected regional changes in climate. These projected changes in climate and the associated impacts and vulnerabilities will have important implications for economically valuable timber species, forest-dependent animals and plants, recreation, and long-term natural resource planning.

Duveneck and Thompson (2019) reported that future forests of eastern North America will be shaped by at least three broad drivers: (*i*) vegetation change and natural disturbance patterns associated with the ongoing recovery from colonial era land use, (*ii*) a changing climate, and (*iii*) a land-use regime that consists of geographically variable rates and intensities of forest harvesting, clearing for development, and land protection. These researchers evaluated the aggregate and relative importance of these factors for the future forests of New England, USA by simulating scenarios for 50 years, nominally spanning 2010 to 2060, including a control with no future land use or climate change, a scenario with continued recent land use, and one with climate change. In the control scenario, the simulated landscape experienced large increases in average aboveground carbon—an increase of 53% from 2010 to 2060 (from 4.2 to 6.3 kg m^{-2}). Adding climate change increased aboveground carbon stores by 8% relative to the control, while the land-use regime reduced aboveground carbon by 16% by 2060.

Using a similar model framework as Duveneck and Thompson (2019), Simons-Legaard et al. (2013) modeled Maine future forests and reported that although suitable climate conditions for spruce-fir will decline as a result of less snow and warmer winter temperatures, habitable patches will remain in the Northeast through 2090 for all but white spruce (*Picea glauca* (Moench) Voss). Ecosystem resilience will help ensure the spruce-fir distribution in

Maine is likely to remain largely unchanged over at least the next 50 years. Ultimately, broad-scale climate models may overstress climate change effects on northeastern spruce-fir forests over the next century. In the Simons-Legaard et al. (2013) study, timber harvesting rates had greater influence on future forest composition in Maine than did long-term climate change. Indeed, despite the historical pressures from atmospheric acid deposition and emerging climate change on spruce, the existing red spruce (*Picea rubens* Sarg.) in New England have recently shown evidence of improved growth. Researchers attributed this improved red spruce growth to recent decreases in acid deposition and more favorable climatic conditions that they said could persist in the short-term, particularly for red spruce at high elevations (Kosiba et al. 2018).

Andrews (2016) reported that key differences in projected habitat occur due to variations in the underlying data and the specific dependent variable. The addition of historical tree data revealed supplementary suitable habitat along the southern edge of species' ranges, due to marginal dynamics potentially overlooked by approaches relying solely on current inventories. Likelihood models provided an adequate surrogate to abundance models, reflecting gradients of suitable habitat. Black spruce (*Picea mariana* (Miller) B.S.P.) responded the best to abundance modeling, due to this species' uniform range. White spruce consistently performed the worst among all species for each model, due to this species' wide distribution at low abundances. The developed presence/absence models could assist in understanding the full range of climatically suitable habitats, while abundance values provide the ability to prioritize suitable habitat based upon higher abundance. The maximum stand density index models from Andrews et al. (2018) indicated a decline in stockability for most species examined, particularly at the southern range of spruce-fir forest. These maximum stand density index models could be utilized for the construction of climate-sensitive Density Management Diagrams and the active management of future landscapes based on robust size-density relationships.

American beech (*Fagus grandifolia*) appears to be gaining prominence in Maine forests, supporting the concept of changing forest community composition in the future. Bose et al. (2017) studied changes in northern New England forest composition over the past three decades and reported a substantial increase in the abundance of American beech, whereas the occurrence and abundance of sugar maple, red maple, and birch all declined. The increase in American beech was associated with higher temperatures and precipitation, pointing to climate as a contributing factor. Their study also underscored the importance of the interaction between management and climate in governing forest composition response. Increasing American beech composition is generally viewed as a challenging trend given its susceptibility to beech-bark disease, its relatively low commercial value, and its capacity to limit the regeneration of other more desirable forest species.

The longer-term effects of climate change on forests in Maine to the end of the century and beyond are logically more uncertain. As research and monitoring continue, we will both better understand some of the processes of change, as well as discover new factors not previously considered that will influence future forests. For example, Miller and McGill (2019) recently introduced the concept of a regeneration debt for forests of the northeastern U.S. Regeneration deficit or debt can threaten the long-term health of forests if too few juveniles are present to replace the mature trees of the existing species. This can occur if there is no regeneration or regeneration is of the wrong species to replace the existing mature forest. They found evidence this was occurring from their analyses of tree species occupying the more mature forest canopy versus ground level regeneration from monitoring data for the region. They reported a relatively low regeneration debt in the northern region that included Maine (meaning sufficient juveniles exist to replace forests), but a high regeneration debt in the middle Atlantic zone. This has implications for the ability of tree species to migrate northward in response to a warming climate. As with most climate change effects, other factors were also important in explaining their results, sometimes more so than the climate effects, that included deer browsing pressures and invasive species in the region. Taken together, the most recent findings about climate change effects on Maine forests underscores the complex interaction of multiple factors, the increasing importance of climate change as one of those factors, and shows emerging evidence of forest change today with more to come.

Impacts on Forest Physiology

Climate change in Maine will expose forests and trees to novel climate conditions that are beyond what they have experienced in the recent past. Experimental and observational studies from Maine and the broader region suggest that the benefits for trees of longer growing seasons and increased CO2 concentrations will usually be outweighed by the negative effects of increased heat and drought stress (both atmospheric drought from dry air and soil drought) and extreme climate events. Although seedlings and saplings are often protected by the forest canopy, these early life stages are particularly vulnerable to climate change and extreme events. The strongest negative impacts are likely to manifest during years of high heat and low growing season precipitation, which are expected to drive shifts in forest composition and structure.

For example, Lienard et al. (2016)our ability to predict exactly how and where forest characteristics and distributions will change has been rather limited. Current efforts to predict future distribution of forested ecosystems as a function of climate include species distribution models (for fine-scale predictions took a stress tolerance model approach to predicting climate change driven impacts on forests that suggested that Maine's forests may be particularly vulnerable to future heat and drought. The combination of low drought tolerance of most native trees, increased variability in rainfall, and rapid warming combine to suggest that large portions of Maine are expected to experience climates that surpass native trees' drought tolerance and that this likelihood increases with the amount of warming. Recent experimental studies by Reich et al (2018) underscore the negative impact of modest water limitations and warming temperatures on photosynthesis of temperate and boreal trees. Experimental warming of temperate trees at their northern range margin increased photosynthesis, but decreased photosynthesis for boreal trees at their southern range margin, like balsam fir. Importantly, moderately dry conditions eliminated the benefit of warming to temperate species and further reduced photosynthesis for boreal tree species.

Comerford et al (2013) reported that increased variability in winter weather is likely to drive ecosystem change at many trophic levels (for more information on changing winter weather, see the Climate and Hydrology chapters in this report). Experimental snowfall removal in a northern hardwood forest simulated the variability in future winter conditions and the impact on forest trees. This study found that removing the snowpack led to reduced shoot growth in trees that lacked the insulating layer of snow. Soil freezing changed the soil chemistry to reduce available soil nutrients for tree growth. Patel et al. (2018) showed how concrete frost formation in winter due to soil freezing and a loss of snowpack in a Maine conifer stand resulted in increased nitrogen losses that they attributed to damage to soil microbial communities and fine roots.

The CO_2 fertilization effect due to rising atmospheric CO_2 concentrations is widely considered a benefit for forests that may increase growth (e.g., Talhelm et al. 2014). However, experimental and ecophysiological models find that there are often other constraints on tree growth limiting the trees ability to take advantage of the additional CO_2. In a study by Sperry et al. (2019), the authors find that the CO_2 fertilization effect is only beneficial in the absence of extreme climate warming, which would lead to reduced tree growth and increased mortality. As forests experience novel climate conditions, it is unclear the extent to which they can acclimate to the new climate stresses. D'Orangeville et al. (2018) found that tree growth in eastern North America declined during dry and hot conditions during the 1985 to 2005 period. The authors examined the growth of 270,000 boreal forest trees modeled for future climate conditions and found that for some trees, moderate warming (2 °C or less) was expected to enhance growth in portions of the range. However, continued warming beyond ~2 °C was expected to reduce tree growth, particularly in southern portions of their range like boreal species growing in Maine.

Forests Pests and Pathogens

Warmer winter temperatures and increased variation in precipitation will impact tree pests and disease in the forests. Warmer falls and winters will likely decrease risk of spruce budworm outbreaks in spruce-fir forests (Cooke 2014) but will allow the hemlock woolly adelgid (Livingston et al. 2017) and balsam woolly adelgid (Kanoti 2006) to spread further inland from the coast (see Figure 3). The southern pine beetle may begin to infest pitch pine in coastal areas as minimum winter temperatures increase (Dodds et al. 2018). Beech bark disease is favored by warmer winters and drier summers (Kasson and Livingston 2012). Drought episodes increase risks of tree mortality in stands suffering from other pest problems and in unmanaged, high density stands (Livingston and Kenefic 2018). Drought will also increase the risk of gypsy moth defoliation due to reduced parasitic fungal infections (Stafford 2019). Increased precipitation in spring increases the risk of foliar pathogen damage, especially in eastern white pine (Costanza et al. 2018).

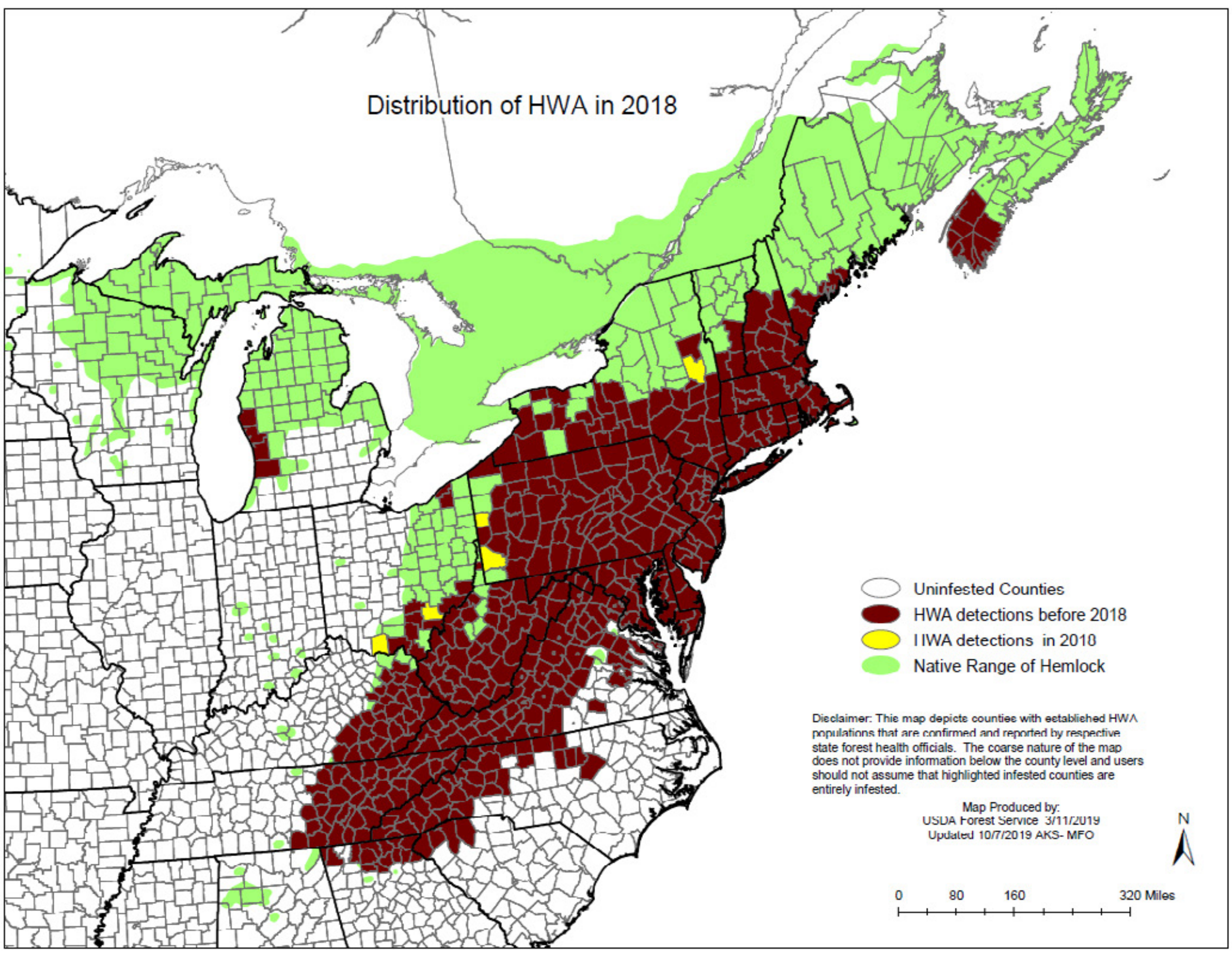

Figure 3 - Hemlock woolly adelgid distribution. (Maine Department of Agriculture, Conservation and Forestry).
https://www.maine.gov/dacf/mfs/forest_health/insects/hemlock_woolly_adelgid_overview.htm

Wildfire in a Climate-altered Maine

Wildfire requires heat (a spark) and fuel (live and dead wood) to burn—and that fuel must be sufficiently dry for the spark to catch and spread (Whelan 1995; Pyne 2019). Tropical rain forests, for example, have plenty of fuel, but, generally lack a spark and are too wet for wildfire, except where altered by humans. Deserts are sufficiently dry, occasionally have lightning, but usually lack a continuous fuel bed for fire to spread. Many ecosystems in between those extremes have the right combination of spark, fuel, and aridity for wildfires to occur at regular intervals.

As a generalization, natural wildfire was not a major component of the Maine landscape in the period before Euro-American settlement (see Barton et al. 2012, 88-89 for a review). Wildfires have occurred since settlement, the most famous being those of 1825 and 1947, but these have largely been the result of human negligence often associated with land use (e.g., large slash piles). These fires, when they occur, have profound influences on forest composition, function, and carbon for decades or more (e.g., Patel et al. 2019). Although Maine has abundant fuel for fire, lightning strikes on the ground are not as common as in other regions. Even more important, the fuel in Maine's forests is too moist to burn easily, except during very severe and prolonged droughts.

What do climate projections relevant to drought suggest about wildfire in the future? Predictions for precipitation and moisture regimes are somewhat uncertain, with evidence already for higher frequency and intensity of precipitation, but potentially more drought (Fernandez et al. 2020). Temperature, precipitation, snow pack, wind, and lightning frequency—as well as the seasonal timing of these factors—are essential ingredients for any predictions about future fire regimes in Maine. Although the climate will likely change in ways that increase and decrease fire risk in complex ways, the balance of parameters suggests overall increased fire risk. Higher temperatures alone will create conditions conducive to wildfire—drought and larger lightning storms.

It is likely that, although summer rainfall events will be larger because of the increase in moisture-holding capacity in the atmosphere due to warming, the time between these large events may also increase. It takes little time for high temperatures to dry out fuels and increase fire risk probabilities, suggesting that the future may bring both wetter and drier periods during the potential fire season. On the other hand, warmer air is correlated with lower wind conditions in Maine (Ambrette et al. 2020), which should reduce wind-driven wildfire conditions in a hotter future.

In summary, two chief drivers—average and variation in temperature and fuel moisture—point to enhanced fire risk, but countervailing forces may mitigate that trajectory. Even if conditions are wetter overall, higher temperatures, especially in the more pessimistic socioeconomic scenarios, will probably create more windows of vulnerability for wildfire. As climate projections become more refined, modeling this system of variables should help clarify likely changes in fire risk.

Despite the lack of projections with high certainty, the future risk of wildfire should still receive serious attention in Maine for several reasons. First, Maine forests exhibit very high live and dead fuel loads, which, under dry conditions, could support high-severity wildfire (McCaskill et al. 2016). Second, wildfires are a major contributor to carbon emissions, although calculating these is challenging (van der Werf et al. 2017). Third, Maine is not well positioned to deal with frequent, large, or intense wildfires. Compared to more fire-prone states, we lack the firefighting infrastructure to quickly mobilize to fight fires, especially large ones. Fourth, a large portion of Maine's housing stock is in close proximity to fuel (forests). Ideas such as "defensible space," an integral part of real estate lexicon elsewhere, are largely unknown in Maine because of the low risk of fire today. Housing development in the wildland-urban/rural interface has greatly exacerbated problems associated with wildfire in the West and elsewhere. Maine homes have been located in this zone for a very long time, and it would be challenging to discourage such housing development in the future. Finally, and often not recognized in fire risk projections, wildfire poses not just direct risks to people, buildings, resources, and ecosystems, but also indirect impacts. The Fourth National Climate Assessment (USGCR 2018a), for example, points out that "More frequent and severe wildfires due to climate change pose an increasing risk to human health through impacts on air quality… Wildfire smoke can travel hundreds of miles, as occurred in 2015 when Canadian wildfire smoke caused air quality exceedance days in Baltimore, Maryland." This suggests that a complete assessment of wildfire risk for Maine must include fire risk well beyond our borders.

Forest thinning and prescribed fire are employed to reduce the risk of high-severity fire in very fire-prone parts of the USA. Such forest management is appropriate in only a few, uncommon ecosystems in Maine, such as the "barrens" of York County, where they are already being employed (e.g., Patterson and Duveneck 2004). Elements relevant to wildfire forecasting—lightning strike incidence, fuel moisture, fuel loads, ambient vapor pressure deficit—should become a standard part of the monitoring system of weather and forest conditions in Maine. Such continuous assessments, along with other weather variables (e.g., drought) already measured would provide an early warning system for trends signaling increased forest fire risk.

Forest Carbon

When we talk about carbon in forests, we are typically referring to organic carbon, or carbon that was originally in the atmosphere as CO2, was taken up by forest vegetation through photosynthesis and turned into various organic compounds, and then is returned to the atmosphere as CO2 when that organic matter is decomposed by microbial respiration (after a leaf, branch, root, or tree dies). Some of that organic carbon is stored for various lengths of time as dead organic matter in forms we know of as coarse woody debris, litter, and soil organic matter (Figure 4). Eventually, the stored organic carbon does return to the atmosphere. Soil organic matter itself has an infinite variety of chemical compositions, but for practical reasons is often divided into various phases that decompose relatively quickly (months) through phases that decompose slowly (centuries to millennia). Various methods exist to measure these fractions, such as those described by Parker et al. (2002) for several Maine watersheds. The exception would be fossil carbon that gets locked away on geologic timescales for millions of years.

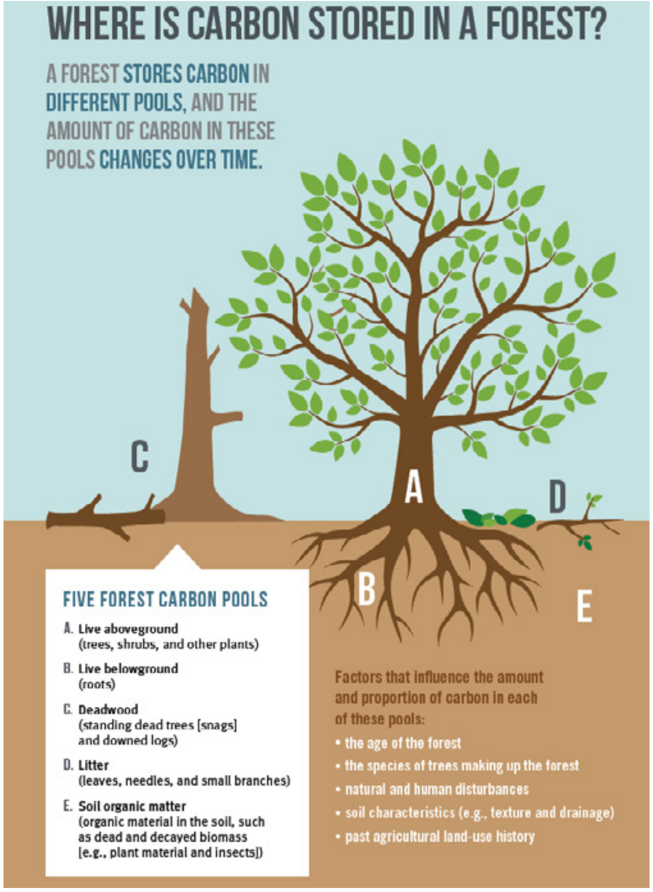

Figure 4 Generalized forest carbon budget components (from Catanzaro and D'Amato 2019).

Accurately measuring carbon cycling in forest stands typically requires intensive and long-term research. These studies become increasingly valuable over time as we address questions about carbon sequestration, and the implications of management alternatives on carbon, because ecological processes unfold on timescales from milliseconds to millennia. Several studies in Maine have shown mixed results on the consequences of varying environmental conditions and management on forest carbon. Puhlick et al. (2016) recently reported on the impacts of management on total ecosystem carbon at the Penobscot Experimental Forest in Bradley, Maine, more than six decades after the initiation of selection, shelterwood, commercial clearcut, and reference treatments. They found decreasing ecosystem carbon with increasing intensity of harvests. Puhlick et al. (2020) more recently reported on modeling results of mixed-species forests at the Penobscot Experimental Forest showing how management strategies that maintain overstory stocking levels necessary to regenerate desired species and promote the development of sawlog-sized trees can enhance long-term carbon sequestration in forests with similar species composition and soils. Another study has been conducted at the Weymouth Point Study Area in northern Maine along Chesuncook Lake as a paired watershed experiment with mechanized whole-tree and stem-only harvesting in 1981 (Smith et al. 1986). Recent research evaluated the effects of treatments on ecosystem carbon 35 years later, and found no significant differences in ecosystem carbon, although numerical trends showed the most carbon in the unharvested watershed (Barusco and Grigaitė, 2019). The most intensively studied forest carbon cycle in Maine to date is at the Howland Forest. Stands in this conifer forest are subject to extensive ecosystem measurements combined with eddy flux tower measures of greenhouse gas exchange between the forested landscape and the atmosphere (e.g., Teets et al. 2018). This type of research is essential to improve models of forest ecosystem function based on intensive and comprehensive data collection.

There is strong interest in the ability of forests to take up carbon from the atmosphere thereby enhancing the world's ability to reduce atmospheric greenhouse gas concentrations. Research promoting the use of forests worldwide as a climate solution has both demonstrated the importance of forests in the global carbon budget (e.g., Bastin et al. 2019a), and raised controversies about the potential of those goals (Bastin et al. 2019b). Interest in utilization of forests as part of "Natural Climate Solutions" has been advanced in recent years by work evaluating the ecological and economic factors that determine the potential for forests and farms to sequester carbon at the global and national scales (Griscom et al. 2017, Fargione et al. 2018). These studies often demonstrate the highest value in preserving forests as forests (i.e., avoiding conversion to other uses), and in reforestation, although where forests already exist there is potential for carbon benefits from forest management (e.g., extending rotations or accelerating growth rates via planting, weed suppression, etc.). These studies also underscore the importance of providing financial incentives (e.g., carbon pricing) to drive the efficacy of management alternatives aimed at carbon sequestration goals, highlighting the interplay between the biogeochemistry of forest carbon and economics. Favero et al. (2020) recently demonstrated the complexity of this interaction in their analysis of the interplay between the promotion of wood bioenergy, forest carbon sequestration, and the ecosystem services provided by natural forests at the global scale. They conclude that all of these objectives can be achieved simultaneously with the appropriate policies and economic incentives.

In order to provide initial insights into the role of forests in Maine's carbon cycle, a group of scientists at the University of Maine, with partners at Bates College and the Maine Forest Service, developed a fact sheet in early 2020 representing an initial and preliminary estimate called The State of Maine's Carbon Budget (Version 1.0). Figure 1 shows the simplified budget highlighting the importance of the forest sector. The simplified budget (Figure 1) represents the importance of forest growth in Maine at present in taking up atmospheric CO_2. The full budget estimate follows the framework used by the U.S. Global Change Research Program's Second State of the Carbon Cycle Report (SOCCR2) (USGCRP, 2018b), and includes numerous carbon stocks and fluxes important to consider when determining the impacts on atmospheric greenhouse gases. This exercise offers insight into Maine's carbon cycle but, of equal value to future policy, highlights the importance of monitoring and research in defining current and future carbon cycling in Maine. One of those challenges is in defining the amount of carbon in Maine's soils. Bai and Fernandez (2020) recently evaluated data on soil carbon across all land uses in Maine providing a comparison of the major available public databases in their strengths and weaknesses.

Forest Operation & Management

Climate change influences the way forests function, but also influences how we manage forest resources in a time of rapid environmental change. Rittenhouse and Rissman (2015) used a mixed-methods analysis, combining meteorological records (1948-2012) and timber harvesting reports (1996-2012) with qualitative interviews, to quantify the associations between variability in frozen ground duration and forest manager response in Wisconsin. Results demonstrated substantial reductions in the length of the frozen ground days per season and an increasing harvest of forest types that grow on well-drained soils. Harvest rates for moist or wet-ground forest types declined during winters with high variability in thaw duration. In addition to shifting harvest removal patterns, interviews suggested that loggers have also adapted by operating on marginally frozen soil and roads or "over-weighting" (e.g., loading more than normal on trucks) during transport to the mill, which has important implications for maintenance of road infrastructure.

Winter harvesting on frozen soil conditions can protect the forest floor, avoiding soil degradation from rutting or soil compaction from heavy machines. If there are fewer frozen days, more equipment and labor are needed, adding to the total logging cost. Kuloglu et al., (2019) conducted a study to assess future logging costs if warming trends continue, including the equipment costs needed to cut, process and haul wood in Alberta, Canada. Results from three future warming scenarios (RCPs 2.6, 4.5, and 8.5) were used to predict future winter weather conditions. For reference, researchers determined that in the 2015–2016 logging season there were an estimated 12 hauling shutdown days due to high temperatures (above 6° C) during the winter harvest period. Projections suggested that the average number of shutdown days will increase from 20+ days by 2030 to up to 48 days by 2080 under RCP 8.5. Using the current type of harvesting machines and hauling directly to the mill, the unit cost of logging operations ($/m^3) was projected to increase by a range of 1.6% to 2.5% in the 2030s, 2.8% to 5.3% in the 2050s and 4.8% to 10.9% in the 2080s compared to the base year of 2015–2016. Increasing temperatures and costs will ultimately mean less predictable conditions for employment during winter operations. Geisler et al. (2016) conducted 32 in-depth, semi-structured interviews with professional loggers, six foresters, natural resource managers, extension agents, and other industry stakeholders to assess the seasonality of challenges faced in forest operations in the Upper Midwest. Those interviewed identified factors with strong seasonal dynamics that influenced timber harvesting and transportation, and results suggested that uncertainties about the timing of seasonal factors hinder planning and increase the financial risk for loggers. Negative impacts to the sector include lost workdays, reduced harvest, and smaller deliveries to buyers. Further, the capacity for loggers to adapt may be limited by high operational costs, low timber prices, and substantial financial investment in equipment. Notably, researchers report that loggers increasingly indicated that they cannot stop active operations because of financial pressures, which may raise the risk of environmental damage.

Climate Change Adaptation for Forests

The science of climate change adaptation in forests and forested landscapes has advanced significantly in recent years. Forest adaptation to climate change encompasses actions taken in response to the impacts of a changing climate and subsequent effects that can be both anticipatory and spontaneous. This section does not provide a comprehensive review of the growing body of literature on climate change adaptation in forestry but introduces the concept and several key literature resources.

The USDA Forest Service has provided leadership in the development of its Climate Change Response Framework (CCRF; Janowiak et al. 2014, Swanston et al. 2016) that provides a relatively comprehensive treatment of the elements of climate change adaptation strategies in forestry. Major research projects are being developed now to compare various approaches to forest management in response, in part, to a changing climate that will yield increasingly valuable insights in the years ahead. The "Adaptive Silviculture for Climate Change" (ASCC) project is one such national research initiative involving both scientists and managers to study alternative silvicultural treatments in varied ecological settings (Nagel et al. 2017). Borrowing from the ASCC, we can view climate adaptation in forestry as being framed across a continuum of resistance (to manage for no change), resilience (accommodates some change but with a return to the original conditions as much as possible), and transition (anticipate change and manage for emerging and future conditions).

As applications of these techniques in both research and management expand, we will increasingly be able to target management prescriptions for the desired short and long-term outcomes. White et al. (2020) recently described a project in Minnesota to evaluate both resilience and transition strategies for conifers being deployed together by a partnership between a nongovernment conservation organization and public land-management agencies. They point out that transition strategies remain less well developed and at times controversial compared to resilience strategies. Nevertheless, the more climate change unfolds in Maine, the more important it will be to understand our adaptation options and look to long-term forest research sites in the state to guide decision-making. In addition, new research such as the Maine Adaptive Silviculture Network (MASN; Zukswert 2018) will be essential to provide Maine-based knowledge in the future about the costs and benefits of alternative forest management decisions (Zukswert et al. 2019).

Priority Information Needs

Forest Impacts

- Updated/new simulations over a broader suite of climate scenarios and models using the latest data
- Better availability and resolution of key data like temperature, precipitation, forest health, pest, disease, land use change
- Information on change in biomass, dieback, and carbon stocks by species and geographic area
- Improved information on and mapping of forest soil attributes
- Greater integration of remote sensing technologies to better map and monitor forests
- More studies that are not just biophysical impacts, but human adaptation component (i.e., management, harvest) under expectation of changing climate/conditions
- Improved data on tree and forest physiology to better predict future forest responses to novel climate conditions and extreme events
- Better understanding of the tradeoff between potential benefits of climate change (longer growing seasons, carbon dioxide fertilization) and the negative consequences of warming (increased heat, drought, and extreme events)

Forest Operation & Management

- Develop and revise existing Best Management Practices, particularly as it relates to roads, water-crossing, and culverts
- Complete a full environmental cycle analysis for forest and forestry products
- Evaluate short- and long-term outcomes of an alternative suite of forest management strategies at a landscape-level
- Intensively monitor and assess forest landscape metrics at relevant spatial and temporal scales

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AGRICULTURE AND FOOD SYSTEMS

HIGHLIGHTS

- Maine agriculture is diverse and generates over $660 million of direct value into the Maine economy, not counting multiplier effects from support industries.
- Opportunities exist to reduce greenhouse gas emissions from Maine agriculture while simultaneously promoting soil heath and farm sustainability.
- Too much *and* too little precipitation are the most extensive climate change impacts on Maine agriculture.
- Relative to most other states, Maine has a favorable outlook for overall continued soil moisture availability.
- Warming temperatures bring both potential benefits from longer growing seasons and lower heating costs, but also potential damages from heat stress to workers, crops and livestock, as well as greater cooling costs.
- Despite enough food to prevent hunger in Maine, food insecurity exists because of uneven distribution due to socioeconomic and other factors.
- ~90% of Maine food is imported from out of state.
- Message framing in discussing climate change risk is a primary issue for effective engagement with the Maine agricultural community.
- Capabilities for locally specific, real-time, weather-based decision support offer large return on investment for government and private sector services to assist farmers in maximizing climatic opportunities and minimizing short-term weather risks.

DISCUSSION

Maine Agriculture Overview

In 2017 Maine had 7,600 farms that collectively produced agricultural commodities worth more $667 million per year (U.S. Department of Agriculture, 2019). Crops accounted for 61% of revenues and livestock (including dairy, poultry and eggs) for 39%. Market value of products sold is concentrated among the largest operations, with 63% of sales by 1.8% (134) of the farms. Almost 90% of sales were by 7.6% (699) of the farms. (Tables 1-4, Figures 1 - 4, and "2017 Maine agricultural sales" in the Appendix).

The 2017 Census of Agriculture counted up to four producers per farm who make day-to-day decisions. Over 56% of those producers were male, and almost 44% female. Thirty five percent of producers work exclusively on the farm, and 65% have some number of days per year of off-farm work, including 39% with 200 days or more per year of off-farm work. The average age is 56.5, with 32% age 65 or older.

Organic production is relatively greater in the Northeast than in most other regions (U. S. Department of Agriculture, 2015). Total organic Maine farm product sales increased almost 65% between 2012 and 2017, and were 9% of total Maine agricultural sales in 2017.

COMMODITY	2017 VALUE (MILLIONS OF DOLLARS)
Potatoes	167
Milk from cows	135
Nursery, Greenhouse, Floriculture	71
Aquaculture	64
Other Vegetables and Melons	55
Lowbush Blueberry and other Berries	33
Cattle and Calves	26
Hay	23
Maple syrup	22
Apples and other tree fruit	19
Poultry and Eggs	17
Sheep, Goats, Horses, Hogs, other animals & products	16
Corn forage	8.6
Barley, Oats, Rye, Oilseeds, Dry beans, Dry peas etc.	7.6
Christmas trees, Wreaths, other short rotation woody products	3.6

Table 1. Maine 2017 agricultural product sales. Dollar values are millions. Values over 10 million dollars are rounded to nearest whole number for clarity. Data from U.S. Department of Agriculture, 2019.

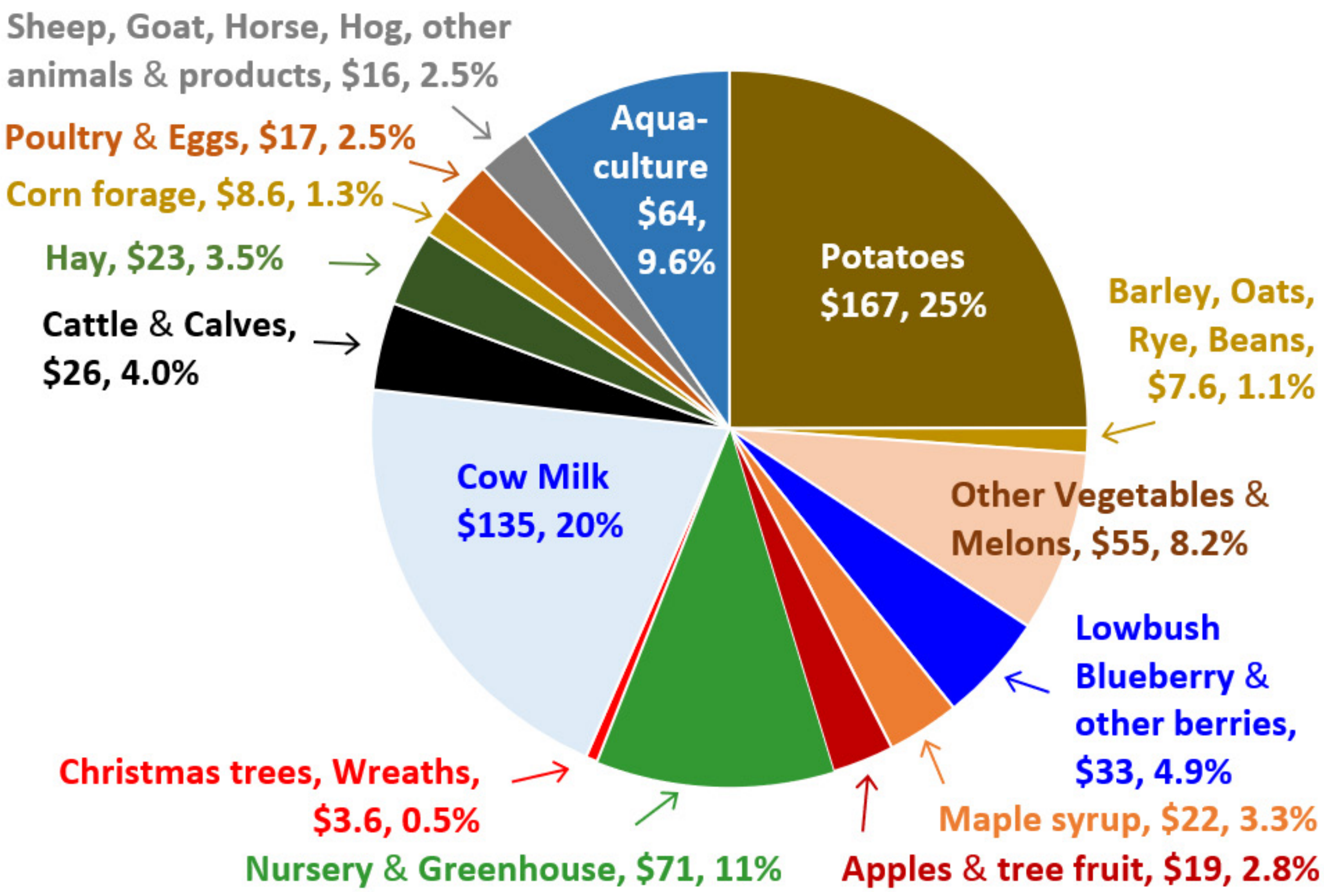

Figure 1. Maine 2017 agricultural product sales and percentage of 2017 total Maine farm commodity sales. Values over $10 million rounded to nearest whole number for clarity. Data from U.S. Department of Agriculture, 2019.

ANNUAL FARM SALES	NUMBER OF FARMS
<$10,000	5,112
$10,000 to $24,999	976
$25,000 to $49,999	479
$50,000 to $99,999	334
$100,000 to $499,999	460
> $500,000	239

Table 2. Maine 2017 individual farm sales volume. Data from U.S. Department of Agriculture, 2019.

LAND USE PRACTICE	NUMBER OF FARMS	NUMBER OF ACRES
Harvested cropland	5,147	360,300
Irrigated land	1,420	32,300
Drainage tile	429	13,400
Artificial drainage ditches	673	29,600
Conservation easement	484	46,700
Cover crop planted	1,161	55,500
No-till cropland	645	21,700
Other reduced tillage cropland	449	32,000
Intensively tilled cropland	1,094	99,200

Table 3. Maine 2017 agricultural land use. Data from U.S. Department of Agriculture, 2019.

CROPS	NUMBER OF FARMS	ACREAGE
Barley	82	7,200
Berries (but not lowbush blueberry)	569	1,200
Corn for grain	82	7,200
Corn for silage or greenchop	154	25,300
Forage (hay, haylage, silage, greenchop)	2,666	175,200
Lowbush blueberry	485	38,700
Oats	110	21,300
Orchards (primarily apple)	581	3,000
Potato	537	50,200
Vegetables, not potato	1,418	12,000
GREENHOUSE, FLORICULTURE & BEDDING, & GREENHOUSE FOOD CROPS	**NUMBER OF FARMS**	**SQUARE FEET**
Greenhouse vegetables and fresh cut herbs	400	3,436,600
Bedding/Garden plants, cut flowers	438	2,034,700
Nursery crops	30	27,200
LIVESTOCK	**NUMBER OF FARMS**	**NUMBER OF ANIMALS**
Beef Cows	1,141	10,400
Milk Cows	450	30,400
Hogs	429	4,600
Poultry (laying chicken inventory)	1,892	3,531,200
Poultry (broilers sold)	366	222,300

Table 4. Maine 2017 number of farms and acreage by commodity (U.S. Department of Agriculture, 2019).

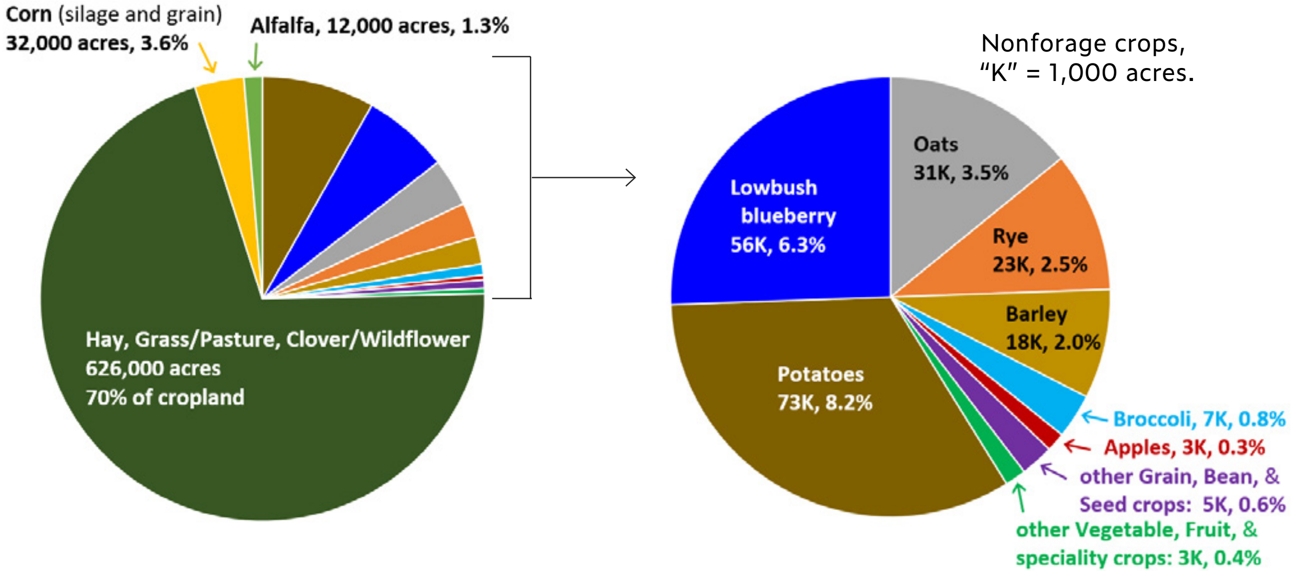

Figure 2. Maine 2019 crop acreages and percentage of total cropland. Data from U.S. Department of Agriculture, 2020. Oats, rye and barley are usually grown in rotation with potato to protect and build soil. Land growing hay, alfalfa, lowbush blueberry, apples and other tree fruit is usually not tilled.

Greenhouse Gas Emissions and Mitigation by Maine Agriculture

Agricultural sources accounted for 2.2% of total Maine greenhouse gas emissions in 2017 (Maine Department of Environmental Protection, 2020). USDA statistics for 2015 (U. S. Department of Agriculture, 2015) show the largest agricultural contributions to greenhouse gas emissions in the Northeast coming from:

1. crop-related nitrous oxide (N_2O), primarily from hay and forage corn and potato production, especially during periods of saturated soils,
2. methane (CH_4) from enteric fermentation, primarily by dairy and beef cattle, and
3. CH_4 and N_2O from livestock manure.

Agriculture-sourced greenhouse gas emissions for N_2O and CH_4 are discussed below (Figs. 3-7). Emissions in the form of carbon dioxide (CO_2) by Maine agriculture (apart from those due to energy production, e.g. fossil fuels used for tractors, electrical generators, refrigeration, heating) are less than 1% of those from N_2O and CH_4.

Nitrous oxide emissions

Agricultural emissions of N_2O due to microbial action on inorganic fertilizers and manure can be reduced by precise timing, method, and application rate; and by careful management of stored manure (U. S. Department of Agriculture, 2015). Nitrous oxide emissions from managed livestock waste in Maine in 2008 was 11,800 metric tons CO_2 equivalent, with 49% by dairy, 49% poultry, 1% beef cattle, and <1% from swine (U.S. Department of Agriculture, 2011a). The Maine contribution was 0.07% of the U.S. total (Ibid).

Methane emissions

Methane emissions from managed livestock waste in Maine in 2008 was 35,600 metric tons CO2 equivalent (including manure on grazed land) (U.S. Department of Agriculture. 2011a). Of that amount, 65% was from beef cattle, 25% from goats, 7% from swine, 2% from dairy cattle, 0.8% from sheep, and 0.3% from horses. The Maine contribution was < 0.1% of the U.S. total (Ibid).

Methane emissions (CH_4) from enteric fermentation in Maine were 153,000 metric tons CO_2 equivalent in 2008 (U.S. Department of Agriculture. 2011a). Dairy cattle were the primary source of enteric CH_4 at 81%, with beef cattle at 19%. (Ibid). Nationally, enteric fermentation and manure account for about 80% of greenhouse gas emissions per unit of milk, with lesser contributions from forage cropping (8%) and fertilizer application (5%) (Ibid).

Increased temperatures and more intense precipitation (see Climate chapter in this report) will likely increase nutrient losses and greenhouse gas emissions from animal manure and N_2O from saturated soils and liquid manure storage systems (Richard Kersbergen, personal communication, March 2020). Nationally, manure management accounted for 14% of agricultural greenhouse gas emissions in 2014 (U.S. Environmental Protection Agency, 2016). Major investments have been made to improve and expand dairy cow manure storage in Maine, but more is needed (Kersbergen, personal communication, March 2020). Difficulty in finding suitable time windows for spreading manure during warm season periods (limited by excessive soil moisture) interferes with optimal manure management.

Dairy cattle, followed by beef cattle and sheep, have the greatest per animal enteric emissions. Dairy cattle emissions per animal are 40 to 50% higher than for beef cattle (U.S. Environmental Protection Agency, 2014). In the Northeast, most dairy cattle manure is handled in engineered systems, with about 30% deposited on pasture, whereas about 80% of beef cattle mature is deposited on pasture (U. S. Department of Agriculture, 2015).

The U.S. dairy industry greatly reduced the environmental impact per unit of milk produced between 1944 and 2007, primarily through increased yield per cow. Methane and N_2O emissions per unit of milk declined by about 80% (Capper and Cady, 2020). More recently, between 2007 and 2017, a 25% increase in milk production was accomplished with only a 1% increase in total greenhouse gas emissions (Ibid). Enteric and manure emissions contributed the major proportion (80%) of GHG emissions per unit of milk, with lesser contributions from cropping (8%) and fertilizer application (5%) (Ibid).

Maine agricultural greenhouse gas emissions data show that in terms of CO_2 equivalents (CO_2e), manure-based and fertilizer-based emissions in Maine (primarily, but not exclusively from dairy) in 2014-2017 averaged roughly 30% and 20%, respectively, of those from enteric fermentation (Knapp 2020).

Studies have found that replacing 5% of the organic matter content of dairy cow feed ration with a tropical seaweed (*Asparagopsis taxiformis*) resulted in a 95% reduction of enteric methane emissions, without detriment to milk production or quality (CABI 2019, Roque et al. 2019). However, the long-term effects of seaweed ingestion on dairy cow gut biome, cow health, and productivity remains unknown. Even if the strategy worked there would be difficult logistic problems in producing the amount of seaweed needed. The methane suppression effect of *A. taxiformis* seaweed as a dietary supplement was not found for other seaweed species tested (Kinley et al 2016). An alternate and more feasible feeding additive that has provided significant enteric methane emission reductions of 25-45% in multiple trials, is the addition of small amounts of 3-Nitrooxypropanol (3-NOP) to dairy cow feed rations (Melgar 2020). According to one researcher, "3-NOP is the only substance that has worked significantly in reducing enteric methane in cattle and not had unacceptable effects on milk production or quality," (Messer 2020). Before 3-NOP can be used in the U.S., it must be approved by the Federal Drug Administration.Anaerobic digestion to create CH_4 fuel from manure and food waste is a proven technology, but still not in widespread use in the U.S. because the cost benefit ratio has not been attractive in context with recent energy prices (U.S. Department of Agriculture, 2011b). This technology reduces the need for extracted fossil fuel, produces a local fuel source to displace imports and recycles material that can be used for livestock bedding. A study conducted in New York State found that anaerobic digesters reduced dairy farm greenhouse gas emissions by 71% (Ebner et al. 2015). Similarly, a preliminary and hypothetical "best case scenario" estimate found that a digester for every 700 dairy cows could virtually eliminate greenhouse gas emissions from dairy manure in Maine (Daigneault 2020).

Infrastructure costs, scale, and dairy profitability are constraints on anaerobic digester use in Maine (Griswold 2020, Lauer 2018) where there is currently one operating unit. A study done on Idaho found that it required 3,000 cows per farm to make a digester cost effective. There are no single farm dairy herds in Maine of the same size; the average Maine dairy herd is 107 (Griswold, 2020). Sharing of anaerobic digestion facilities among multiple farms and manure transportation could reduce the scale constraint but additional costs due to distances between farms in Maine could limit adoption. Average herd size is increasing, anaerobic digester costs are declining, and new technologies are being developed to increase both the potential benefits and feasibility. The "Climate Smart Agriculture" program in California promotes land conservation, water efficiency, healthy soils, and alternative manure management. It may provide a model for governmental support to increase adoption of this and other emission reduction methods (California Department of Agriculture 2019, Nieves 2020).

Another approach with lower upfront infrastructure costs is manure solids separation through compaction of liquid manure to reduce emissions, convert waste into livestock bedding or high organic matter compost, and improve soil health.

Reducing the consumption of meat, milk and other livestock products is being proposed as another approach for greenhouse gas emission mitigation. At present such behavioral change occurs at the personal rather than the state or national policy level. However, it can also be said that existing government policies that subsidize livestock production provide production incentives that reduce prices and thereby enhance animal product consumption. The social and political ramifications of changing those policies for the purpose of greenhouse gas mitigation are complex and the subject of debate (e.g., Gustin 2019, Kim et al. 2019, Lawless, 2020). Total life cycle assessment of dairy environmental footprints provide a quantitative foundation for that discussion (Rotz et al. 2020).

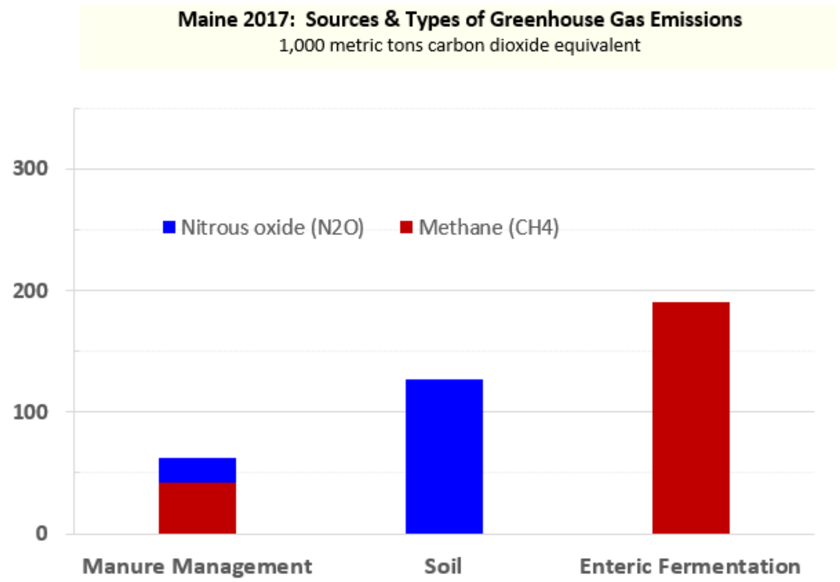

Figure 3. Maine agricultural greenhouse gas emissions in 2017. (data from Knapp 2020).

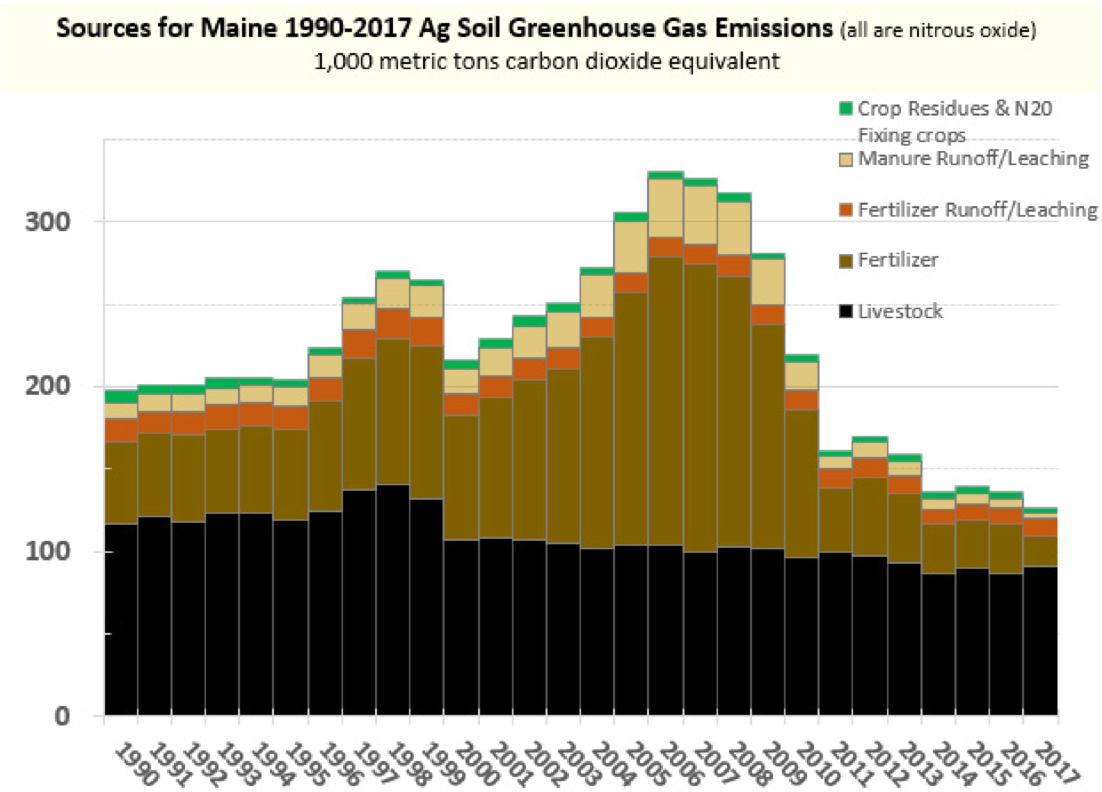

Figure 4. Maine agricultural soil greenhouse gas emission sources in 1990-2017. (data from Knapp 2020).

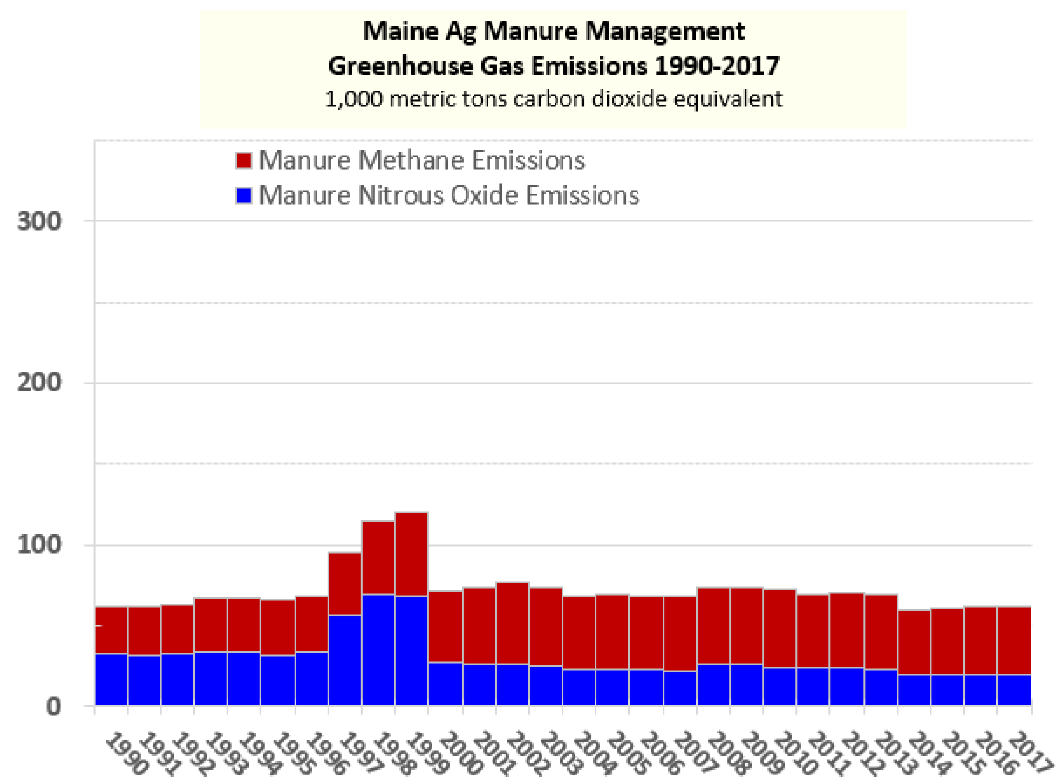

Figure 5. Maine agricultural manure management greenhouse gas emissions 1990-2017. (data from Knapp 2020).

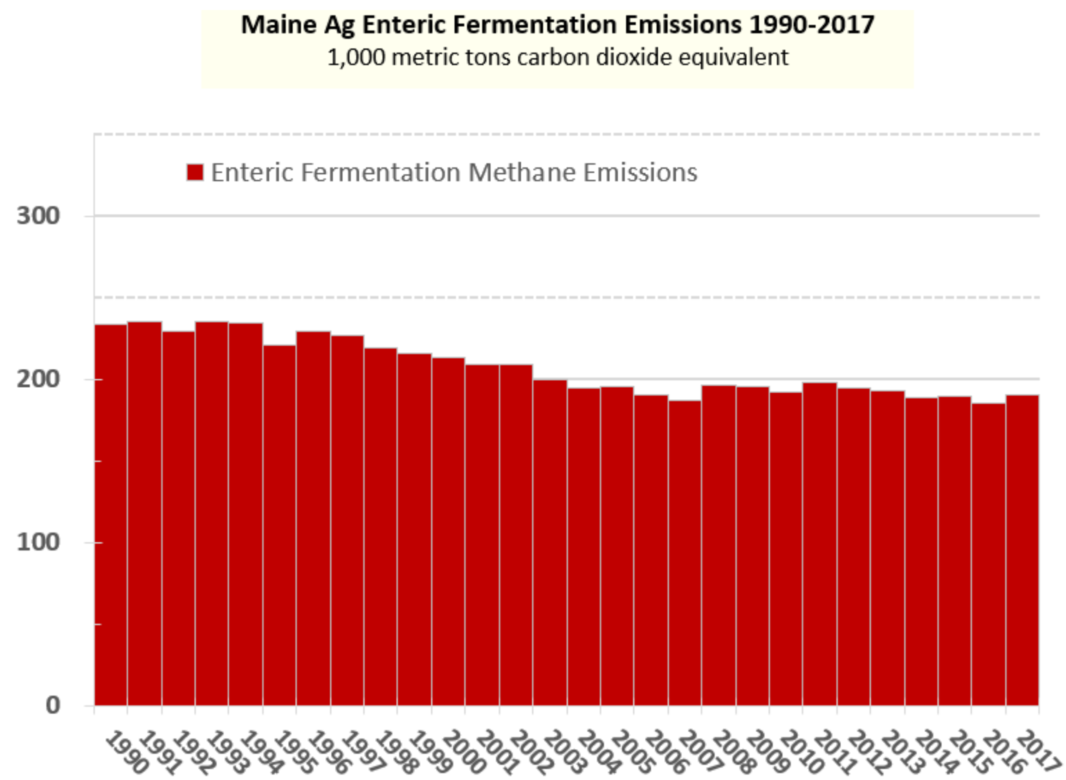

Figure 6. Maine greenhouse gas emissions from enteric fermentation 1990-2017. (data from Knapp 2020).

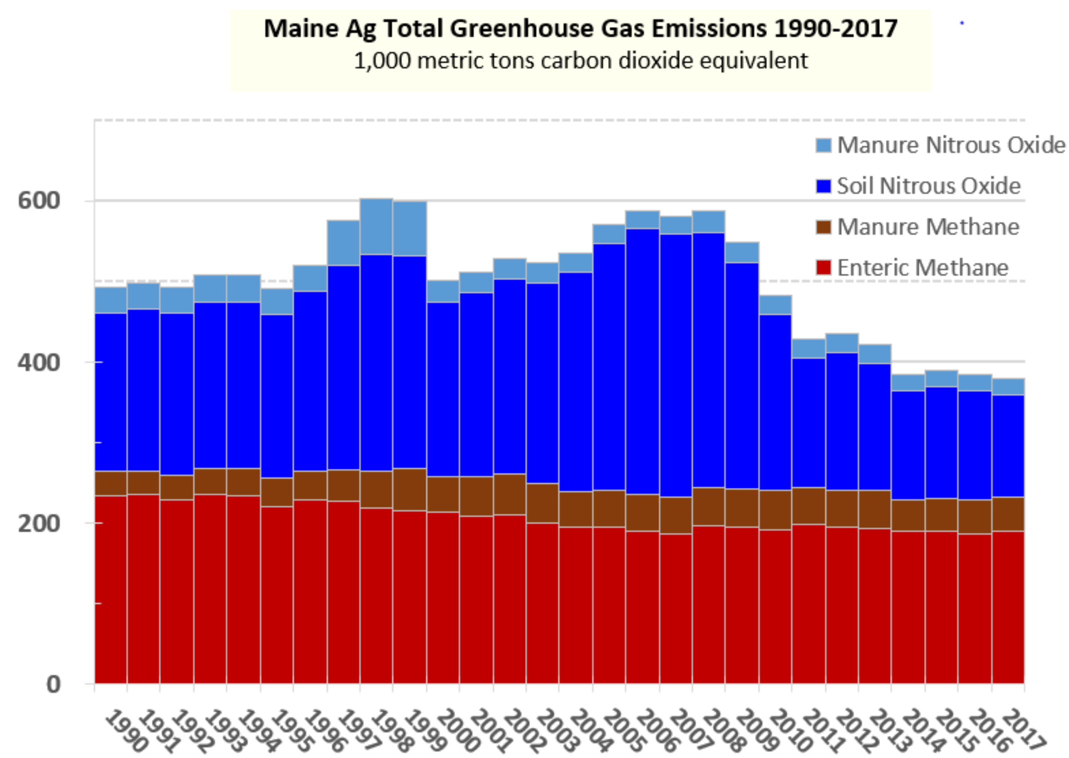

Figure 7. Total Maine agricultural greenhouse gas emissions 1990-2017. (Maine-specific agricultural sector data for emissions from energy-use by tractors, trucks, heating, cooling etc. are not available and excluded from the graph. The ratio between greenhouse gas emissions due to energy-use versus other ag sources in national emissions data indicates that energy-use emissions are much lower than those shown on the graph. Other minor Maine agricultural greenhouse gas emissions, such as CO2 from urea fertilizer are reported as <1% of those shown and are also excluded). (data from Knapp 2020).

Carbon sequestration

Soil carbon sequestration methods in agriculture can be summarized into three categories (E. Mallory, personal communication, April 2020):

1. Reduce Tillage - Protect what's already there,
2. Rotations and Cover Crops - Build it and protect it,
3. Amendments - Add it.

In 2008, Maine annual crop acreage on mineral soils had net soil carbon stock loss of 30,000 metric tons CO_2 equivalent, while hay acreage had a net gain of 90,000 metric tons (meaning carbon was buried or sequestered in soils). Land in the Conservation Reserve Program had a gain of 30,000 metric tons. Thus, the statewide total was a net gain of 90,000 metric tons of carbon sequestered in Maine agricultural land on mineral soils in 2008 (U.S. Department of Agriculture, 2011a). Twenty-five of the 50 U.S. states had higher total soil carbon sequestration on mineral agricultural soils in 2008. Zero net change was reported for carbon stock change for agricultural land on organic soils in Maine (and 27 other states) in 2008 (Ibid), presumably in most cases due to a paucity of agricultural land organic soils. Irrigated cropland on mineral soils had a net loss 10,000 metric tons CO_2 equivalent in 2008, while the net change for non-irrigated cropland was a 110,000 metric tons gain, for a statewide net gain of 100,000 metric tons CO_2 equivalent.

There is increased interest and use of methods to reduce soil carbon losses on intensively managed cropland by maintaining vegetative cover through use of cover crops, no-till or low-till production. In 2017, there were 55,400 acres of cover crop acreage in Maine, an 89% increase over 2012 (LaRose and Myers, 2019). The national average increase was 50% between 2012 and 2017. Maine ranked 10th among the 50 U.S. states for rate of increase in cover crop acreage between 2012 and 2017 (Ibid). Building soil health and cover cropping are effective and widely used adaptations for both excess and deficient water (Maine Farmland Trust, 2020). Between 2012 and 2017 in Maine no-till operations increased 67%, no-till acres increased 119%, conservation tillage operations increased 51%, conservation tillage acres increased 68%, cover crop operations increased 25%, and cover crop acres increased 89% (U.S. Department of Agriculture, 2019).

The organic matter content of Maine agricultural soils is stable or slightly increasing for most crops, and stable or declining slightly for potato soils, as indicated by a recent review of 176,174 soil test results done by the University of Maine Soil Laboratory from 1995 to 2018 (Birthisel et al. 2020).

Raising the organic matter content percentage, and thereby carbon content of agricultural soils, brings many benefits including enhanced nutrient availability, increased water storage, faster drainage from saturated soils, and improved symbiotic soil biota.

Corn production in Maine is primarily used as silage and grain for livestock feed. This acreage provides another opportunity for increasing carbon sequestration in Maine although the organic matter content of most of these soils is relatively high due to repeated manure applications. Reduced tillage practices in corn systems with cover crops would also bring benefits such as reduced soil erosion and improved soil health. Recent studies in Maine have documented a $50/acre savings in fuel and labor when dairy farmers adopted no-till corn production (Kersbergen et al., 2013).

A preliminary and hypothetical "best case scenario" estimate found that switching from intensive tillage to reduced tillage on all of the Maine acreage used for barley, corn, potatoes, vegetables and wheat could compensate for as much as 15,000 metric tons CO_2e emissions annually (Daigneault 2020). Using the same methodology, a parallel estimate found that a similar amount of carbon sequestration could be achieved use of oats and peas as cover crops on those crop acres. These hypothetical estimates do not account for unresolved questions on how to economically produce those crops with reduced tillage or use of oat-peas cover crops.

In another idealized scenario, with a 25% increase in cover crop adoption, a 75% increase in reduced or no-till adoption, and a 25% increase in adoption of nutrient management strategies that replace 25% of synthetic nitrogen inputs, an estimated 66,000 to 133,000 tons of CO_2e per year could be removed by the combination of soil carbon sequestration and reduced emissions. This would represent 0.4% to 0.8% of the total annual Maine greenhouse gas emissions in 2017 (Moore-Kucera et al. 2020). Increased use of high-quality grass-based livestock systems would also help reduce net Maine agricultural greenhouse gas emissions.

The capability for soil organic matter sequestration in Maine agricultural soils through organic matter increase is limited by economic constraints for individual farms and the number of acres in production systems that make substantial soil organic matter increase practically feasible. The largest crop acreages in Maine either require tillage that interferes with soil organic matter accumulation (potato), or are never tilled (perennial forages and pastures, lowbush blueberries) and therefore have fewer opportunities for improved and effective organic matter accumulation. While the tillage requirement for land used for potato crops interferes with soil organic matter accumulation, adding non-potato rotation crop years and spreading livestock manure or compost would benefit those soils and contribute to carbon sequestration (Mallory 2019).

Recent developments and adoption of no-till seeding technology along with reduced tillage methods to effectively incorporate cover crops offer realistic options that could alter production methods on significant corn silage acreage in Maine (Kersbergen et al. 2013). This adds to the potential for increased carbon sequestration and provides some resilience to adverse weather conditions (droughts and excessive precipitation).

Certification for a program to incentivize increasing soil organic matter would have to be done by rewarding supported practices instead of relying on documented changes in soil organic matter because of the time lag and many confounding factors that affect soil organic matter measurement. NRCS (Natural Resource Conservation Service) EQIP (Environmental Quality Incentives Program) policies promote some of these practices. Participants in these programs benefit from technical assistance to increase the chance for successful use of supported practices and follow-up evaluation(s) to track performance and identify problems.

The ecosystem services provided by agriculture for soil health, water and air quality, flood control, biodiversity, recreation space, aesthetic appeal, and other beneficial effects provide a foundation for incentivizing soil health practices that also contribute to carbon sequestration and greenhouse gas emission reduction (U.S. Department of Agriculture, 2012). The benefits from crop and livestock farmer land-sharing to promote no-till adoption and crop rotation has been demonstrated in Maine (J. Jemison, personal communication, April 2020). A major constraint to such collaboration is the distance between manure sources (e.g., dairy and beef) and potential spreading areas (e.g., potato farms in Aroostook County). The lack of a USDA certified meat processing facility is one impediment to a more vibrant beef industry in Aroostook County (Ibid).

A preliminary and hypothetical "best case scenario" estimate found that applying manure as a soil amendment to all of the Maine acreage used for apples, barley, lowbush blueberries, corn, hay, potatoes, vegetables and wheat could compensate for as much as 40,000 metric tons CO_2 equivalent emissions (Daigneault 2020). A parallel estimate found that applying biochar as a soil amendment to those same acres could compensate for 569,000 metric tons CO_2 equivalent emissions (Ibid).

Biochar is an old method to manage soil carbon that is being reexamined for a potential new role in emerging economic and environmental contexts. In addition to logistical, supply, and economic issues, there are also important unresolved questions about undesirable effects such as pH changes caused by large scale biochar application. However, biochar amendments to soils appears to offer promise as a beneficial soil amendment that promotes carbon sequestration in soils (e.g., Atkinson et al. 20210, Laird et al. 2010).

A recently emerged concept is enhanced silicate rock weathering (Beerling et al. 2020). Rock dust spread over large agricultural acreage could be economically feasible and provide potentially substantial carbon sequestration along with beneficial effects on soil and ocean acidification.

Energy costs and fossil fuel use by Maine agriculture.

Diesel, gasoline, oils and other fossil fuel products accounted for 6.4% of total farm expenses in 2017(USDA 2019). Nationally, diesel fuel energy consumption on farms is about four times that of gasoline (U.S. Department of Agriculture, 2016b). Diesel has higher energy content but emits 3% more CO_2 per BTU (U.S. Energy Information Administration 2014). With no local sourcing for fossil fuels, those expenditures represent money exported out of the Maine economy. Change in tillage practices affects several energy consumptive field operations. In general, an increase in no-till acreage would result in decreased fuel use.

Electricity and other utility costs account for 4.4% of Maine total farm expenses, (USDA 2019). The balance between decreased heating costs and increased cooling costs with warming temperatures will be situation specific. Livestock, irrigation, and specialty crops are more likely to be negatively affected by higher electricity costs than other agricultural activities (Ibid). Increased use of irrigation would increase significant energy cost for pumping water (U.S. Department of Agriculture, 2016). Upgrading irrigation equipment can provide substantial energy savings in addition to more effective water delivery and more efficient use of water supplies.

Greenhouse gas reduction programs would increase demand for renewable energy, increasing opportunity for farms to add renewable energy production to their enterprise (U.S. Department of Agriculture, 2016b). The proportion of U.S. farms generating renewable energy more than doubled between 2007 and 2012 from 1.1 to 2.7%, including farms producing solar, wind, and geothermal (% does not include farms that harvest biomass feedstocks such as corn, soybeans, and cellulosic materials or that lease their wind rights to others) (Ibid). In addition to corn production for ethanol, it is also possible to derive cellulosic fuels from crop residues, non-food and energy crops grown on marginal land, and biological waste products (Ibid). Corn as an energy crop is not currently relevant in Maine, but that could change with changes in technology and market conditions. Fertilizers are another large cost for Maine crop growers, at 5.6% of total expenses (Ibid). Nitrogen fertilizer and pesticide production are both energy intensive. Fertilizers are produced at much higher volume and used at much greater bulk weight per acre than pesticides. Fertilizer production uses about 1 percent of total global energy supply (Worell et al., 2000). Energy cost increases would affect fertilizer costs proportionally more than other farm inputs.

For U.S. organic farms where synthesized nitrogen fertilizers are not used, the decrease in energy for fertilizer is often counteracted by the increased use of mechanical weeding machinery. In addition, organic production relies heavily on tillage for mechanical weed control and cover crop management, decreasing the potential to sequester carbon.

Organic farms typically have greater fuel and utility energy costs than non-organic farms producing the same crop or livestock (U.S. Department of Agriculture, 2016b). One exception was lower energy expense for organic dairy.

Climate Change Vulnerabilities and Opportunities for Maine Agriculture

Impacts on crop production

While global impacts on agriculture productivity are not necessarily translatable to Maine, Porter et al. (2014) estimated that warming and changing precipitation and soil moisture will have a net negative effect on global food production if the global average surface temperature increases 3.6°F (2°C) above late 20th century levels. After 2050, with projected temperatures exceeding 3.6°F, the risk of more severe impacts increases (Fig. 2). In addition to lowering of average crop yields, interannual yield variability is likely to increase. They also found that for higher latitude locations, there are mixed positive and negative trends with warming temperature, with currently cooler areas benefiting in some cases (Fig. 4).

Nelson et al. (2010). concluded "Our analysis suggests that up to 2050, the challenges from climate change are "manageable," in the sense that well-designed investments in land and water productivity enhancements might, conceivably, substantially offset the negative effects from climate change. But the challenges of dealing with the effects between 2050 and 2080 are likely to be much greater than those to 2050. Starting the process of slowing emissions growth today is critical to avoiding a calamitous post-2050 future." Assumptions about the efficacy of adaptation measures have a major influence on future yield projections. For example, Porter et al. (2014) found that basic adapation measures such as variety selection and other adpatations are likely to affect wheat yields (Fig. 5). At temperatures above 3.6°F projected from high greenhouse gas emissions scenarios, effects on global food production become increasingly negative. However, the success of adaptation measures is difficult or impossible to include in comprehensive, long-range estimates. This is due to a cascade of uncertainties about the future trajectory of human greenhouse gas emissions, the effect of those emissions on future temperature, precipitation and other weather variables, and finally to the effects of weather variables on crop and livestock physiology and the logistics of agricultural production.

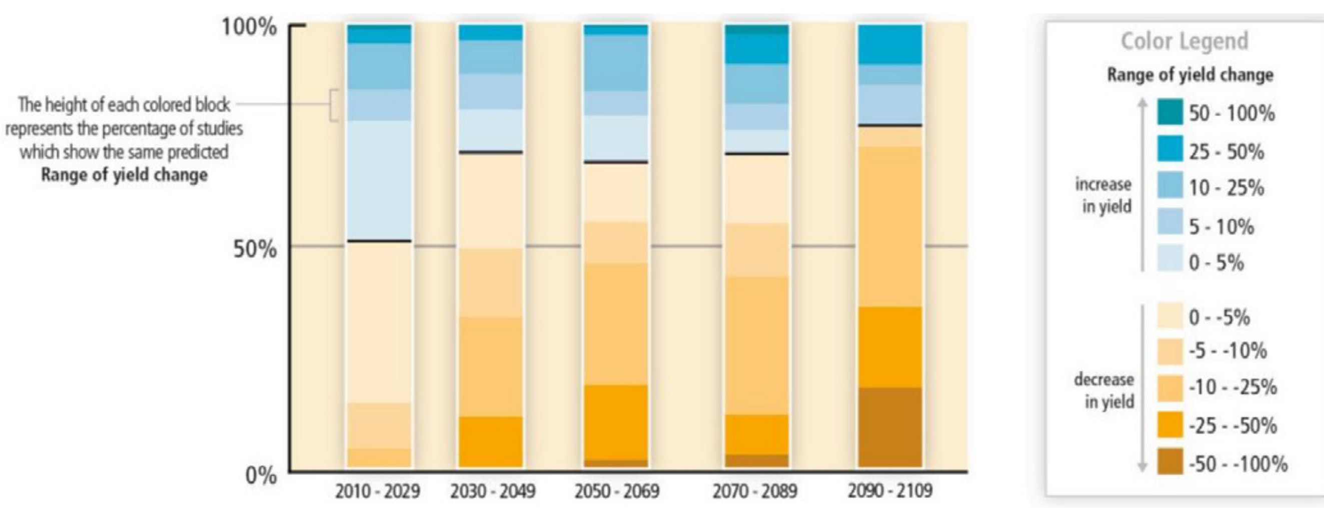

Figure 8. Summary of crop global crop yield studies. Adapted from: SBC Energy Institute, 2015.

Lawrence et al. (2020) found that "our understanding of the extent to which these impacts may propagate as cascades, compounding to form multiple impacts across sectors, is limited. Cascades result from interdependencies between systems and sub-systems of coupled natural and socio-economic systems in response to changes and feedback loops. The combined effects of interacting stressors may affect the ability of individuals, governments, and the private sector to adapt in time, before widespread damage occurs. "

With a 7.2°F (4°C) rise in global average temperature, the World Bank (2013) concluded that negative impacts may interact with each other in unpredictable ways, that current agriculture models are not able to predict what will happen from such interactions, and that there is no certainty that adaptation to a 7.2°F world is possible.

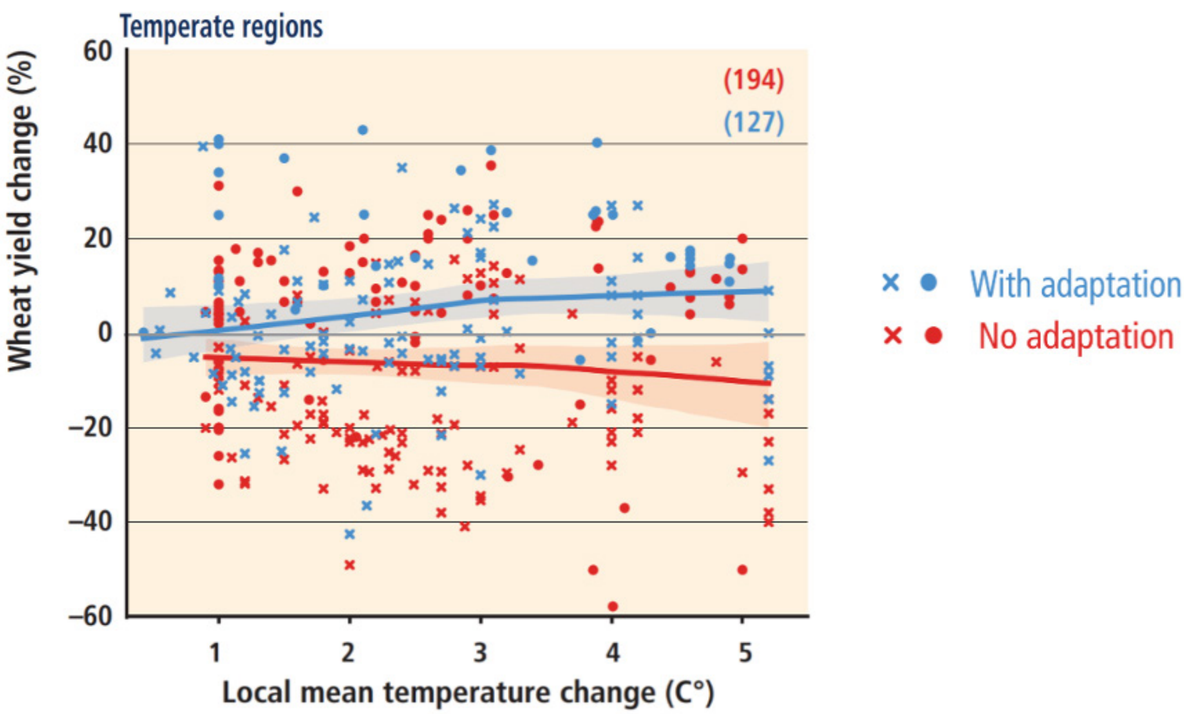

Figure 9. Percent simulated yield change as a function of local temperature change for wheat grown in temperate climates. Dots indicate where a known change in atmospheric CO2 was used; remaining data are indicated by "x". Values do not measure a CO2 fertilization effect because changes in other factors such as precipitation may differ between studies. Colored lines show estimated trend for presence (blue) or absence (red) of simple agronomic adaptation measures such as cultivar and planting date adjustment, irrigation and fertilization optimization. Shaded areas show the 95% uncertainty around trend estimates. Numbers in upper right corner show number of studies for each group. Adapted from Porter et al., 2014.

Regional and State Impacts

Studies done for the Northeastern U.S. and New England provide an overview for likely climate change vulnerabilities and opportunities for Maine agriculture (Tables 5 & 6). The 2-page factsheet "Farm Response to Changing Weather" (Maine Climate and Agriculture Network, 2017), and the agriculture chapter in the Maine Climate Futures Report (Griffin, 2009), (both in the Appendix) summarize the major climate change impacts for Maine agriculture as:

- Longer growing season and northward shift in plant hardiness zones,
- Early Spring Warm-up Increases Frost/Freeze Risk
- More Frequent or Intense Heat Waves

- More Frequent Intense Downpours
- More Frequent and Longer Dry Spells

The factsheet also lists adaptation measures to consider for each impact.

Water and soil moisture surpluses or deficits are the issues most frequently and prominently mentioned by individual Maine farmers, and in regional and national reviews (e.g., Birthisel et al. 2019; U. S. Department of Agriculture, 2015; National Academies of Sciences, Engineering, and Medicine,2019). While drought is a concern, excess water is generally a bigger concern. As one apple grower put it, "I can make it rain (i.e., via irrigation), but I can't make it drain."

In addition to direct and indirect (through pests and pathogen) impacts on crop quality and livestock health, excess moisture is a threat through loss of fieldwork days which leads to delayed planting or pasture access, rotting seeds, and other costly problems. Continued and enhanced animal monitoring will be necessary to address direct climate change effects on livestock health, as well as monitoring and management of livestock pathogens and disease vectors.

Increased drought coupled with increased frequency of heavy precipitation has already and will continue to negatively impact crop and livestock production in the Northeast (Wolfe et al., 2018). A large portion of all crop losses reported to the USDA Farm Service Agency from 2013 to 2016 were associated with excessive precipitation in the Northeast region of the U.S. (Ibid). Damage varies by commodity. For example, from 2011 to 2018, 31% and 6% of USDA tree fruit crop insurance payments in Maine were for excess or deficient water, respectively (Fig. 10).

Model-based commodity-specific studies on the effects of expected climate change trends have been undertaken for the Maine potato cropping system (Tooley 2019, E. Mallory, personal communication, March 2020), but not for other crops or livestock sectors in Maine. A preliminary analysis of the potential geographical shift in the optimal climatic zone for lowbush blueberry production by 2060-2080 suggested a negative effect on production in Maine by 2060-2080 (Fig. 11).

Being on the cool side of the optimum thermal envelope for many crops, increased warming with longer growing seasons is considered an advantage for warm season crops. However, due to heat stress, contributions to drought and frost risk (from accelerated early spring plant development) and other effects, warming is a disadvantage in other settings.

Through in-depth interviews with 30 farmers and 16 farm advisors in Maine and Vermont, Johnson et al. (2019) found that farmers had mixed opinions about the relative beneficial and negative effects of climate change.

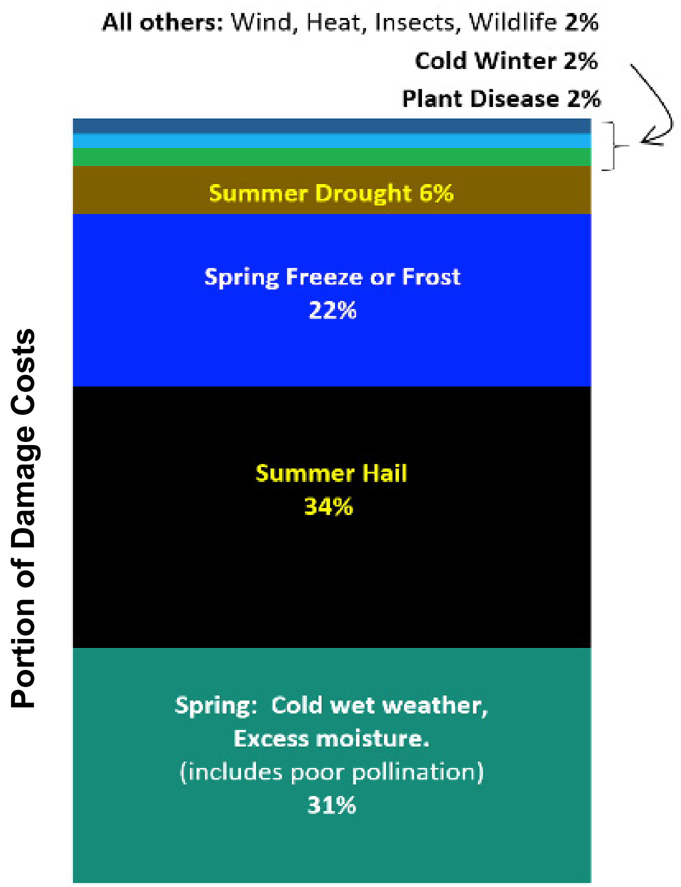

Figure 10. Roche and Koehler, 2019. Maine tree fruit crop

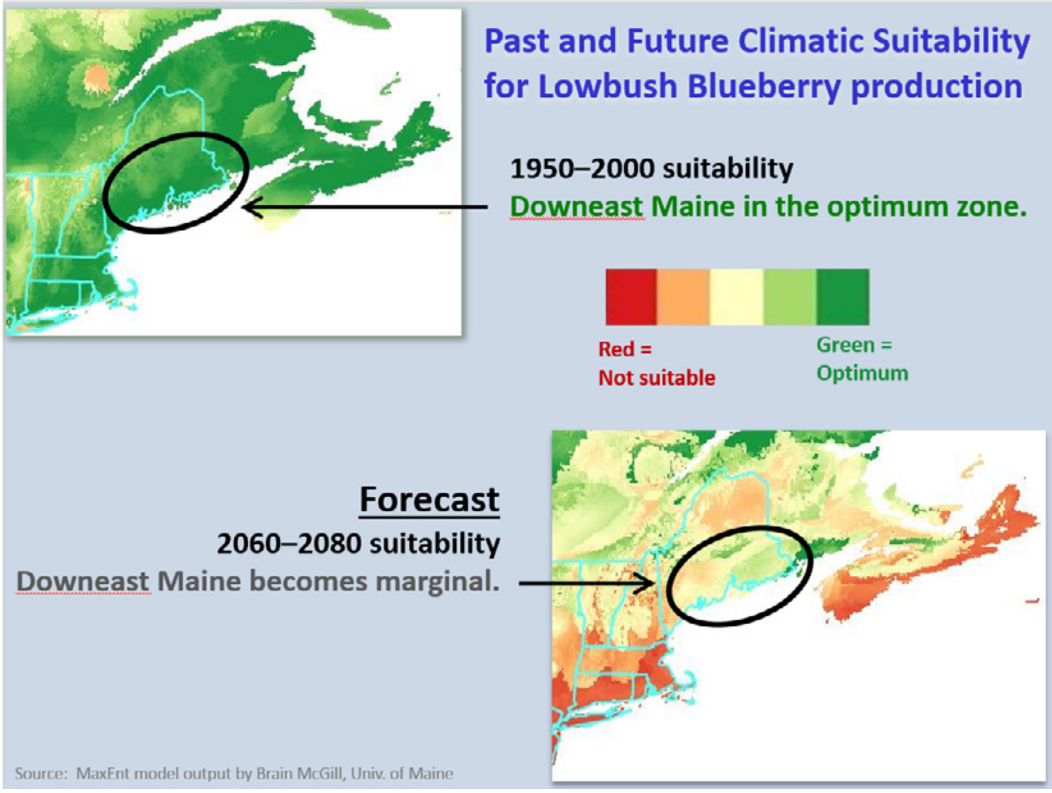

Figure 11. Potential decline in suitability of downeast Maine for lowbush blueberry production.
B. McGill, personal communication, November 2017.

CLIMATE VULNERABILITY	VEGETABLES	DAIRY	GREENHOUSE, NURSERY, ORNAMENTAL	BERRIES & TREE FRUIT	FORAGE, GRAINS, SEEDS, BEANS	BEEF CATTLE, HORSES, HOGS, SHEEP, GOATS, OTHER LIVESTOCK	POULTRY & EGGS	AQUACULTURE	ECOSYSTEM SERVICES
Extreme precipitation, Flooding	✓	✓	✓	✓	✓	✓	✓	✓	✓
Drought, Water stress	✓	✓	✓	✓	✓	✓			✓
Reduced snow cover	✓			✓					
Heat stress & Cooling costs	✓	✓	✓	✓	✓	✓	✓	✓	✓
Warmer avg. temperature	✓		✓					✓	✓
Warmer winters		✓		✓	✓	✓			
Temperature vari-ability (Frost)				✓					
Wind damage	✓	✓	✓	✓					
Increased CO2 in water								✓	
Sea level rise								✓	✓
Elevated ground level ozone	✓	✓	✓	✓	✓				✓
New or increased pests & pathogens	✓	✓		✓		✓	✓	✓	✓

Table 5. Summary of climate vulnerabilities for Maine agriculture. (Data from U. S. Department of Agriculture, 2015; Hristov et al., 2018; U.S. Department of Agriculture, 2016a; Choquette et al. 2015, Cox et al. 2016, Koehler et al. 2019; Mills et al. 2017, White et al. 2018; and Wolfe et al., 2018).

CLIMATE OPPORTUNITY	VEGETABLES	DAIRY	GREENHOUSE, NURSERY, ORNAMENTAL	BERRIES & TREE FRUIT	FORAGE, GRAINS, SEEDS, BEANS	BEEF CATTLE, HORSES, HOGS, SHEEP, GOATS, OTHER LIVESTOCK	POULTRY & EGGS	AQUACULTURE	ECOSYSTEM SERVICES
Increased rainfall			✓						
Extended growing season or range expansion	✓		✓	✓		✓		✓	
Reduced heating costs			✓				✓		
CO_2 fertilization	✓		✓		✓				
Support for bio-energy production		✓			✓		✓		✓

Table 6. Summary of climate opportunities for Maine agriculture. (Data from U. S. Department of Agriculture, 2015; Hristov et al., 2018; U.S. Department of Agriculture, 2016a; Koehler et al. 2019; White et al. 2018; and Wolfe et al., 2018).

Extreme precipitation events and flooding.

The most commonly noted observation and concern related to climate change among Maine farmers is an increase in growing season precipitation intensity and grouping of precipitation events with longer dry periods in between. High volume rain events cause localized flooding, make fields impassable by tractors and unsuitable for planting or other field work, increase losses of planted crops, fertilizer, soil-applied residual pesticides, and increase soil erosion and compaction. The increase in high intensity precipitation is confirmed by the U.S. National Climate Assessment (Easterling et al. 2017) regionally, and within Maine (Birkel and Mayewski 2018; Climate chapter, this report). Future precipitation changes are more difficult to project than temperature changes (Porter et al. 2014).

Longer growing season

Warmer temperatures and a longer growing season would benefit many sectors of Maine agriculture. Increased warm season length or cumulative growing degree-days may lose their utility if erratic frost dates constrain the continuous frost-free period. "Frost-free" has different meaning for different commodities and production settings and does not always refer to the standard 32° F threshold for beginning or ending of a growing season. For perennial crops like apple, peach, highbush and lowbush blueberry, strawberry, woody ornamentals, and some forage crops, early spring warmth followed by a spring frost that is late relative to plant development can reduce yields or even survivability. The functional growing season is determined by soil moisture being under a threshold and soil temperature being over a threshold as much as air temperature. A 7% decline in the average number of growing season fieldwork days per week in Maine since 1995 has caused problems with spring planting and other operations (Birthisel 2018).

Solar radiation does not migrate with northward migration of thermal norms, nor do soil resources. Maine has adequate resources for both. Maine also has better prospects with respect to drought than most other agricultural regions in the United States.

Maine agriculture is connected to national and global supply chains and markets. Thus, how climate change affects those other regions indirectly affects Maine. Other production regions are expected to confront increasing heat stress and water stress. Examples from other states relevant to Maine are vegetable and fruit production in California, corn production in the Midwest grain belt, and potato production in Idaho and Colorado (J. Jemison, personal communication, April 2020).

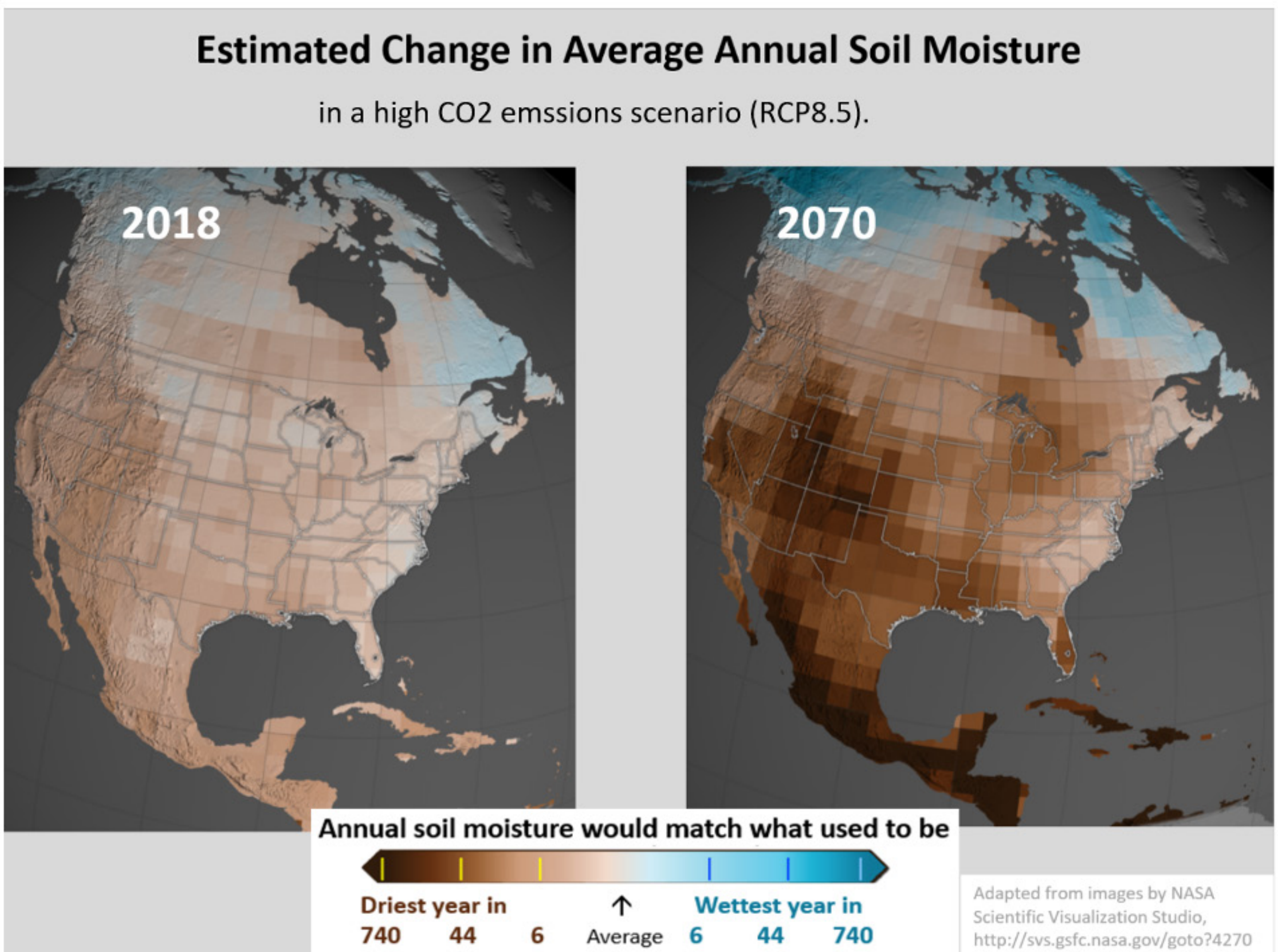

Figure 12. Projected change in average annual soil moisture projected for the RCP8.5 scenario. Soil moisture expressed as level relative to historical observations for each location. Maine shows essentially no change between 2018 and 2070 while the average annual soil moisture in the southwestern United States and parts of Mexico are projected to fall to levels previously only experienced during extremely rare and severe droughts. Chart adapted from Cook et al., 2015. RCP8.5 scenario as described by IPPC, 2014.

Due to a relatively high ratio of precipitation to evapotranspiration losses of water vapor, Maine soils are prone to leaching and erosion. Maine has a relatively neutral change in the water balance projected for the future in contrast to a negative net soil moisture balance prospect for most other areas of the U.S. (Fig. 12). Moreover, compared to many other regions, precipitation in Maine is more evenly distributed across seasons.

Maine also has an advantage of proximity to large population centers. Transportation costs may go up with fossil fuel prices and amplify that advantage, but transportation cost is only a small percentage of final retail food price. Food processing and marketing receives a bigger portion of the consumer food dollar than raw product providers, i.e. farmers.

Through in-depth interviews with 30 farmers and 16 farm advisors in Maine and Vermont, Johnson et al. (2019) found that farmers had mixed opinions about the relative beneficial and negative effects of climate change. One theme in farmer responses was uncertainty, for example, "We know that climate change exists and that it's real, but we don't know what that means and what it's gonna do."

Variability and Extremes

For both water and temperature, variation around the changing average conditions, and extreme events in particular, are equally or more important than incremental change in long term averages. Increased variability brings reduced predictability, and with it a reduction in farmers' ability to prepare for quickly developing weather-based risks.

With more weather extremes, environmental control is becoming more important. This has increased the use of irrigation, hoop houses, black plastic, greenhouses, hail netting, row covers and other methods. Technology tools such as weather-based decision support, precision agriculture analytics, monitoring and metering; artificial intelligence; and crop genetics are increasingly important for climate change adaptation.

Irrigation (overhead and low volume drip) is becoming increasingly prominent in many crops. In addition to financial and management requirements, increased use of irrigation requires expert assistance for design and installation as well as for water access and storage capability.

In addition to damage to forage crops, livestock are sensitive to climate change effects, including heat stress and excess water. Dairy cow health and reproduction and productivity are directly and negatively affected by heat stress, as are poultry and other livestock (Hristov 2018). The reduction in Maine milk production by 2030 due to heat stress is estimated at only 0.6%, much smaller than impacts on dairy in other U.S. regions and possibly indicating a future competitive advantage for Maine dairy.

Subsequent temperature increases and impacts for dairy are larger (Key et al. 2014). Such estimates are complex. They may overestimate impacts because they do not account for technological compensations, dairy cow breeding for heat resistance, more energy efficient cooling for animal housing, operator adaptation, and farm policy. These estimates may also underestimate impacts by focusing on production volume and overlooking negative effects on milk quality such as protein and fat content. In addition, negative impacts may increase with climate change effects on feed crops, livestock parasites and pathogens.

The effects of climate change on the beef industry in the Northeast are expected to be minimal and broiler production in the region may benefit from warmer winter and summer temperatures. Providing adequate housing and ventilation to offset warmer temperatures (and possibly more intense moisture fluctuations) will be important for all forms of animal husbandry, especially for the poultry broiler and layer industries, which may increase the price of eggs.

CO2 fertilization effect

More than 95% of the world's plant species use CO2 from the atmosphere through the C3 photosynthetic pathway. Most of the other plant species use the C4 pathway and are adapted to thrive in low CO2 conditions. C3 plants are often better able to increase production in response to additional CO2 than C4 plants. Corn is a C4 plant, and therefore not likely to benefit from elevated CO2 concentrations (U.S. Department of Agriculture, 2012).

Other crops that use the C3 pathway will not be able to fully benefit from the CO2 fertilization effect if temperature, water, insect, disease, or weed pest stresses, or nutrient supply do not allow for optimum growth. In addition, where it does take effect, elevated CO2 has been found to reduce nutrient density for protein, iron, and zinc (Willet et al. 2019). Thus, the gross yield of some crops may benefit, but at the cost of lower food nutrient density. Evidence confirms the stimulatory effects of CO2 in most cases and the damaging effects of elevated surface ozone (O3) on crop yields (Porter et al. 2014). Experimental and modeling evidence indicates that interactions between CO2 and O3, mean temperature and extremes, water, and nitrogen are nonlinear and difficult to predict.

Changes in climate and atmospheric CO2 concentration will enhance the distribution and increase the competitiveness of agronomically important and invasive weeds, exacerbated by elevated CO2 causing reduced effectiveness of some herbicides (Porter et al., 2014). The effects of climate change on disease pressure on food crops are uncertain, with evidence pointing to changed geographical ranges of insect pests and diseases but less certain changes in disease intensity (Ibid).

Overall, increased average maximum temperatures, more days with temperatures exceeding 77°F (25°C), higher annual precipitation in the Northeast, and increased atmospheric CO2 concentration may either increase or decrease forage productivity depending on the crop, and may also decrease protein content and forage digestibility (Porter et al., 2014).

Adaptation Resources and Constraints

Subsidized crop insurance administered by the USDA Risk Management Agency has largely replaced disaster relief funds as the main channel of Federal aid for weather based agricultural losses. Numerous other USDA agencies and programs including the Natural Resource Conservation Service, Farm Service Agency, Rural Development, and Rural Business-Cooperative Service provide technical, financial and other forms of assistance to help producers adapt to climate change effects. The Climate Adaptation Fellowship developed Extension curriculum guides (https://www.adaptationfellows.net/) for northeastern U.S. dairy, tree fruit, and vegetable farms

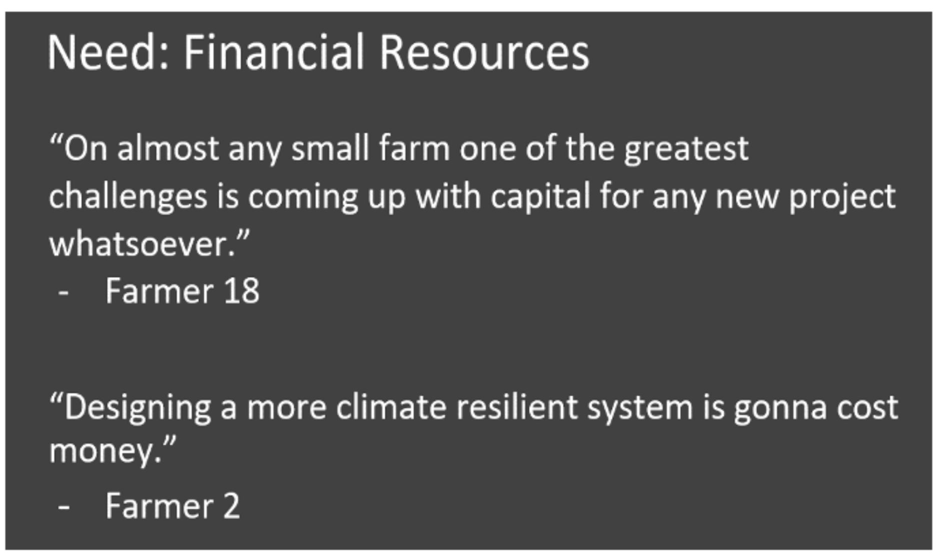

Figure 13. Examples of farmer responses in interviews about adapting their operations to climate change. Johnson et al. 2019

(Faulkner et al. 2019). Other recent comprehensive regionally focused agricultural adaptation guides include U. S. Department of Agriculture 2015 and 2016a (an excerpt of which is in the Appendix).

Farmers and farm consultants in Maine and Vermont pointed to investment capital, financing, time, and information resources as all being major impediments to climate change adaptation (Fig. 13). Rosenzweig et al. (2020) rated the efficacy of various responses for climate change mitigation and adaptation (Fig. 14).

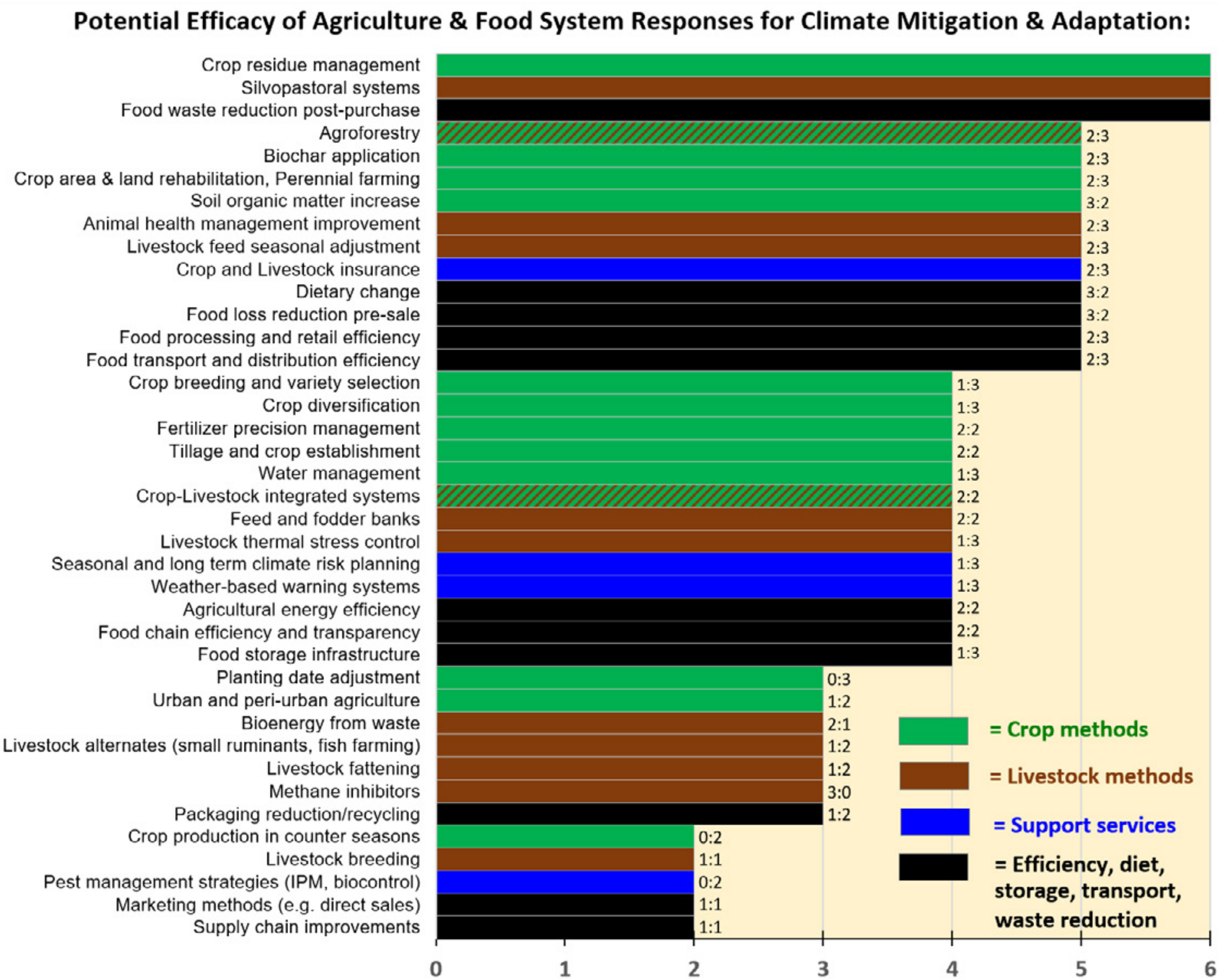

Figure 14. Potential for food system responses to reduce greenhouse gas emissions and adapt to climate change. Individual scores are 0 = none, 1 = Limited, 2 = High, 3 = Very high. The scores for mitigation and adaptation were combined into a single rating. The highest possible combined score is 6. Paired numbers to the right of bars are the individual mitigation:adaptation ratings. Ratings adapted from Rosenzweig et al. 2020.

Maine Food System and Climate Connections

Food security

The Maine food system is embedded in a larger, interconnected national and international system. Climate impacts at those scales was mentioned above (e.g. Lawrence et al. 2020).

Food security manifested as hunger in Maine involves many socioeconomic issues. Statewide food supply does not appear to be a driving factor. For example, "'We have enough food in this state right now to make sure everybody can eat. And so it's a matter of putting in the right policies and investments in our people, in our economy, to make sure that everybody has access to healthy food.' said Kristen Miale, President, Good Shepherd Food Bank," (Troutman 2019). Food insecurity in Maine is a persistent problem that has increased since the 2008 recession (Ibid) and likely also in response to the COVID-19 outbreak (e.g. Tonsberg et al., 2020). Gunderson et al. (2019) found that the portion of Maine children meeting their criteria for food insecurity was 21.4% (2015), 19.8% (2016), and 18.5% (2017).

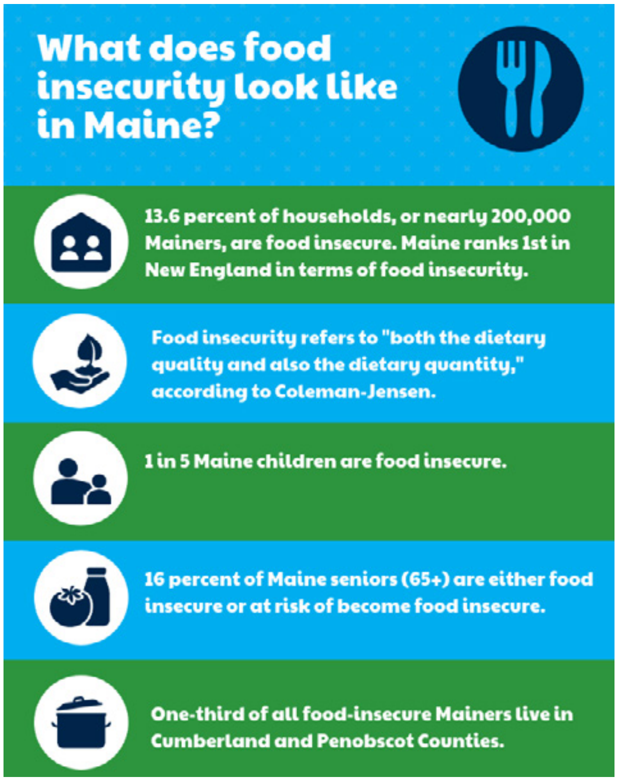

Figure 15. Adapted from Troutman 2019.

Myall (2019) describes the following demographic groups in Maine as having increased chance of being at risk for food insecurity (data are from before COVID-19 outbreak):

- **Single parent households** have the highest group food insecurity rate at 42%.
- **Households headed by Mainers of color** experience more than twice the rate of food insecurity at 28%, the rate among whites and non-Hispanics is 13%
- **Mainers with healthcare issues**: 26% of Mainers with physical or mental health issues. Those that cannot work are at 39%
- **Workers in low-wage industries**: 33% of personal health aides, 22% of restaurant employees and 17% of grocery store workers live in food insecure households.
- **Mainers without jobs**: 23% of unemployed Mainers live in food insecure households.
- **Families with children**: 16% of Maine households with children are food insecure.
- **Working Mainers**: 10% live in households without enough nutritious food.

Hickman (2019), adds the following observations on hunger in Maine:

- **37% of the Maine people who face hunger, food insecurity or malnutrition do not qualify for any public assistance**

- Many emergency food relief sites in the State regularly **lack fresh fruits and vegetables and other nutrient-dense foods** for residents struggling with hunger, food insecurity or malnutrition;

- For the consumer, producer and the environment, **the cost of food produced by and for the global industrial food system has risen in the last decade**

Maine agriculture plays a role in hunger reduction efforts through supplying food to food banks (Maine Department of Agriculture, Conservation & Forestry, 2020). Many food pantries work with the Good Shepherd Food Bank which operates the largest program to acquire fresh produce from Maine farms, the "Mainers Feeding Mainers" program. Mainers Feeding Mainers has over 70 farm partners and in 2018 they moved over 2.1 million pounds of fresh Maine grown food to food pantries across the state and directly invested over $770,000 into Maine's agricultural economy. Some pantries have established a relationship with local farms for gleaning, donations or purchase. (Ibid)

The Maine Cooperative Extension "Maine Harvest for the Hungry" program has collected over 3.0 million pounds of food since its inception in 2000. This program engages the community in providing fresh produce to soup kitchens, food pantries and community meals. Other organizations such as Healthy Acadia, which serves Washington and Hancock Counties, focus on healthy communities and "Healthy Food for All" with initiatives around SNAP-Ed, summer food programs, gleaning at partner farms, connecting farms with schools, helping farms and seniors connect to Maine Senior Farm Share and other initiatives to help address hunger and food insecurity in their counties (Ibid)

The Maine Center for Economic Policy estimates the total cost of food insecurity of Maine's economy at $709 million annually. This includes health care services (mental and physical), loss of worker productivity, special education services and loss of earnings. (Myall 2019).

Future food production and prices

Hertel et al. (2010) applied low, medium and high productivity scenarios to 2001 food production estimates to examine the impact on population welfare in 2030 for many countries including the United States.

The low-productivity scenario depicts a world with rapid temperature change, high sensitivity of crops to warming, and a CO2 fertilization effect at the lower end of published estimates. The high-productivity scenario represents a world with relatively slow warming, low sensitivity of crops to climate change, and high CO2 fertilization effect. These estimates are intended to bracket a range of plausible outcomes and can be thought of as the 5th and 95th percentile values in a distribution of potential yield impacts (Ibid). Estimates were made without consideration of adaptations that may reduce negative or enhance positive outcomes, such as the development of new crop varieties or the significant expansion of irrigation infrastructure in a region (Ibid).

Under the low and medium and productivity scenarios, welfare in the United States was reduced approximately 20% and 2%, respectively. Under the high productivity scenario, U.S. welfare increased by approximately 4%. Hertel et al. (2010) note that the impact of agricultural productivity is not the sole or even major determinant for human welfare and access to food. Other issues such as global trade, household source of income and poverty rate are more important. They also concluded that using centralized estimates of climate change impacts on food production are inadequate because doing so does not represent the range of possible outcomes. This highlights the importance of reducing uncertainty and thus narrowing the probable range of such impacts.

All aspects of food security are potentially affected by climate change, including food access, utilization, and price stability (Porter et al., 2014). The global impact on crop production is generally negative, especially if average surface temperatures exceed more than 2oC above the 1850-1900 average used as a proxy for preindustrial average. With that much warming, a lowering of average yields would be exacerbated by increased interannual variablity.

Tigchelaar et al. (2018), and other studies (summarized by Mehrabi 2020) have found sensitivity of agricultural commodity markers to production changes traceable to climate impacts such as heat waves, drought or floods. Market price shocks are much more likely if multiple primary production areas are affected within a single year. Tigchelaar et al. (2018) report that the top four maize-exporting regions account for 87% of global maize exports. They estimated that the probability of all four of those regions having simultaneous production losses greater than 10% in any given year is presently virtually zero, but increases to 7% under 3.6°F of warming and 86% under 7.2°F of warming. Given the tight coupling of global supply and price, rising instability in global grain trade and international grain prices are expected under increased warming.

In addition to food quantity, negative effects on food and fodder quality, including protein and micronutrients (such as zinc and iron) could be affected by elevated CO2, but understanding of these relationships is poor. What seems clearer is that global temperature increases of ~7.2°F or more above late-20th-century levels, combined with increasing food demand, would pose large risks to food security globally and regionally (Porter et al. 2014).

Maine food imports

It is noteworthy that 90% of the food Maine people consume is imported from out of state (Hickman, 2019). Even a partial and temporary interruption of a key transportation route such as the Interstate 95 Piscataqua River bridge that connects New Hampshire and Maine could have a noticeable effect on re-supply and wholesale pricing for Maine grocery stores and other food vendors.

The Maine Emergency Management Agency has primary authority for addressing emergency situations in Maine, but while the listing of staff responsibilities includes natural hazards, dams, cyber and technological issues, food supply is not directly mentioned (Maine Emergency Management Agency, 2019). Numerous voluntary organizations in Maine would presumably activate to provide assistance but would have to rely on accessible stored food reserves. Food pantries do not have the capacity to function as a food reserve for the entire state population. The Maine Militia is an example of a voluntary nongovernmental organization that attends to emergency management scenarios. For example, each Maine Militia member is expected to have a "three-day pack", containing enough first aid, food and water to survive in case of emergency" (Curtis, 2010).

Local food production

The global and national food system within which the Maine food system is embedded embodies values and choices that affect food security at the state and local level. The effects became more apparent in the COVID-19 pandemic (e.g., Gustin 2020), and as described by Pollan (2020):

"A system that's really efficient sacrifices resiliency, and now it is resiliency that we need. Whenever you achieve efficiency, one of the things you're doing is sacrificing redundancy. So, when we move from a system where we had hundreds of regional slaughterhouses and tens of thousands of small farmers, if there was a problem at any one of those slaughterhouses, it wouldn't be in the newspapers. It would just barely make a ripple in the food system because you had all this redundancy."

"You don't get cheap food without sacrificing other values. We have put price at the center: pile it high and sell it cheap is the motto of the American food system."

"We tolerated the concentration of the meat industry and other parts of the food industry, because it promised lower prices to consumers. And it did deliver that. But if you think about the cost now, in terms of the fragility, the brittleness of the food system, it was too high a price to pay."

"There has never been a more eloquent case for diversifying the food chain for having many different ways to get ourselves fed, not just this supermarket food chain, and support local agriculture as a matter of national security."

It is beyond the scope of this report to discuss the details of a food system change in Maine. Many factors are involved in climate effects on the Maine food system and incremental vs. systemic adaptive responses (Fig. 16).

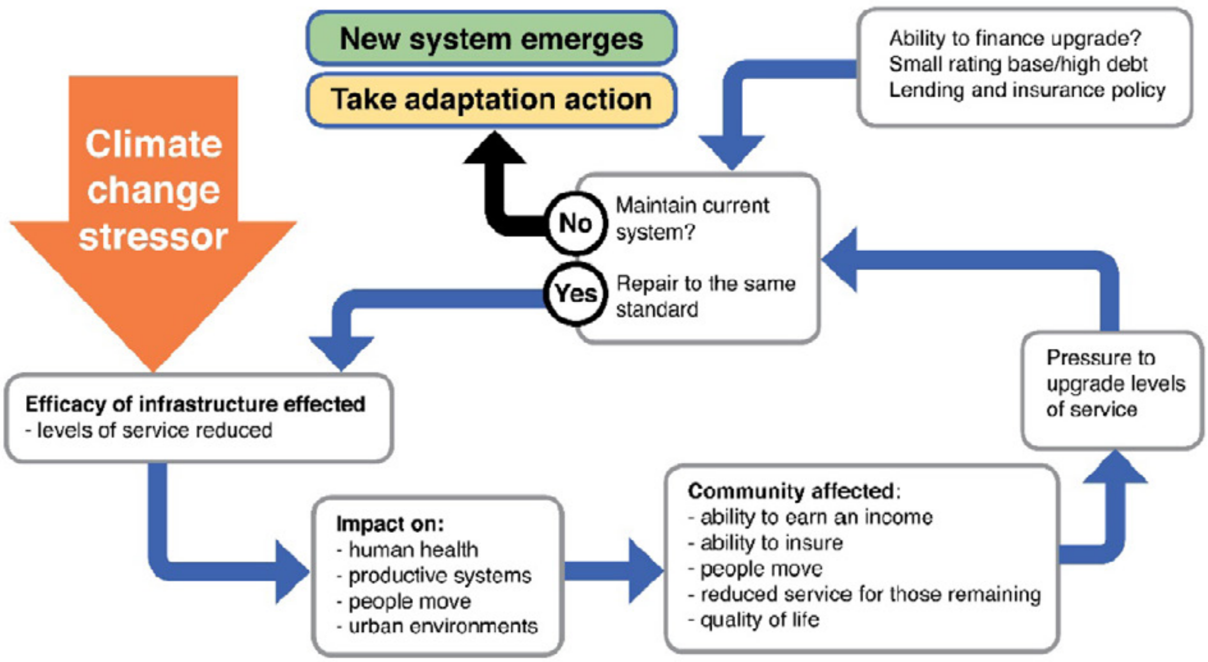

Figure 16. Lawrence et al. 2020. Water supply and waste management system adaptations that are also applicable to food systems.

Extended excerpts from "Reclaiming Maine's Lost Farmland", by John Piotti, President and Chief Executive Officer of American Farmland Trust (Piotti 2020)

> "New England could produce as much as two-thirds of all its own food by the year 2060, but only if the region expands its agricultural production by 3–4 million acres. A good chunk of that land will need to come from Maine, simply because it isn't available elsewhere in New England."
>
> "In the 1880s, 6.5 million of Maine's 20 million acres was cleared land used for farming—either for growing crops or grazing livestock. Today, only about 700,000 acres of land are used in this way. Of the remaining 5.8 million acres, some has been lost to development, but probably not much more than a million acres or so. Over 4.5 million acres of once-farmed land has reverted to woods—and very little of that land is part of Maine's great northern forest, on which our paper mills rely. Here is a way that Maine could contribute millions of acres to the emerging vision that New England might someday grow most of its own food."
>
> "As Maine considers how it should once again grow food on once-farmed land, both silvopasture and forest farming have a role to play. "
>
> "Maine should never have been farming 6.5 million acres in the 1880s—or at least not those particular 6.5 million acres in that manner. The landscape across much of southern and central Maine during that period was basically devoid of trees, except for orchards. Land was often cleared right up to the banks of rivers and streams. Pastures were often over-grazed and crops worked with little regard for soil conservation. As a result, we depleted our topsoil and despoiled our waterways."
>
> "As Maine now moves to farm more, we need to learn from past mistakes."
>
> "Farmers are used to the notion of "best agricultural practices," various operational standards articulated in farm publications and, at times, in law. But when it comes to farmland reclamation, the standards that exist are insufficient, either because they weren't designed to take the full ecosystem into account, or because they don't respond to the realities of a changing climate. We need to move beyond our current "best practices" to what I call "next practices." "
>
> "If we are smart about it, Maine could simultaneously advance local food production and local environmental health, while also making strides to reduce carbon emissions."
>
> "Maine has the chance to do something truly significant, powerful on its own and even more powerful because it could be a model for others. Maine can do far more than feed itself and help feed New England: Through our farmers, Maine can lead the way to restoring our planet."

End of excerpts from Piotti 2020.

Reducing food waste

Maine could reduce greenhouse gas emissions and improve economic efficiency of its food system by reducing waste of purchased food. Gunders (2017) states that nationally, Americans do not eat 40% of their food, and that just one third of that amount would be enough to feed all the U.S. citizens who face food insecurity. Food waste is responsible for 2.6% of U.S. greenhouse gas emissions from the growing of food that is not used and from the CH4 produced from food rotting in landfills (Gunders 2017). Over 20% of food waste occurs at the consumer/household level (Ibid).

Net Greenhouse Gas Emissions for Food Waste under different Management Options

FOOD WASTE MANAGEMENT METHOD	METRIC TONS CO_2e PER SHORT TON OF FOOD
Prevention (assumes food is not produced)	-3.66
Redistribution to People	-0.43
Anaerobic Digestion	-0.18
Composting	-0.05
Landfill	0.54

Figure 17. Adapted from Gunders 2017.

There are many simple practical methods available, such as planning food shopping, better storage, understanding that "sell by", "use by" and "best by" expiration dates do not mean that food is unsafe by those dates, making use of leftovers as ingredients, and donating unspoiled food to food banks (U.S. Environmental Protection Agency 2020a). Gunders (2017) provides details on where in the supply chain losses occur (Fig. 17), and recommendations for reducing food waste at the farm, retail, consumer, state and Federal levels.

Legislative action in Massachusetts provides a model that may be useful for a food waste reduction effort in Maine (Mellion, 2017). Reducing food waste will involve many steps in the food supply chain, and is one of many aspects to include in consideration of the linkages that define food system resiliency and security (Figs. 18 and 19).

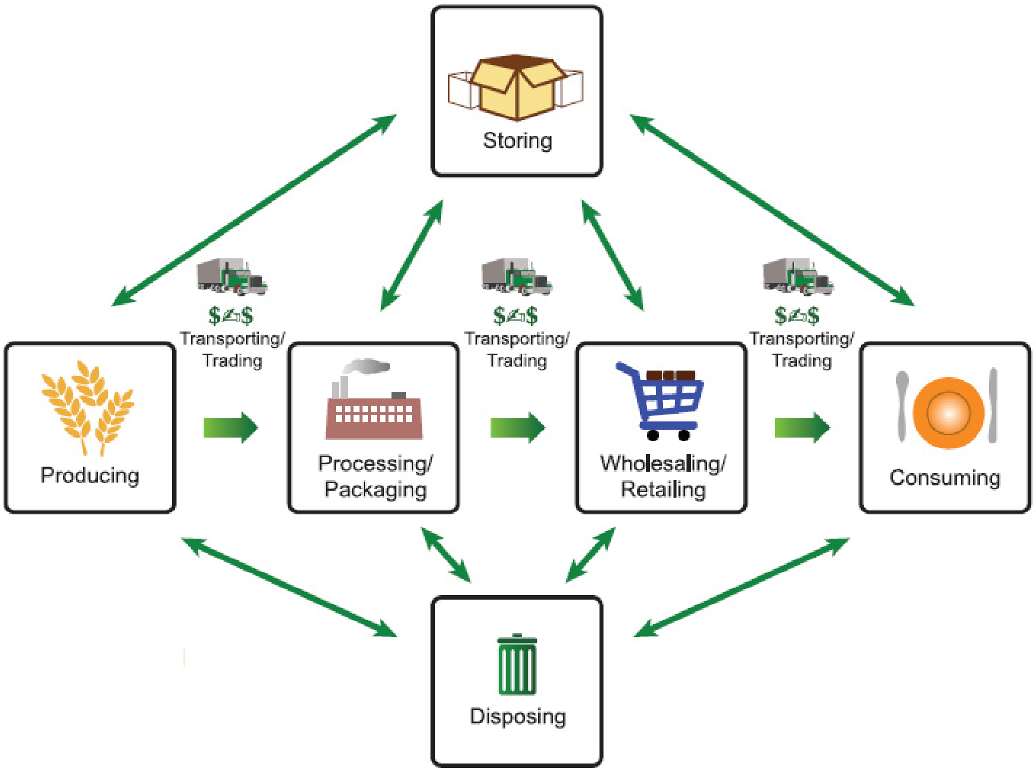

Figure 18. Food waste linkages to multiple steps in the food supply chain. Brown et al. 2015.

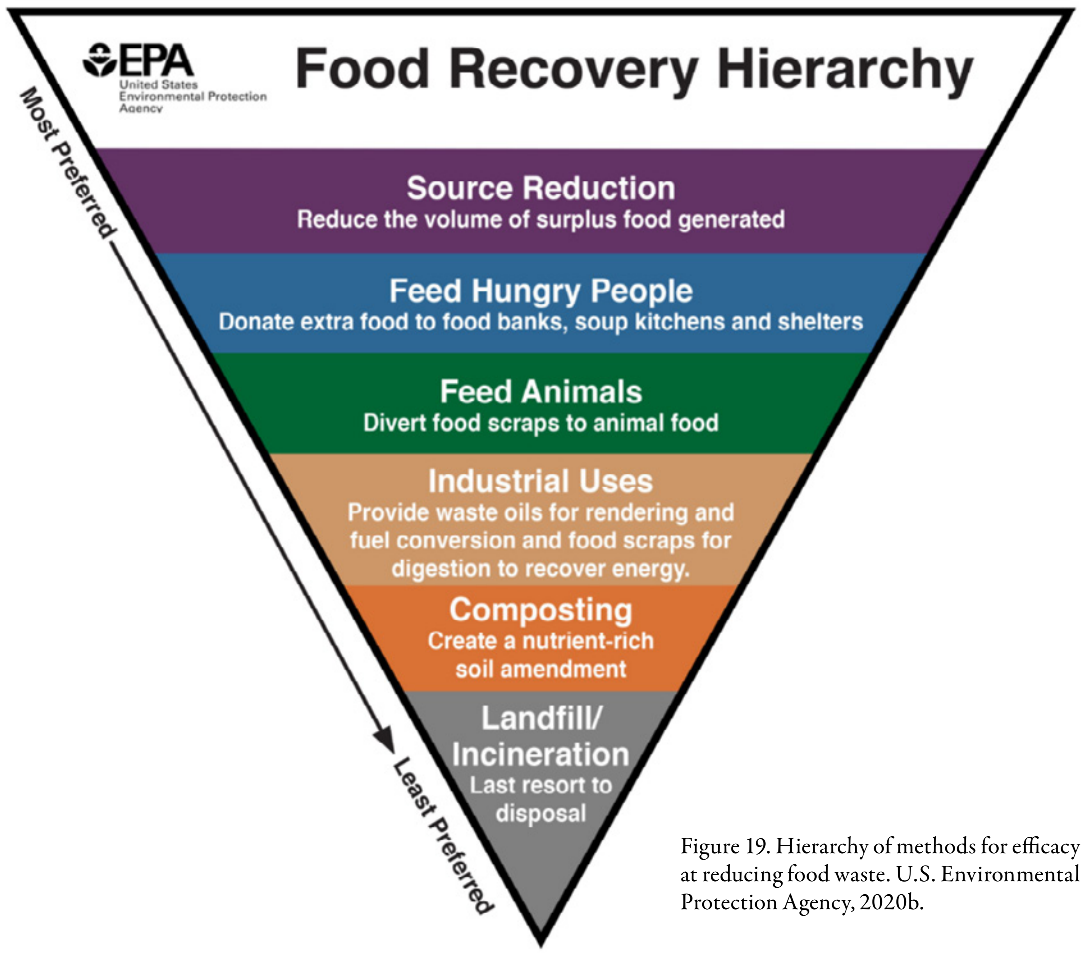

Figure 19. Hierarchy of methods for efficacy at reducing food waste. U.S. Environmental Protection Agency, 2020b.

Strategic Considerations

Message framing to communicate with the Maine agriculture community

Policies that affect the Maine farmers are more likely to be successful if developed and implemented in concert with farmer agreement and participation. A well thought out policy could be rendered moot if communicated in such a way as to alienate the population to be most involved in carrying it out (NOAA 2015a). As astute weather observers, Maine farmers are aware of changes in weather patterns, especially those that affect their business operations (e.g., Birthisel et al. 2019). The framing of messages about climate change, and what to do about it, can have a strong effect on how those messages are perceived by members of the agricultural community, and on stakeholder engagement to pursue the goals of climate change mitigation and adaptation. In Maine, assistance with climate change adaptation was a major theme that arose in a 2019 census of Maine farmer priorities (Skakalski 2019) and in structured interviews with individual farmers (Birthisel et al. 2019). The focus of this report is on productivity, profitability and numbers. But as documented by Johnson et al. (2019), agriculture is also a matter of emotion, personal and community identity, and values (Fig. 17).

Priority Information Needs

Greenhouse gas emissions mitigation by agriculture

1. Estimate the CH_4 emission reduction potential from livestock manure management, anaerobic digesters, and feed additives or other livestock diet alterations.

2. Estimate the per acre and statewide cumulative potential for carbon sequestration potential in agricultural soils. This must include quantifying differences between production regimes (e.g. rotation schedule, tillage practice, cover cropping).

3. Estimate N_2O emission reduction potentials for alternative soil, fertilizer, and manure management approaches.

4. Review logistics for how greenhouse gas emission reduction strategies can be implemented in harmony with farmer values and motivations, economic viability, and food production objectives.

5. Identify and evaluate candidate components for a synergistic network of educational, technical, financial, regulatory, marketing, infrastructure and other statewide governmental and private sector approaches to facilitate agricultural greenhouse gas mitigation and adaptation objectives. Components are needed that address agriculture in general, and other that target specific commodities, geographic regions, market segments (e.g. wholesale vs. retail, organic vs. conventional), and production scales.

Maine food system-climate connections

1. Document food security gaps, and the potential to enhance food security and reduce CH_4 emissions by incentives and regulations to reduce food waste.

2. Identify linkages between local food production, systemic food supply resiliency, individual food security, public health, childhood education, and economic development.

3. Identify and evaluate candidate governmental and private sector components for a network of mutualistic approaches to facilitate local food production, food security, CH_4 emission, and public health objectives.

4. Capabilities for locally specific, real-time, weather-based decision support offer large return on investment for government and private sector services to assist farmers in maximizing climatic opportunities and minimizing short-term weather risks.

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APPENDIX:
AGRICULTURE AND FOOD SYSTEMS

1. **2017 Maine agricultural sales** National Agricultural Statistics Service. (United States Department of Agriculture, 2019). https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Rankings_of_Market_Value/Maine/

Census of Agriculture
2017 Ranking of Market Value of Ag Products Sold

Item	Farms	Sales ($1,000)	Rank by Sales	Percent of Total Sales
Total sales	7,600	666,962	(X)	100.0
Vegetables, melons, potatoes, and sweet potatoes	1,448	221,265	1	33.2
Milk from cows	286	134,560	2	20.2
Nursery, greenhouse, floriculture, and sod	965	71,401	3	10.7
Aquaculture	81	64,070	4	9.6
Fruits, tree nuts, and berries	1,149	51,510	5	7.7
Other crops and hay	2,552	44,867	6	6.7
Cattle and calves	1,253	26,423	7	4.0
Poultry and eggs	1,541	16,683	8	2.5
Grains, oilseeds, dry beans, and dry peas	307	16,220	9	2.4
Other animals and other animal products	489	7,972	10	1.2
Sheep, goats, wool, mohair, and milk	730	4,596	11	0.7
Cultivated Christmas trees and short rotation woody crops	247	3,575	12	0.5
Horses, ponies, mules, burros, and donkeys	222	1,926	13	0.3
Hogs and pigs	696	1,892	14	0.3
Tobacco	-	-	-	-
Cotton and cottonseed	-	-	-	-

Table Definitions

Grains, oilseeds, dry beans, and dry peas sales. Data are for the total market value of cash grains sold, including corn for grain, seed, or silage; wheat for grain; soybeans for beans; sorghum for grain, seed, or silage; barley for grain; rice; oats for grain; and other grains. Also included is the total market value of cash oilseeds sold, including sunflower seed (oil and non-oil), flaxseed, canola, rapeseed, safflower seed, mustard seed, dry beans, and dry peas.

Nursery, greenhouse, floriculture and sod. Data are for total square feet under protection and acres in the open. Individual crop data were collected for area under glass or other protection, area in the open, and sales of aquatic plants, floriculture and bedding crops, nursery crops, sod, propagative materials, food crops grown under protection, and mushroom crops. Total sales data are the summation of all crops.

Other animals and other animal products sold. This category includes number of farms and value of sales for all animals and animal products not listed elsewhere. Some examples are honey, rabbits, semen, manure, and other animal specialties.

Other crops and hay. Data are for the total market value of all crops not categorized into one of the prelisted crop sales categories on the report form and include hay sales. This category includes crops such as grass seed, hay and grass silage, haylage, greenchop, hops, maple syrup, mint for oil, peanuts, sugarcane, and sugarbeets.

Market value of agricultural products sold. This category represents the gross market value before taxes and production expenses of all agricultural products sold or removed from the place in 2017 regardless of who received the payment. It is equivalent to total sales and it includes sales by the producers as well as the value of any shares received by partners, landlords, contractors, or others associated with the operation. It includes value of organic sales, direct sales and the value of commodities placed in the Commodity Credit Corporation (CCC) loan program. Market value of agricultural products sold does not include payments received for participation in other Federal farm programs. It does not include income from farm-related sources such as customwork and other agricultural services, or income from nonfarm sources.

The value of crops sold in 2017 does not necessarily represent the sales from crops harvested in 2017. Data may include sales from crops produced in earlier years and may exclude some crops produced in 2017 but held in storage and not sold. For commodities such as sugarbeets and wool sold through a co-op that made payments in several installments, respondents were requested to report the total value received in 2017.

2. **Maine farm climate adaptation summary**. Maine Climate and Agriculture Network, 2017. https://umaine.edu/climate-ag/farm-response-changing-weather/

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Maine Climate and Agriculture Network

umaine.edu/climate-ag

Farm Response to Changing Weather

Changes in average and extreme weather are affecting Maine agriculture, bringing both risks and potential opportunities. Here are some observations of how Maine weather is now different from the past, what may lie ahead, and examples of farmer choices and actions that can minimize risk and help ensure productivity.

Temperature

Longer Growing Season and Plant Hardiness Zone Shift

- The average length of Maine's frost-free growing season is now 12–14 days longer than in 1930, and is expected to further increase by 2–3 days per decade.
- Winter minimum temperatures that define plant hardiness zones are increasing faster than daily highs or temperatures in other seasons.

Potential Response Actions

- Choose longer season crops or varieties, or be flexible with earlier or later planting dates for current selections.
- Double cropping, inter-cropping, and greater use of cover crops.

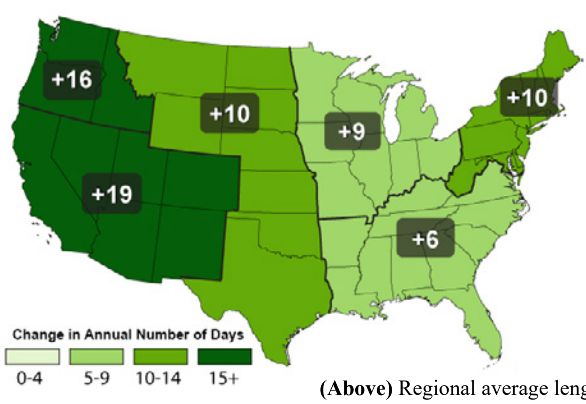
Early Spring Warm-up Increases Frost/Freeze Risk

- Late winter/early spring temperature variability has caused early crop development before the last spring freeze date. Spring frosts affected Maine apple, blueberry, and peach crops in 2012 and 2016.

Potential Response Actions

- Consider spring frost risk in site/crop/variety, and planting date decisions.
- Minimize frost risk (hoop houses, mulch, row covers, inter-cropping, no-till).
- Enhance emergency response capacity (freeze forecasts, wind machines, irrigation, heaters, frost protectants).
- Diversify farm enterprise. Consider crop insurance to spread risk.

(Above) Recent, current, and future projected plant hardiness zones. Zone numbers labeled in top map. *Data Source: PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu.*



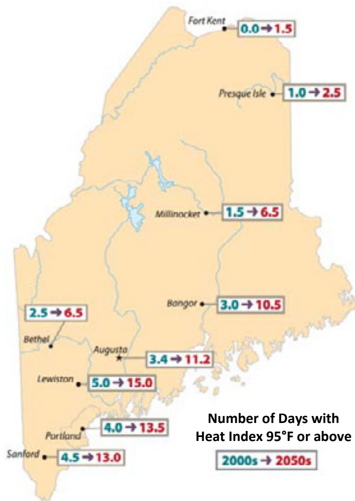
(Above) Regional average length of frost-free season for 1991-2012 compared to 1900-1960. *Adapted from Melillo et al. (2014), Climate Change Impacts in the United States.*

More Frequent or Intense Heat Waves

- Daily high and overnight temperatures are increasing. Extreme caution is advised for outside work when the heat index exceeds 90°F.
- High temperatures can damage crops such as apples and peppers, and can reduce productivity and health of dairy cows and other livestock.

Potential Response Actions

- Consider temperature sensitivity in site/crop/variety and breed selection.
- Adjust crop planting date or livestock feed rations for temperature stress.
- Row cover, shade cloth, overhead or trickle irrigation, companion crops.
- Manage soil moisture to reduce crop sensitivity to heat stress.
- Adjust schedule and facilities to reduce worker heat exposure.
- Livestock cooling, barn design, stress monitoring, adjust reproductive timing.
- Use crop heat stress protectants, adjust harvest timing and handling.



(Right) Number of days per year with heat index at or over 95°F for 2000-2004 and 2050-2054. *Source: Fernandez et al. (2015). Maine's Climate Future: 2015.*

Water

More Frequent Intense Downpours

- The frequency of extreme precipitation events in Maine increased 74% between 1948 and 2011. Intense storms that used to occur an average of once per 12 months now happen once per 7 months. The maximum hourly rate of precipitation increased by about 35% between 2001 and 2013. The frequency and intensity of extreme precipitation events are expected to continue increasing in the coming decades.
- Intense rain during the growing season increases risk of soil erosion, seed loss, soil saturation, flooding, and nutrient runoff. Loss of fieldwork days interfered with potato and corn planting in 2015.

Potential Response Actions

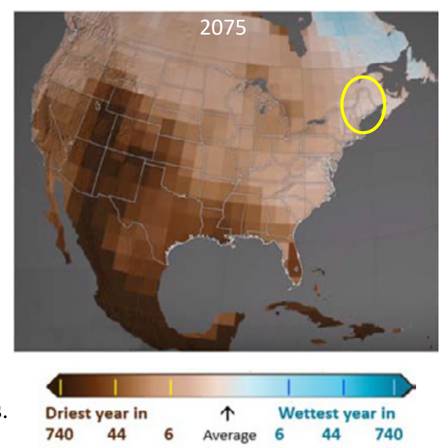
- Strategies to reduce soil losses (cover and companion crops, reduced/no-till, crop residue, mulch bare areas, plasticulture, increase soil organic matter/soil health, contour planting, avoid slopes and flood zones).
- Selected flood-tolerant crops/varieties, use overseeding to advance crop establishment.
- High-capacity equipment or short-term labor to accelerate fieldwork if number of suitable days is limited.
- Ditches, berms, drainage tiles, and engineered solutions to handle excess water.
- Reduce vehicle traffic on wet soils.
- Just-in-time fertilizer application, adjust pesticide interval for rain.
- Greater use of greenhouse and hoop house production.

More Frequent and Longer Dry Spells

- Higher average temperatures and longer heat waves lead to lower average soil moisture. Winter precipitation in Maine may increase, but little or no increase is expected in summer, and winter increases will not replace heat-driven losses.
- Increased rain intensity leads to more water lost as runoff.
- Maine apple, blueberry, potato and other vegetables, forage, and hay yields were affected by drought in 2016.

Potential Response Actions

- Drip or overhead irrigation system installation/efficiency improvements.
- Farm pond, wells, and other water source and storage improvements.
- Soil monitoring and weather-based irrigation scheduling.
- Increase soil organic matter, use mulch to enhance water retention.
- Site/crop/variety/breed selection for drought tolerance.



(Above) Average summer soil moisture from surface to 12 inches depth in 2075 compared to past 1000 years. High CO_2 emissions scenario. *Source: NASA's Scientific Visualization Studio.*

NEXT STEPS: The Maine Climate and Agriculture Network website at **umaine.edu/climate-ag** offers information and contacts to help you identify, finance, and implement weather adaptations that fit your farm.

This publication was supported by the USDA National Institute of Food and Agriculture.

3. Agriculture chapter from the 2009 Maine's Climate Future (Griffin 2009)

Maine's Climate Future

IV SECTOR ISSUES & OPPORTUNITIES

Agriculture

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Tim Griffin

The plant hardiness zones used by farmers and gardeners have shifted north, allowing Mainers to grow crops, plants, and flowers previously available only in warmer climes. Warmer temperatures will give farmers and the horticulture industry continued access to new crops and livestock.

Farmers and gardeners can expect a greater need for irrigation, particularly for high value crops, to offset increased soil moisture loss through evaporation and transpiration. Increasing temperatures will also negatively affect confined livestock in the state.

New pests, invasive plants, and pathogens will increasingly encroach into Maine, threatening plants, animals, and humans, and making management more difficult.

Agriculture is a diverse industry, contributing over $1 billion annually to Maine's economy. Although agriculture has undergone significant consolidation in the US over the past 40 years, farming in Maine is still dominated by small to moderate-sized, family-owned farms, with major products including dairy, potatoes, grains, vegetables and fruits, wild blueberries, and ornamental and turf products.

This industry, like other natural resource-based industries in Maine, faces substantial effects from projected increases in temperature and shifts in the amount and distribution of precipitation. In addition to factors like soil texture and management inputs, temperature and precipitation are two of the driving forces controlling the productivity and, ultimately, the viability of agriculture in Maine. This includes both direct effects (like the effect of higher temperature on current or potential crops) and indirect effects (changing pest pressure, for example).

Climate and agriculture: direct and indirect effects

Increasing temperature affects the length of the crop growing season and frost-free periods. Amounts and patterns of precipitation determine the amount of water available in the soil.

But agricultural systems can also be affected directly by increasing atmospheric CO_2 concentration. The "CO_2 fertilization effect" is an increase in plant biomass or yield resulting from increased CO_2 concentration in the air, which increases a plant's photosynthetic rate and water use efficiency. CO_2 concentrations of 550-600 ppm (which is predicted under the IPCC's B1 scenario) have been shown to increase plant biomass up to 35% (Long *et al.* 2004), although an increase of 12-15% is probably more realistic. The CO_2 effect is particularly striking for cool-season crops, of which Maine has many: potatoes, oats, barley, lettuce, broccoli, strawberries. In addition to enhanced growth, some evidence suggests that plants under these conditions may be moderately more drought-tolerant.

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One consistent plant response to increasing CO_2 levels is a reduction in protein concentration in the plant (Idso and Idso 2001, Taub *et al.* 2008), which has clear implications for both human and animal nutrition. Potentially serious and unpredictable effects, such as how plants defend themselves against insects and other pests, could result as plant chemistry changes in response to CO_2 concentrations.

Maine farms in the future

All plants respond to temperature. A plant's growth rate generally increases up to some optimum temperature (or range), and then declines with further warming. Different crops have different optima, which means that the effect of warming will not be the same for all of the crops that are grown (or could be grown) in Maine. Potatoes have a relatively low temperature optima (15-18°C/60-64ºF; about the growing season average for Presque Isle), and projected temperature increases would result in common yield reductions of 25-35%. Some cool-season grains would be affected in a similar way, although these losses can be moderated by changes in cultural practices like planting date. Other vegetable crops, like tomatoes and pumpkins, have temperature optima of 25°C (77ºF) or above, so in some parts of Maine, projected temperatures would be moving *towards*, not away from, their optimal range. An optimum temperature range of 30-35°C (86-95ºF) makes warm-season grasses like corn currently challenging to grow in Maine; these crops would benefit from both higher temperatures and a longer growing season (depending on related changes in precipitation). Warmer temperatures will give farmers access to a broader range of hybrids or cultivars for many crops.

Winter temperatures, which may increase more rapidly than growing season temperatures in some parts of Maine, will affect a broad range of perennial crops, from the forage grasses and legumes grown on dairy farms to tree fruits and wild blueberries. Winter warming can negatively influence perennials in several ways. First, warm periods during the winter may be sufficient to deacclimate these plants, causing them to lose their winter hardiness. Subsequent cold weather increases the likelihood of winter injury or winterkill (Bélanger *et al.* 2002). Second, a number of crops benefit from the consistent insulation provided by snowpack. If winter warming reduces (or eliminates) the snowpack, or results in the formation of ice sheets, severe winterkill is likely. Warming in winter and during the growing season will also shift the timing of significant developmental events (like bud break and flowering) for tree fruit and other crops. Wolfe *et al.* (2005) have already documented that leaf and flower emergence of lilac, apple, and grape shifted two to eight days earlier in the spring during the period from 1965 to 2001. These changes are similar to those shown by Chmielewski *et al.* (2004) in Europe. While the US Department of Agriculture has not yet revised the official plant hardiness zones, the Arbor Day Foundation (2006) released new maps in 2006 (*Figure 20*).

Even if precipitation during the growing season is uniformly distributed, less water will be available for plants, because the higher temperatures will result in greater transpiration (loss of water from the plants) and evaporation (from soil). The more frequent, high-intensity rainfall events predicted for the future are less effective at replenishing soil water supplies and more likely to erode soil. Crops that complete their development and set yield during the summer months (including high-value wild blueberries and potato) will be severely affected if irrigation is not available.

Agricultural pests, including insects, weeds, viruses, and other pathogens, are serious threats. Like crops, weeds respond to increasing CO_2 concentration, and could gain advantage over associated crops. Higher temperatures increase development rates of insects, just as they do for plants, and this can alter plant-pest interactions in several ways (Ward and Masters 2007). Current pests like the Colorado potato beetle, which completes one full generation per season in Maine under current conditions, may complete multiple generations under warmer temperatures and a longer growing season, increasing potential crop damage *and* the cost of control

Maine Hardiness Zones, 1990 and 2006

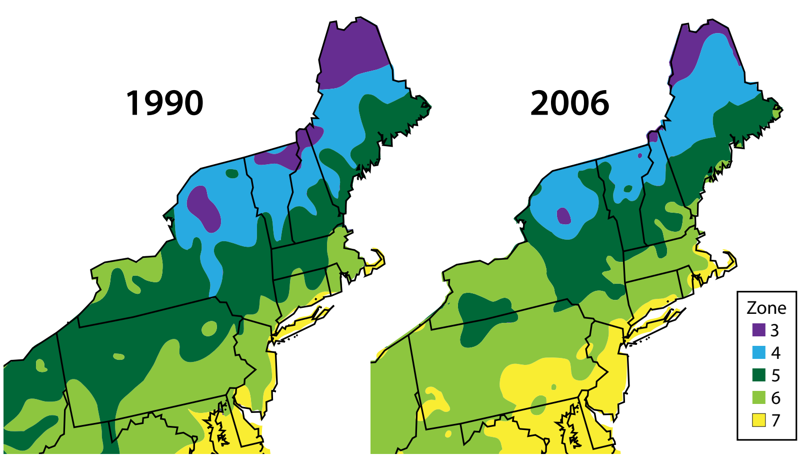

Figure 20 The Arbor Day Foundation (2006) revised plant hardiness zones used by farmers and gardners, based on data from 5,000 National Climatic Data Center cooperative stations across the continental United States. A northward shift in zones reflects a warming climate.

strategies. Multiple generations of this pest already occur in Massachusetts and Connecticut.

With warmer temperatures, new pests will arrive and survive in Maine. For example, the blueberry gall midge, which has been a problem in southern areas like New Jersey, is already affecting wild blueberries in eastern Maine. Moderating winter temperatures, especially in coastal and southern Maine, also increase the likelihood that pests that are currently migratory and thus sporadic in Maine could successfully overwinter here; for example, many aphid species arrive with storm fronts from the south each year (aphids are primary vectors for many plant viral diseases). While there is a possibility that natural predators and the activity of beneficial insects may also increase, most of these potential changes in plant pests suggest increased use of pesticides, which carries economic, environmental, and human health implications.

Scott Bauer

The effects of increasing temperatures are largely negative for animal agriculture in the state. As pointed out by Wolfe *et al.* (2008), a few days of high temperatures (and humidity) have a prolonged impact on productivity or output, and semi-confined animals like dairy cows already experience periods of heat stress. In simulations of the higher emission scenarios, Wolfe *et al.* (2008) noted the heat stress would be prevalent throughout most areas of Maine (and the Northeast), except for perhaps the northern part of Maine. As the cumulative amount of time under even moderate heat stress increases, productivity declines, reproductive function may be compromised, and the incidence and severity of infections like mastitis (an udder infection of dairy cows) increases. Increased temperature and precipitation also present a challenge to farmers in managing feedstocks on their farm. Feed stored in silos can spoil where it is exposed to air and humidity, and feed degrades more rapidly in warmer temperatures.

Higher winter temperatures, a greater proportion of rainfall to snow, and more frequent high-intensity events all result in wetter or muddier conditions, which contribute directly to animal stress and may also increase populations of organisms responsible for mastitis. For cattle in particular, this increased stress level contributes to respiratory infections (pneumonia).

Opportunities & Adaptation

A warmer growing season represents an opportunity for crop agriculture in Maine. Farmers will have access not only to new crops that are not currently viable here, but also to a broader genetic base for current crops. The likelihood that energy prices will increase in the future adds to this opportunity; about 71 million people currently live within a day's drive of Maine, and transportation costs may make cross-continental (or international) movement of food cost prohibitive.

Agriculture can also play a significant role in the mitigation of climate change, as soil is a large potential sink for carbon. No-till and low-tillage agriculture, reduced use of inorganic nitrogen fertilizers, legume-based cover cropping strategies, and on-farm composting all reduce greenhouse gas emissions from agriculture. The increasing prevalence of farmers markets, community supported agriculture (CSAs), and wholesale and retail outlets relying on locally produced foods also can reduce the greenhouse gas contributions of food production and can increase food quality.

Several prospects temper these opportunities. First, crop production will require more inputs; as noted previously, pesticide inputs will likely increase and the reliance of agriculture on petroleum remains a vulnerability. Second, the infrastructure and supporting industries (including input retailers, marketing, and processing) have been shrinking in Maine for decades as the physical footprint of farming has gotten smaller. Crop acreage in Maine has fallen from 600,000 to 250,000 acres in the last 40 years. It is not realistic to expect that Maine can take advantage of any opportunities that climate change may present without a concurrent investment in infrastructure, including protecting farmland from development.

A recent report from the USDA Forest Service (*Figure 21*; White and Mazza 2008) identifies portions of Maine that are expected to experience significant residential expansion. This report is relevant to farmland since agriculture and forest are intertwined throughout the state, as most farms include forest acreage.

Water availability can be manipulated to some extent by management techniques, but increased irrigation capacity will be a necessity for many sectors of the agricultural industry in Maine, particularly for high-value crops. Groundwater is used to a limited extent for irrigation in Maine, and withdrawals are replenished by precipitation and snowmelt before the next season. Reduced precipitation inputs and increased evapotranspiration may result in long-term depletion of some aquifers. Where groundwater is not a feasible source of irrigation water, constructed impoundments (ponds) will be needed, requiring significant investment. Withdrawing water from streams and rivers during the growing season will likely be a less prominent source of irrigation because of regulation and habitat protection concerns.

Transitional issues like crop selection or modification of specific production practices are extensions of what Maine farmers have been doing for generations. There are, however, several areas where farmers will likely have to make changes that require capital expenditures. For example, increased temperatures can be managed on dairy farms by either modifying existing buildings to provide better ventilation and cooling, or constructing new facilities. This is clearly expensive, and larger farms may find it easier to capitalize on these changes than smaller farms. The same could be said of orchards: if climate change results in current apple varieties becoming less viable, replacement represents a very large investment.

Public policy and investment can reduce the negative economic impact of these types of changes, and ease the transition. Educational programs and research on short-term adaptation is critical, including in such areas as crop adaptation and changes in crop management. Medium-term infrastructure improvement, including the development and refinement of irrigation, could be aided by cost-share agreements, as they have been in the past. Assuring long-term access to both land and water resources requires clarification and extension of existing policy.

Knowledge gaps

What are the potential effects of increased temperatures on the diverse mix of crops and animals produced in Maine? For example, the interactions among the components of climate change (this includes temperature, water, and CO_2 concentration) are complex, and much of the research to date deals with single factors or components.

What are the estimated costs of replacing infrastructure and building flexible capacity for changing crops?

Tim Griffin

4) **Risk Communication resources from the NOAA Office for Coastal Management.**

Online training module

Seven Best Practices for Risk Communication (Self-guided Module)

National Oceanographic and Atmospheric Administration, 2019.

https://coast.noaa.gov/digitalcoast/training/best-practices-module.html

Resource documents

Seven Best Practices for Risk Communication Quick Reference.

(National Oceanographic and Atmospheric Administration, 2016b).

https://coast.noaa.gov/data/digitalcoast/pdf/risk-communication-best-practices.pdf

Risk Communication Basics.

(National Oceanographic and Atmospheric Administration, 2016a).

https://coast.noaa.gov/data/digitalcoast/pdf/risk-communication-basics.pdf

Risk Communication Strategy Template.

(National Oceanographic and Atmospheric Administration, 2018) https://coast.noaa.gov/data/digitalcoast/pdf/risk-communication-strategy.pdf

Introduction to Stakeholder Participation.

(National Oceanographic and Atmospheric Administration, 2015a). https://coast.noaa.gov/data/digitalcoast/pdf/stakeholder-participation.pdf

Introduction to Conducting Focus Groups

(National Oceanographic and Atmospheric Administration, 2015b). https://coast.noaa.gov/data/digitalcoast/pdf/focus-groups.pdf

Introduction to Survey Design and Delivery.

(National Oceanographic and Atmospheric Administration, 2015c). https://coast.noaa.gov/data/digitalcoast/pdf/survey-design.pdf

5) **Summary of agricultural adaptation methods**. U.S. Department of Agriculture, 2016a.

Box 3.2:
Menu of Adaptation Strategies and Approaches

Strategy 1:	**Sustain fundamental functions of soil and water.**
Approach 1.1:	Maintain and improve soil health.
Approach 1.2:	Protect water quality.
Approach 1.3:	Match practices to water supply and demand.
Strategy 2:	**Reduce existing stressors of crops and livestock.**
Approach 2.1:	Reduce the impacts of pests and pathogens on crops.
Approach 2.2:	Reduce competition from weedy and invasive species.
Approach 2.3:	Maintain livestock health and performance.
Strategy 3:	**Reduce risks from warmer and drier conditions.**
Approach 3.1:	Adjust the timing or location of on-farm activities.
Approach 3.2:	Manage crops to cope with warmer and drier conditions.
Approach 3.3:	Manage livestock to cope with warmer and drier conditions.
Strategy 4:	**Reduce the risk and long-term impacts of extreme weather.**
Approach 4.1:	Reduce peak flow, runoff velocity, and soil erosion.
Approach 4.2:	Reduce severity or extent of water-saturated soil and flood damage.
Approach 4.3:	Reduce severity or extent of wind damage to soils and crops.
Strategy 5:	**Manage farms and fields as part of a larger landscape.**
Approach 5.1:	Maintain or restore natural ecosystems.
Approach 5.2:	Promote biological diversity across the landscape.
Approach 5.3:	Enhance landscape connectivity.
Strategy 6:	**Alter management to accommodate expected future conditions.**
Approach 6.1:	Diversify crop or livestock species, varieties or breeds, or products.
Approach 6.2:	Diversify existing systems with new combinations of varieties or breeds.
Approach 6.3:	Switch to commodities expected to be better suited to future conditions.
Strategy 7:	**Alter agricultural systems or lands to new climate conditions.**
Approach 7.1:	Minimize potential impacts following disturbance.
Approach 7.2:	Realign severely altered systems toward future conditions.
Approach 7.3:	Alter lands in agricultural production.
Strategy 8:	**Alter infrastructure to match new and expected conditions.**
Approach 8.1:	Expand or improve water systems to match water demand and supply.
Approach 8.2:	Use structures to increase environmental control for plant crops.
Approach 8.3:	Improve or develop structures to reduce animal heat stress.
Approach 8.4:	Match infrastructure and equipment to new and expected conditions.


HUMAN AND
ANIMAL HEALTH

HIGHLIGHTS

Climate change impacts human and animal health in a wide variety of ways. The following areas are of highest priority for further research and development of adaptation strategies, based on a high risk of adverse health outcomes for Mainers:

High Priority

Temperature extremes

- Although Maine has generally enjoyed a relatively cool climate, extreme heat in Maine has increased in recent decades, and is projected to increase further in a changing climate, with the number of "extreme" heat days increasing from current levels by two- to four-fold by the 2050s.
- Mainers experience heat-related illnesses every summer, and recent research has found that there are approximately 10% more all-cause emergency department visits and all-cause deaths on extremely hot days (95°F/35°C), as compared to moderate days (75°F/24°C).
- Mainers are vulnerable to the health effects of exposure to extreme heat because of a lack of physiological adaptation to heat; low rates of home air conditioning rates; older demographics; high rates of some chronic diseases; high rates of outdoor occupations; and a high proportion of the population living in rural areas.
- As Maine's climate warms, we will experience more heat-related illnesses and deaths.
- Mainers currently experience more cold-related than heat-related illnesses and deaths, but this is expected to change over the coming decades, as winters warm more quickly than summers.

Extreme weather

- Extreme weather events, primarily extreme precipitation events, coastal storms, and nor'easters, are likely to increase in frequency and intensity as Maine's climate warms, which may lead to increases in storm-related injuries and deaths; outbreaks of waterborne diseases; carbon monoxide poisonings and foodborne illnesses following power outages; and mental health impacts.
- Droughts and distant wildfires may impact Maine as well, with implications for reduced water quality and quantity, and effects on respiratory health.
- Certain categories of storms, such as ice storms and severe wind storms, are complex and difficult to predict, but may become more frequent and/or intense under warming conditions, leading to adverse health impacts such as injuries, deaths, and effects of power outages among Mainers.

Tick-borne diseases

- Tick-borne diseases (TBDs) transmitted by the deer tick (*Ixodes scapularis*) in Maine include Lyme disease, anaplasmosis, babesiosis, and Powassan encephalitis virus.
- Case numbers and geographic extent of TBDs have been increasing in Maine since the late 1980s.

- Through warmer, shorter winters and earlier **degree-day accumulation**, climate change has played a role in this expansion and will continue to do so unless mitigated through landscape-scale policies.

- The lone star tick (*Amblyomma americanum*), a vector of erlichiosis and capable of causing red meat allergy, may soon begin to establish in Maine as well.

"Degree-day accumulation":

Whenever the temperature exceeds a threshold that allows tick development, degree days are accumulated. Accumulation of enough degree days allows ticks to move from one developmental stage to the next, e.g., eggs can hatch into larvae. Warming climate leads to earlier accumulation of degree days, hence earlier tick development, which benefits tick survival.

The following areas are of medium priority for further research and development of adaptation strategies, based on a lower risk of adverse health outcomes for Mainers, or more limited availability of data and information:

Medium Priority

Food- and water-borne infections:

- Vibrios are a type of highly pathogenic bacteria particularly responsive to sea surface temperature and salinity, which can cause a range of adverse health effects, from gastroenteritis and skin infections to septicemia and death following contact with contaminated seawater or ingestion of contaminated seafood. Warming sea surface temperatures, coupled with climate-driven changes in salinity and turbidity in coastal waters, can lead to increased growth, abundance, seasonal growth windows, and range of vibrio bacteria, which is expected to lead to increasing risk of human exposure and subsequent illness.

- Climate change is likely to change the distribution, range, frequency, and severity of some harmful algal blooms (HABs) and associated illnesses, with increases expected. This assessment is based on inference and not data. Data on environmental hazards of HABs are more robust compared to data on exposures. Data associating HAB exposures with climate change are sparse to non-existent. However, it would be prudent to assume climate change will increase exposure to HABs.

Pollen:

- Earlier spring arrival, warmer temperatures, changes in precipitation, and higher carbon dioxide concentrations can influence plant-based allergens, hay fever, and asthma by increasing the duration of the pollen season and increasing the amount of pollen produced by plants.

- The frequency and severity of allergic illnesses, including asthma and hay fever, are likely to increase as a result of a changing climate.

- Reliable pollen monitoring and forecasts are needed for allergy pretreatment. Despite having had as many as three pollen-counting stations historically, Maine has no publicly available, statewide mechanism for reporting pollen data.

Mosquito-borne diseases (MBDs):

- MBDs in Maine include West Nile virus (WNV), Eastern Equine Encephalitis (EEE), and Jamestown Canyon virus (JCV).

- Through increased growing season precipitation and earlier degree-day accumulation in spring, it is likely climate change will increase the size of vector mosquito populations and increase viral amplification within mosquitoes during spring and summer. Thus, we anticipate greater incidence of MBDs.

Mental Health

- Exposure to climate-related events and disasters, such as extreme storms, flooding, drought, and extreme heat, can cause mental as well as physical health effects.

- Anxiety, depression, post-traumatic stress disorder, and suicidality have been documented in communities that have been displaced or severely impacted by storms or flooding.

- Exposure to extreme heat has been associated with decreased well-being, reduced cognitive performance, aggression, violence, and suicide.

- Those with existing mental illness are often disproportionately vulnerable to other effects of exposure to extreme weather or other climate-related exposures; and especially to the effects of exposure to extreme heat.

Discussion – Human Health

Direct Impacts of Climate and Weather on Health in Maine

Temperature Extremes

Heat-Related Impacts

Increasing exposure to extreme heat is perhaps the most direct impact of a warming climate on human health. Exposure to extreme heat has been linked with a wide range of health outcomes, including heatstroke and heat exhaustion; renal failure and other impacts on kidney function; dehydration and electrolyte imbalance; exacerbations of existing cardiovascular, respiratory, cerebrovascular, and diabetes-related conditions; effects on fetal health; preterm birth; and mental health conditions (Ebi et al., 2018). Studies of daily measures of heat exposure and daily population-level measures of deaths and emergency department visits for all causes also show associations between exposure to extreme heat and all-cause morbidity and mortality. This illustrates that heat exposure can exacerbate pre-existing conditions and create physiological stress that in turn leads to cascading effects on multiple systems (Sarofim et al., 2016).

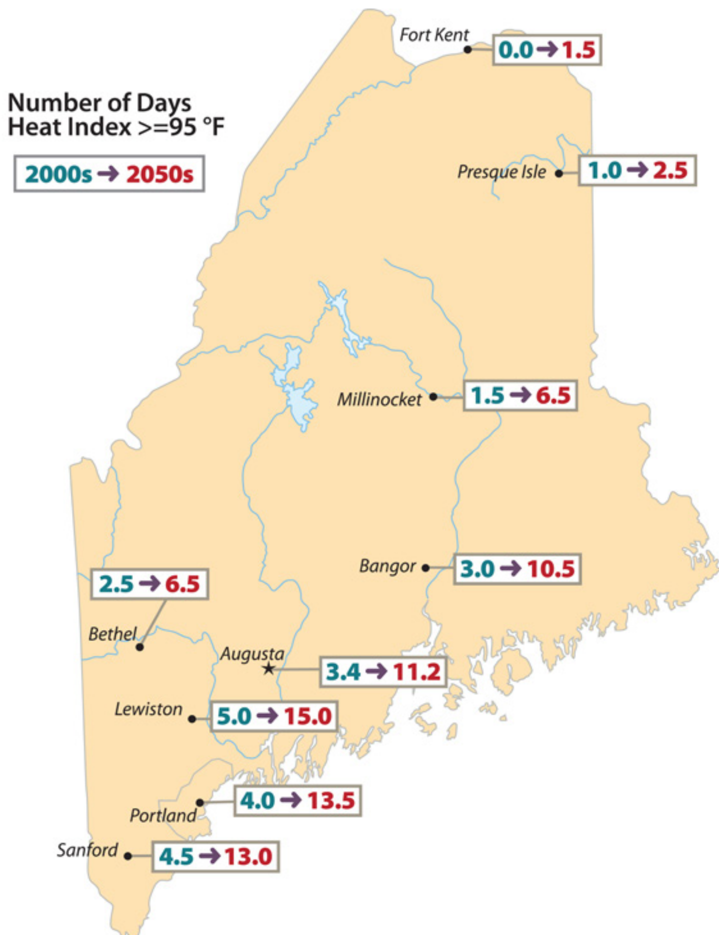

Figure 1. Average number of days when the heat index is greater than or equal to 95°F at selected sites for 2000-2004 and 2050-2054. Predicted values derived from a 48-km downscale simulation of one ensemble member of the CCSM3 model for the IPCC A2 emissions scenario. Source: Fernandez et al. (2015).

In Maine, as in the rest of the US, exposure to extreme heat has increased in recent decades as the climate warms. Annual average temperatures in Maine increased by 3°C between 1895 and 2014 (Fernandez et al., 2015), and climate modeling suggests that Maine will experience further annual average warming, on the order of 3-5°C by the 2035-2054 period (Fernandez et al., 2015). This warming will lead to more 'extreme heat' days, where the heat index (a combination of temperature and relative humidity that approximates the 'felt' temperature) exceeds 95°F (35°C). Figure 1 shows the projected number of extreme heat days around the state by the 2050s, with most areas showing a two-fold to four-fold increase over a baseline of the 2000s.

While extreme heat has increased, and is projected to increase further, it is still relatively uncommon in Maine. However, a number of factors make Mainers especially vulnerable to extreme heat when it does occur. First, residents of cooler climates are less physiologically adapted to extreme heat exposure, and experience disproportionate health effects on hot days when compared to residents of warmer climates (Anderson & Bell, 2011). Second, the prevalence of air conditioning, one of the most effective tools for preventing heat illness, is significantly lower in Maine than in the rest of the region and the country. While almost 90% of US households have access to air conditioning (U.S. Energy Information Administration, 2018), in Maine that rate is 53% (Maine Center for Disease Control and Prevention, 2020; Figure 2).

In addition to this lack of acclimation and access to air conditioning, certain groups are more at risk of experiencing a heat illness: older adults; those with existing chronic disease; those living in older homes; those who work outdoors; pregnant women and young children; and those who are socially isolated (Dupigny-Giroux et al., 2018). Maine has the oldest population in the US (US Census Bureau, 2017); Mainers have high rates of asthma and other chronic diseases (US Centers for Disease Control and Prevention, 2016); and several important industries in the state – such as agriculture, forestry, outdoor recreation and tourism, and construction – involve outdoor work. In addition, Maine's rural nature may be an additional risk factor. While heat islands can contribute to elevated risk of heat illnesses in urban areas, some research has shown proportionally higher rates of heat-related illnesses in rural, as opposed to suburban or urban areas (Schmeltz et al., 2017; Seltenrich et al., 2015; Sheridan & Dolney, 2003). This may be due to higher rates of work in outdoor industries such as agriculture and construction, less access to air conditioning, or the longer distance residents must travel to cooling centers or to healthcare facilities for treatment (Dahl et al., 2019).

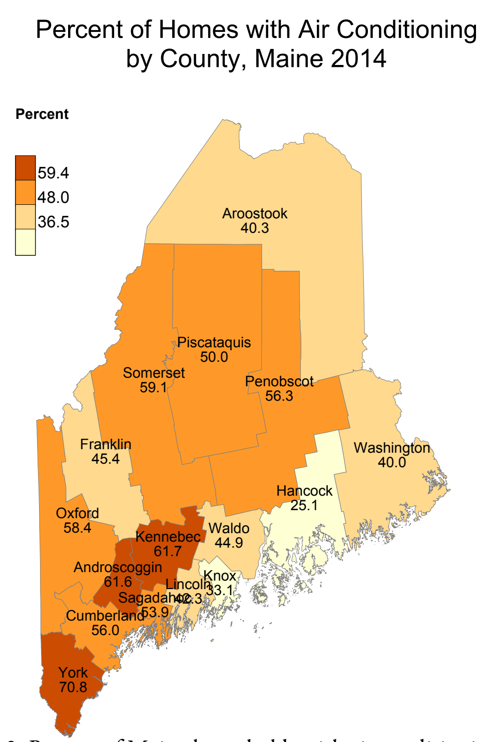

Figure 2. Percent of Maine households with air conditioning, by county, in 2014. Source: Maine Center for Disease Control and Prevention (2020).

Available data illustrate these vulnerabilities. Between May and September each year, Mainers experience an average of just over 200 emergency department visits and almost 15 hospitalizations for heat-related illnesses (Maine Center for Disease Control and Prevention, 2020). In addition to these direct heat-related illnesses, a 2017 study examined the associations between daily maximum heat index and the rates of deaths and emergency department visits from all causes among residents of selected towns in Maine, New Hampshire, and Rhode Island (Wellenius et al., 2017). The study found that there was a clear and significant increase in rates of emergency department visits and deaths with increasing daily maximum heat index (Figure 3); for example, on days with a maximum heat index of 95°F (35°C), there were approximately 7% more emergency department visits and 6% more deaths than on days with a maximum heat index of 75°F (24°C). And for Maine alone, these effects were stronger than for the region as a whole: 10% more emergency department visits and 10% more deaths on days of heat index 95°F (35°C) as compared to days of heat index 75°F (26°C) (Figure 3).

As the climate in Maine warms, and daily maximum heat indices continue to rise, we can expect to see increasing numbers of emergency department visits and deaths associated with heat exposure. While projections have not been made for Maine, models suggest that by 2050, the Northeast region as a whole will see around 650 more excess deaths per year due to extreme heat, under lower (RCP4.5) compared to higher (RCP8.5) emissions scenarios; and around 960 (under RCP4.5) to 2,300 (under RCP8.5) more excess deaths per year by 2090 (Dupigny-Giroux, 2018; USEPA, 2017).

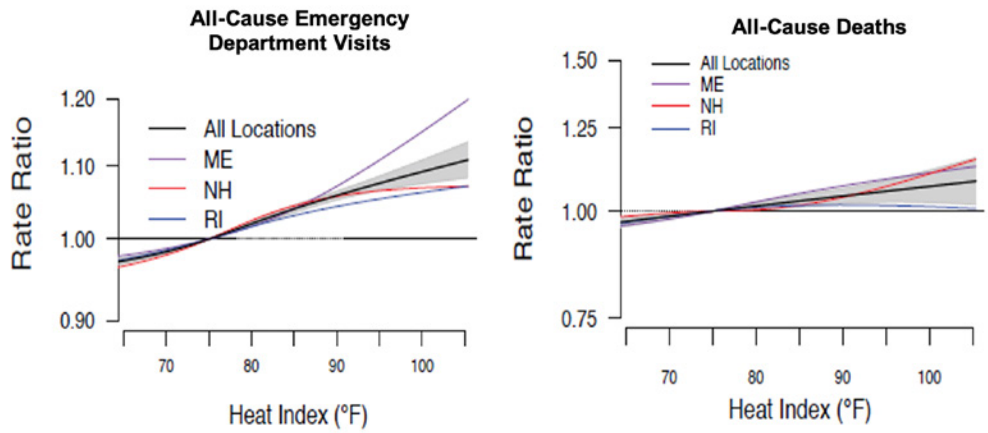

Figure 3. Associations between maximum daily heat index and all-cause emergency department visits for the 7 days following heat exposure (left); and all-cause deaths on the same day as heat exposure (right), for sites in Maine, New Hampshire, and Rhode Island. Note the y-axis scales are not scaled consistently between figures. Source: Welleni

Cold-Related Impacts

As a warming climate in Maine brings more cases of heat-related illness, we can also expect warmer winters, and somewhat fewer cases of cold-related illnesses and deaths (Crimmins et al., 2016). While the burden of cold-related illness in Maine is currently higher than the burden of heat-related illness (Figure 4), modeling of heat- and cold-related illness projections for Portland, Bangor, and 207 other US cities suggest that reductions in cold-related

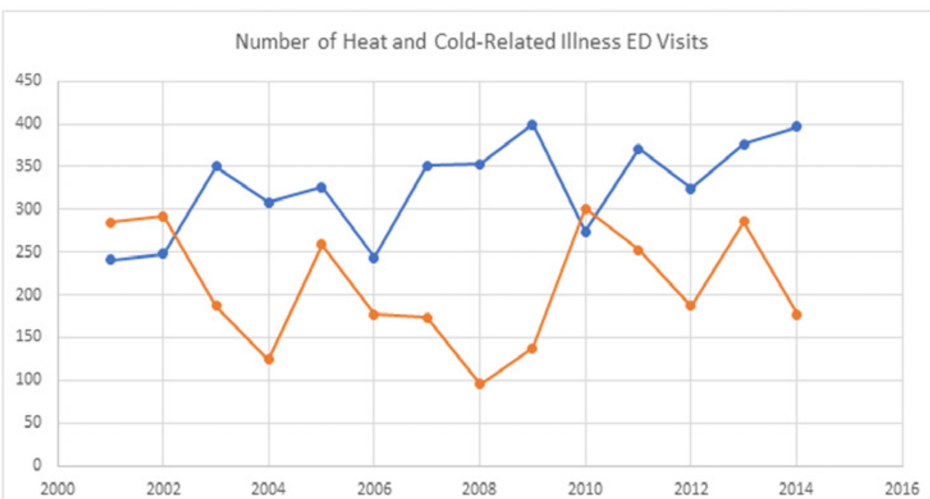

Figure 4. Counts of emergency department (ED) visits for heat-related illness (orange) and cold-related illness (blue) in Maine, 2001-2014. Note that heat-related illness cases are only from May-September while cold-related illness cases cover the full year. This is because most (95%) of heat-related illnesses occur in summer months, while cold-related illnesses are more evenly distributed across the entire year. Source: Maine Tracking Network (Maine Center for Disease Control and Prevention, 2020). Preliminary Data.

impacts will be more than offset by increases in heat-related impacts. For example, under one of the projected scenarios (RCP6.0 emissions scenario, GFDL-CM3 Model) shows an annual reduction in Bangor of 12 cold-related deaths, against an increase of 29 heat-related deaths, by 2100. In Portland, by 2100, annual cold-related deaths would decrease by 26 and annual heat-related deaths would increase by 47 (Schwartz et al., 2015). Figure 5 shows the overall projected change in deaths across all 209 U.S. cities by 2100. On the other hand, Maine has experienced several 'polar vortex' cold events in recent years, most notably in November 2018 and January 2019 (e.g. Samenow, 2019), with associated increases in emergency department visits for hypothermia, frostbite, and other cold-related illnesses (Figure 6). Whether these weather patterns are related to climate change, and whether they are likely to increase in the future or not, are open research questions.

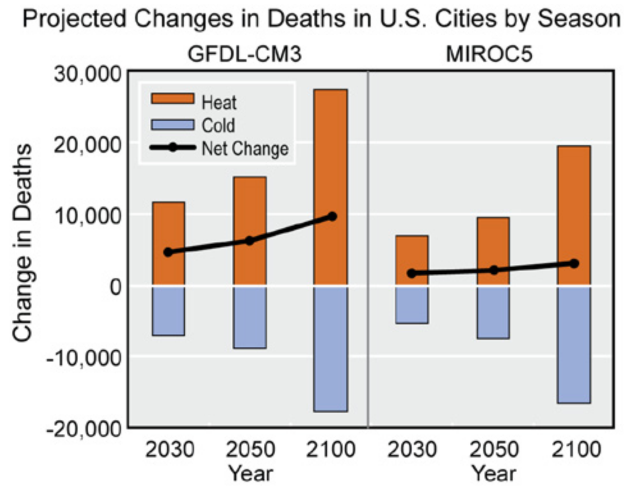

Figure 5. Projected changes in heat-related, cold-related, and net (total) deaths in 209 US cities. Source: Sarofim et al. (2016), adapted from Schwartz et al. (2015).

Extreme Weather Events

The frequency and severity of some extreme weather events are predicted to increase under climate change (Crimmins et al., 2016), and these events can cause significant harm to human health, in addition to the harm they cause to property, infrastructure, and the economy (Bell et al., 2016). These extreme events can include flooding from extreme precipitation or storm surge; winter storms and wind storms; drought; and wildfires. The health effects of exposure to these events are diverse: death; traumatic injury; hypothermia and frostbite; exacerbation of underlying medical conditions; waterborne diseases spread by contaminated flood waters; carbon monoxide poisoning and foodborne diseases related to power outages; mental health impacts; and disruptions to healthcare infrastructure and the delivery of healthcare that can lead to long-term health consequences at the population level (Bell et al., 2016).

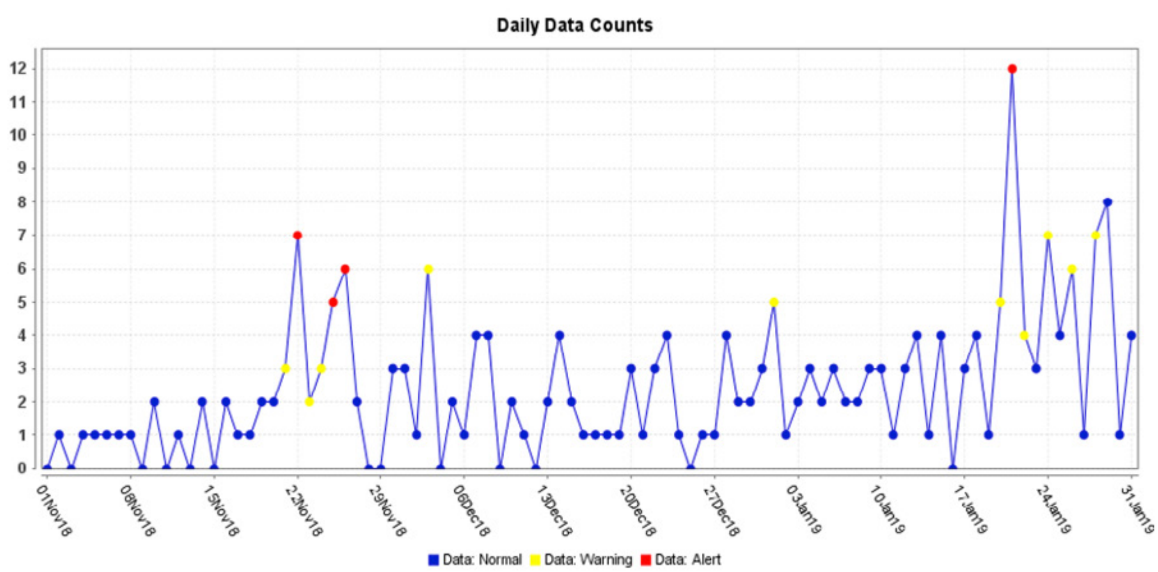

Figure 6. Daily counts of visits to all Maine emergency departments for cold-related illnesses, as identified by the Maine Center for Disease Control and Prevention's syndromic surveillance system. Source: Maine Center for Diseases Control and Prevention, 2020. Cases are classified as "cold-related illnesses" based on either a diagnosis code of hypothermia, frostbite, or other effects of exposure to natural cold, or a chief complaint (the self-reported reason for the visit) that includes keywords referencing cold-related illness.

Flooding from Extreme Precipitation or Storm Surge Events

In Maine, extreme precipitation events have increased in most areas of the state in recent decades (Fernandez et al., 2015, 2020) and are predicted to increase even further in the future (see Climate chapter in this report). The frequency and severity of coastal storms in the northeast US are also projected to increase, and the effect of this coupled with projected rising sea levels will be an increased risk of nuisance and storm-driven flooding in the region (Dupigny-Giroux et al., 2018; see also the Sea Level Rise section of this report). The most direct effect of flooding events on human health are traumatic injuries and deaths, including drownings. These injuries and deaths can occur before, during, or after an event; preparations for, and cleanup and recovery after a flooding event can also expose people to hazards. In the period from 2009-2018, floods caused an average of 95 deaths per year in the US; the last flood-related death in Maine recorded by the National Weather Service was in 2014 (National Weather Service, 2016, 2020).

Flooding events can also lead to indirect health effects, most notably the contamination of drinking water sources by bacteria and harmful chemicals via runoff, flooding of well heads, and combined sewer overflows (CSOs) in areas where wastewater and stormwater runoff are handled by the same collection system. Between 1948 and 1994, almost 70% of waterborne disease outbreaks in the U.S. directly followed extreme precipitation events (Curriero et al., 2001). Of special note is a *Cryptosporidium* outbreak in Milwaukee in 1993, the largest documented waterborne disease outbreak in U.S. history, which caused approximately 403,000 illnesses and more than 50 deaths, following the heaviest rainfall in 50 years in that area (Hoxie et al.,1997; Patz et al., 2008).

Outbreaks of generalized gastrointestinal (GI) illness, as well as specific outbreaks of campylobacteriosis, salmonella, and cryptosporidiosis, have been linked to extreme precipitation events and to the presence of a combined sewer system (Jagai et al., 2015; Soneja et al., 2016; Jiang et al., 2015). In these CSOs, when the combination of stormwater runoff and wastewater exceed the capacity of the system in a flooding event, a mixture of stormwater and untreated wastewater can be discharged directly into a surface water body, leading to outbreaks of GI illness and chemical exposures from recreational contact or drinking of untreated water. Although these systems are more common in the Northeast, where infrastructure is older (Dupigny-Giroux et al., 2018), states are working to reduce the number of CSOs in their communities. Since the implementation of a National CSO Control Strategy by the federal Environmental Protection Agency and the establishment of a CSO Program at Maine DEP, the number of communities with one or more CSO discharge points has dropped from approximately 60 to 31 (Maine Department of Environmental Protection, 2019).

Finally, more than 50% of Mainers rely on a private well for their drinking water (Maine Center for Disease Control and Prevention, 2020), one of the highest rates in the country. These wells are not regulated under the federal Safe Drinking Water Act or any state laws, and homeowners are therefore responsible for maintaining their own water quality. Increased flooding in areas served by private wells will likely lead to an increase in the incidence of waterborne diseases among those served by a private well, in addition to the added burden of cleaning and disinfecting affected wells.

Nor'Easters, Ice Storms, and Wind Storms

More frequent and intense storms are likely to affect Maine year-round as the climate warms, and extreme storms such as nor'easters, ice storms, and wind storms present threats to Mainers' health via direct injury as well as indirect effects of disruption of infrastructure and prolonged power outages – including carbon monoxide poisoning from exposure to portable generators or alternative home heating sources (Bell et al., 2016), and foodborne illnesses from consuming spoiled food following a power outage (Ziska et al., 2016). Widespread and long-lasting power outages have also been shown to be associated with more broad and significant health effects, including increases in hospitalizations for renal disease, cardiovascular disease, and respiratory disease, and increases in accidental mortality, non-accidental mortality, and all-cause mortality (Anderson & Bell, 2011; Dominianni et al., 2018; Lin et al., 2011;).

Historically, nor'easters – cold-season coastal storms associated with extreme precipitation, strong winds, and flooding – have caused more harm and damage than any other type of extreme event in Maine (Runkle et al., 2017). However, other types of storms have also caused significant harm and damage in recent years. A catastrophic ice storm in 1998 left more than half of Mainers without power, some for two to three weeks, and resulted in at least five fatalities from falling trees or ice, hypothermia, or carbon monoxide exposure (Curtis et al., 2018) as well as more than 200 carbon monoxide poisonings (Graber & Smith, 2007). Almost a third of these poisonings were related to use of domestic fuel, a category that includes improper generator use as well as use of inappropriate appliances, such as ovens, to heat homes without power (Graber & Smith, 2007). Maine has also experienced more significant windstorms in recent years, most notably in October 2017, October 2019, and November 2019, events which produced hurricane-strength winds and left hundreds of thousands of Mainers without power. Between 2009 and 2018, an average of between 7 and 8 carbon monoxide poisoning cases related to storms per year were reported to the Maine Center for Disease Control and Prevention, with the highest number of cases in 2015 and 2017 (Maine Center for Disease Control and Prevention, unpublished data). Because the role a warming climate plays in these events is currently unclear, further research is needed to determine important contributing factors and to determine whether storms of this type are likely to increase under various warming scenarios.

Drought and Wildfires

Especially when compared to other regions of the US, droughts and wildfires do not have a significant impact in Maine, and are not expected to increase significantly with a warming climate. Drought in Maine has been intermittent in recent decades, with periods of extreme drought occurring across much of Maine in the early 2000s, and more recently, over smaller areas in 2017 (National Integrated Drought Information System, 2020). If droughts were to occur more frequently, health effects would likely center around reduced quality and quantity of drinking water, as well as respiratory and mental health effects.

Wildfires are also rare in Maine, though when they occur, they can lead to respiratory impacts from smoke inhalation; burns and other injuries; and mental health impacts related to displacement (Bell et al., 2016). A more likely impact for Mainers is exposure to wildfire smoke originating in other parts of the US or Canada. This smoke can be transported hundreds of miles once it's fully aloft, such as in 2015, when smoke from Canadian wildfires caused air quality exceedances in Baltimore, MD (Dreessen et al., 2016), and in 2019, when smoke from wildfires in western Canada was visible in Maine, though without causing any exceedances (Graham, 2019).

Extreme Weather and Pandemics

Any extreme weather event or natural disaster that leads to emergency evacuation and grouping of people will exacerbate the spread of a pathogen such as SARS-CoV-2, the agent of COVID-19 and cause of a worldwide pandemic in 2020 (https://www.cdc.gov/disasters/hurricanes/covid-19/public-disaster-shelter-during-covid.html).

Ecosystem-Mitigated Impacts of Climate Change in Maine

Vector-borne diseases

Tick-borne disease

Hazard: Of 15 known tick species in Maine, the deer tick (*Ixodes scapularis*) is responsible for the vast majority of tick-borne diseases (TBDs) affecting humans and domestic animals in Maine. Deer ticks can transmit the agents of Lyme disease, anaplasmosis, babesiosis, Powassan virus (deer tick virus) encephalitis, and tick-borne relapsing fever. See Health Impacts Appendix for more detail on these TBDs. Populations of the lone star tick (*Amblyomma americanum*) have been expanding northward and recently become established in Cape Cod, Massachusetts (Telford et al., 2019). This tick transmits agents of ehrlichiosis, tularemia, southern tick-associated rash illness (STARI), and can cause alpha-gal (red meat) allergy (U.S. Centers for Disease Control and Prevention, 2020a). The lone star tick is capable of overwintering in southern coastal Maine (Linske et al., 2019) and is predicted to establish in all but the northern tip of Aroostook County by 2040 under RCP 4.5 (Sagurova et al., 2019).

Exposure: Beginning in 2002, Maine became a high Lyme incidence state, defined as a state with ≥10 cases/100,000 annually (U.S. Centers for Disease Control and Prevention, 2020b). Maine had record case numbers (1,424) in 2017 and the highest 3-year average incidence in the US at 89.2 cases/100,000during 2 015-2017 (U.S. Centers for Disease Control and Prevention, 2020b). Increases in Lyme disease, babesiosis, and anaplasmosis are associated with range expansion of the deer tick (Smith, Elias et al., 2014; Cavanaugh et al., 2017; Robich et al., 2019, Smith et al., 2019; Elias et al., 2020a,b). Geographic range expansions of deer ticks over time in the US have been attributed to a mosaic of factors. These include 20th century reforestation followed by suburbanization, burgeoning populations of white-tailed deer (*Odocoileus virginianus*) and, at the northern edge of the deer tick's range, **climate change** (e.g., Eisen 2016 Telford 2017). Maine has been experiencing warmer and shorter winter seasons, and relatively more so in the northern tier (Fernandez et al., 2015). Key research findings specific to Maine are:

- During 1990-2013, more deer ticks were associated with **higher relative humidity, warmer minimum winter temperatures and more degree-day accumulation by the end of August** (Figure 7), all of which are increasing in Maine. Warmer winters most influenced tick abundance where deer density exceeded about 5/mi2 (which currently ranges from ~5/mi2 to >15/mi2 in the southern tier) (Rand et al., 2004, Elias, 2019).

- More deer ticks are associated with **higher deer densities** (Rand et al., 2003, Rand et al., 2007, Elias et al., 2011, Elias, 2019).

- More deer ticks with higher infection rates have been found in areas infested by **Japanese barberry** (*Berberis thunbergii*) (Lubelczyk et al., 2004, Elias et al., 2006).

It is strongly suspected that the lone star tick will colonize Maine. The white-tailed deer is a key mammalian blood meal source for the lone star tick (Paddock and Yabsley, 2007).

Health Impacts from Climate Change: We expect illnesses from the deer ticks to continue to increase where ticks are established (southern tier of the state) due to increasing pathogen load in ticks and where ticks are emergent (northern tier of the state) due to increasing tick abundance. We can expect illnesses from the lone star tick to emerge. Ticks and tick-borne diseases are a <u>chronic</u> problem that can be mitigated through statewide, integrated tick management policy and actions. A Lyme disease vaccine could mitigate this as could an anti-tick vaccine, but these are not yet available. In the meantime, integrated tick management strategies applied statewide could reduce risk.

Mosquito-borne disease

Hazard: Currently, mosquitoes that vector Eastern Equine Encephalitis virus (EEEv) and West Nile virus (WNv) are of concern. These arboviruses circulate in nature among mosquitoes and bird and mammal hosts and often do not spill over into human and domestic animal populations. The principal vector of EEEv is the tree hole mosquito (*Culiseta melanura*) which is associated with forested wetlands, such as Maine's ubiquitous red maple swamps. *Culex pipiens* and *Cx. restuans* transmit WNv and are associated with urban and surburban environments where containers, storm drains, and other catchment basins provide ideal habitat for eggs and larvae.

Exposure: Temperature and rainfall patterns affect mosquitoes and the viruses they carry. Among infectious diseases, mosquito-borne diseases (MBDs) may be the most sensitive to climate change (Smith, Woodward et al., 2014). Thus, in some years conditions lead to viral "spillover" into human and domestic animal populations. This is known as an epizootic outbreak. Exposure is increased where humans are outside during peak mosquito activity, e.g., school sports competitions taking place towards the end of the day.

Maine experienced its first veterinary EEEv outbreak in 2009, with 15 horses dying (Lubelczyk et al., 2014). A hard frost in late September 2009 may have prevented human illness. The Maine Center for Disease Control and Prevention (2019a, 2019b) recorded Maine's first and second human cases of EEEv in 2014 and 2015. Tree hole mosquito eggs and larvae rely on forested wetlands, which normally become drier during summertime and limit mosquitoes. Key research findings specific to Maine are:

- EEEv occurs statewide in Maine (Lubelczyk et al., 2014, Mutebi et al., 2015).
- Record summer rainfall in 2009 corresponded with record numbers of tree hole mosquitoes in 2009, corresponding with Maine's first EEEv outbreak (Lubelczyk et al., 2013).

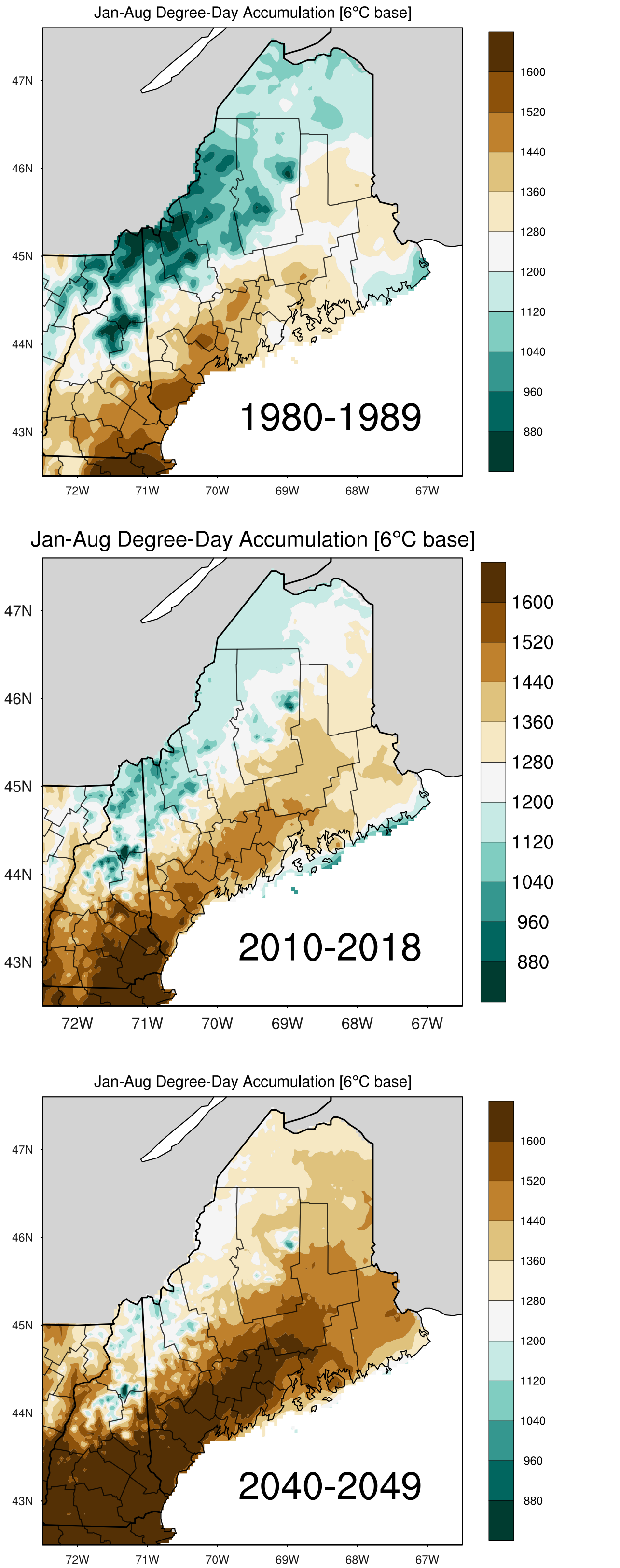

Figure 7. Accumulation of degree-days >6°C across Maine. Orange and white depict areas where enough degree-days (1,240) accumulated for tick eggs to hatch by the end of August. Note expansion of orange and white two decades ago versus the current decade versus a a future warmer by 1°C (Elias et al., 2020c). Figure: Sean Birkel, Climate Change Institute.

Health Impacts from Climate Change: Earlier, warmer springs could allow earlier attainment of a degree-day threshold allowing earlier amplification (multiplication) of the viral load in *Cs. melanura*. Attainment of this threshold in Maine was 12 days later than in the Hockamock Swamp in Massachusetts, known as a hotspot for EEEv in humans Lubelczyk et al., 2013). Increases in summer precipitation and humidity, frequency of extreme rain events and earlier degree day accumulation, and warmer falls (Birkel & Mayewski, 2018) will exacerbate EEEv transmission.

Warmer temperatures are likely to boost *Culex* populations and WNv infection prevalence (Ruiz et al., 2010), but the impact of precipitation is difficult to predict. Too little rain will dry up larval habitat, but too much rain in a short time causes larval "washout" (Jones et al., 2012; Valdez et al., 2017). Unlike tick-borne disease risk, which is chronic, mosquito-borne disease risk has an outbreak dynamic (Lubelczyk et al., 2014; Elias et al., 2017).

Food- and water-borne infections

The National Outbreak Reporting System (NORS) is a web-based platform that launched in 2009. It is used by local, state, and territorial health departments in the United States to report all waterborne and foodborne disease outbreaks and enteric disease outbreaks transmitted by contact with environmental sources, infected persons or animals, or unknown modes of transmission (U.S. Centers for Disease Control and Prevention, 2020c). The NORS dashboard (https://wwwn.cdc.gov/norsdashboard) can be used to access the number of outbreaks, illnesses, hospitalizations and deaths, and can be filtered by location (Maine) and etiology (cyanotoxin, vibrio). This is a useful tool but highlights the sparsity of data on these conditions.

Vibrios

Vibrios are a family of naturally-occurring bacteria in coastal environments, which derive from the same family as the bacteria that cause cholera (*V. cholerae*), and which can cause illnesses from mild gastroenteritis and skin infections to septicemia and death, through both direct skin contact with seawater and ingestion of contaminated seafood which is raw or undercooked (Trtanj et al., 2016). Vibrios are particularly responsive to water temperature, salinity, and other environmental conditions, and warming sea surface temperatures, coupled with climate-driven changes in salinity and turbidity in coastal waters, can lead to increased growth, abundance, seasonal growth windows, and range (Bebber et al., 2015; Baker-Austin et al., 2107, Semenza et al., 2017). This in turn is expected to lead to increasing risk of human exposure to vibrios (Trtanj et al., 2016).

While waterborne diseases are likely to go unreported (Scallan et al., 2011), rates of vibrio-caused illnesses have tripled since 1996 (Newton et al., 2012, 2014), with northward expansion and increasing cases of shellfish-associated vibriosis documented in the Northeast region (Dupigny-Giroux, 2018). In Maine, several species of vibrio are common; in 2018, 14 cases of vibriosis were reported to the Maine Center for Disease Control and Prevention (Maine Center for Disease Control and Prevention, 2018), with 43% of cases reporting consumption of shellfish prior to illness. In 2017, there was one fatal vibrio infection in an immunocompromised individual (Sinatra and Colby, 2018).

A regional modeling study used predicted sea surface temperature and salinity conditions obtained from various global climate models to predict changes in vibrio occurrence. The study found significant increases in vibrio abundance, range, and seasonal extent with climate change, with the amount of coastline with favorable conditions for vibrios increasing by as much as 60% in some areas (Jacobs et al., 2015).

Harmful Algal Blooms

Hazard: A harmful algal bloom (HAB) occurs when toxin-producing algae grow rapidly in a water body such as an ocean or lake. When algal toxins are released into the surrounding water or air, they can cause serious illnesses and sometimes death in people and animals. Cyanobacteria produce:

- hepatotoxins (liver toxins, e.g., microcystins), with exposure causing vomiting, diarrhea, fever, cramps
- neurotoxins (e.g., anatoxins, saxitoxins), with exposure causing paralysis, seizure
- dermatoxins, with exposure causing irritation to eyes, ears, throat, rashes, and skin lesions

Microcystins and anotoxins for acute illnesses are more often metrics used for health compared to other threats (Nathan Torbick, Applied Geosolutions, email communication, 1/9/2020).

In Maine, marine blooms of HABs can result in Paralytic shellfish poisoning (red tide), and lake blooms of HABs can cause liver damage. For more detail on freshwater HABs, please see the Water Quality chapter of this report, specifically the section "Trophic Changes in Lakes and Freshwater Harmful Algal Blooms".

Freshwater HABs. HABs that occur in freshwater such as the Great Lakes are dominated by the cyanobacteria Microcystis, which produces a liver toxin that can cause gastrointestinal illness and liver damage. Several studies have shown direct relationships between Microcystins and increased risk of non-alcoholic liver disease (Nathan Torbick, Applied Geosolutions, email communication, 1/9/2020). Of recent concern is the molecule β-N-methylamino-L-alanine or BMAA, believed to target motor neurons in the brain. A concentration as low as 10 μM can potentially cause neurological affects (Lobner et al., 2007). Preliminary research and pilot investigations using eco-epidemiological and Bayesian hierarchical modeling have shown potential risks to human health in hot spot regions or regions with elevated risk after factoring for age, sex, and population density

Cyanobacteria can be particularly noxious when anthropogenic eutrophication (i.e., intensive agriculture, excess fertilizers, urbanization, and runoff) of water bodies causes large concentrations of nutrients to increase cyanobacterial blooms (Nathan Torbick, Applied Geosolutions, email communication, 1/9/2020). Since 2008, the Maine Department of Environmental Protection has been measuring concentrations of microcystins in lakes that regularly support algal blooms. Toxin concentrations of shoreline scums may be 100-1000 times and swimming areas and deep water up to ten times the level of concern issued by the EPA. The toxins are produced later in the bloom period, when cell counts are highest and at onset of high rate of cell mortality (Maine Department of Environmental Protection, 2020a, 2020b). The data will inform a future Maine Center for Diease Control and Prevention health advisory.

Marine HABs. Two groups of marine phytoplankton, diatoms and dinoflagellates, produce HAB toxins. Marine HAB toxins can build up in seafood when fish or shellfish eat toxin-producing algae. According to the Maine Department of Marine Resources, the types of phytoplankton that make shellfish unsafe for consumption include: *Alexandrium*, *Pseudo-nitzschia*, and *Dinophysis*, which produce the toxins that cause Paralytic Shellfish Poisoning; Amnesic Shellfish Poisoning; and Diarrhetic Shellfish Poisoning, respectively. In Maine, HABs typically occur between April and October, but in recent years Pseudo-nitzschia, which causes Amnesic Shellfish Poisoning, has bloomed during winter months (Maine Department of Marine Resources, 2020), possibly a manifestation of warming in the Gulf of Maine (Fernandez et al. 2020).

Exposure: As with many environmental exposures, children and the elderly may be especially sensitive to HAB toxins. Populations that rely heavily on seafood are also at risk of long term health effects from potentially frequent exposures to HAB toxins.

Freshwater HABs. During a HAB, people and animals may be exposed to toxins from swimming in or drinking the water, by breathing in aerosolized toxins (toxins in airborne water droplets) near the water, and from fish they catch and eat. Cooking contaminated seafood or boiling contaminated water does not destroy the toxins. Water treatment that kills the algae must remove toxins from the water column that are released when the algal cells die. Detectable aerosolization of BMAA particles surrounding New Hampshire lakes has been found (Banack et al., 2010, 2015). BMAA has been found at relatively high concentrations in fish species living in the New Hampshire lakes which experience ALS (Amyotrophic Lateral Sclerosis) clustering (Banack et al., 2010, 2015; Spencer et al., 2019). Due to the low numbers of individuals eating these fish in Maine, this is most likely not a major exposure pathway. Still this raises the issue of higher exposure among native American populations that consume more freshwater fish. There is not robust enough data on quantity aerosolized to quantity ingested and accumulated for BMAA, to accurately determine what water concentration would put a population living around the lake in imminent danger (Rodgers et al., 2018). While blooms often cause local authorities to warn of acute health risks, the health impacts of chronic exposure to low or moderate levels of cyanotoxins are also largely unknown and potentially more pivotal for certain diseases and illnesses (Nathan Torbick, Applied Geosolutions, email communication, 1/9/2020). Large cohort analysis extended over decades is needed.

Marine HABs. Paralytic Shellfish Poisoning is caused by eating shellfish contaminated with saxitoxins, produced by dinoflagellates of the genus *Alexandrium* which are common in the Gulf of Maine. Saxitoxins cause neurologic problems and can be found in shellfish (mussels, clams, scallops, oysters, crabs, and lobsters). Domoic acid poisoning (Amnesic Shellfish Poisoning) is caused by eating shellfish contaminated with domoic acid, a toxin produced by the diatoms *Psuedo-nitzschia*, *Nitzschia*, and *Amphora*. States at risk for marine HABs have monitoring programs in place to close harvesting when toxins are present in shellfish.

Warming waters in the Gulf of Maine have already caused several changes in the composition, abundance and timing of HABs. It is hypothesized that climate change has led to the incursion of Gulf Stream waters deep into the Gulf of Maine, possibly transporting and supporting the growth of new HAB species. Maine first documented Amnesic Shellfish Poisoning (ASP) in 2016 and has monitored blooms since. The annual Paralytic Shellfish Poisoning (PSP) bloom over the past decade has begun earlier in the season and persisted longer (Kohl Kanwit, Maine Department of Marine Resources; Mike Plaziak, Maine Rural Water Association, email communication, 1/9/2020). Clark et al. (2019) found no evidence that harmful algal blooms are increasing in the Gulf of Maine, but did find blooms of species new to the Gulf in the past few years *(Karenia mikimotoi* and *Pseudo-nitzschia australis*), outbreaks of which have been linked to fish and wildlife mortality elsewhere. This represents a potential threat if changing conditions in the Gulf of Maine support these species (Clark et al., 2019; de la Riva et al., 2009). Seto et al. (2019) found that growth rates of *Alexandrium catenella* decrease at future temperature levels, whereas co-occurring non-toxic dinoflagellate competitors increase, suggesting fewer future toxic blooms in the southern Gulf of Maine but more toxic blooms may in the northeastern Gulf of Maine.

HAB Health Impacts from Climate Change: Climate change is likely to change distribution, range, frequency, and severity of some HABs and associated illnesses, with increases expected. This assessment is based on inference and not direct evidence. Data on environmental hazards of HABs are more robust compared to data on exposures. Data associating HAB exposures with climate change are sparse and ongoing research is necessary to characterize linkages between HAB-associated illness and climate warming.

In their paper *Impacts of climate variability and future climate change on harmful algal blooms and human health*, Moore et al. (2008) stated: "The incidence of human syndromes associated with exposure to HAB toxins will increase as HABs occur more frequently and over greater geographic areas due to climate change. If we are going to be in a position to assess whether the human health effects from HA are increasing as more people come in contact with HABs, it is critical that data are collected describing baseline frequencies of the human illnesses associated with HABs, including the shellfish poisonings, ciguatera fish poisoning, cyanobacterial illness, and respiratory irritation from Florida red tide. One way to address this is to support HAB-related disease surveillance, such as the Harmful Algal Bloom-related Illness Surveillance System (HABISS) created by the Centers for Disease Control and Prevention (CDC). This system will collect data on human illnesses, animal illnesses, and the characteristics of the blooms themselves...HABISS will be able to be used to assess whether increased contact between HABs and people and animals has a substantial impact on the frequency of HAB-related illnesses in a warmer climate." The One Health Harmful Algal Bloom System (OHHABS) (www.cdc.gov/habs/ohhabs.html) has supplanted HABISS (Lorraine Backer, National Center for Environmental Health, email communication, 1/13/2020).

In addition to health concerns, HABs can damage the environment by depleting oxygen in the water, which can cause fish kills, or simply by blocking sunlight from reaching organisms deeper in the water. This means the economic impacts of HABs to fisheries and recreational areas could be extensive.

Air Quality

Ground-level ozone and particulate (PM) matter are air pollutants that adversely affect human health and are monitored and regulated with national standards. Short- and long-term exposure results in negative respiratory and

AQI AIR QUALITY INDEX

Air Quality Index for Ozone

(Based on 8-hr average concentrations)

Index Values (Conc. Range)	Air Quality Descriptors	Who needs to be concerned	What should I do?
0 – 50 (0-54 ppb)	Good	It's a great day to be active outside.	
51 – 100 (55-70 ppb)	Moderate	Some people who may be unusually sensitive to ozone.	Unusually sensitive people: *Consider reducing* prolonged or heavy outdoor exertion. Watch for symptoms such as coughing or shortness of breath. These are signs to take it easier. Everyone else: It's a good day to be active outside.
101 – 150 (71-85 ppb)	Unhealthy for Sensitive Groups	Sensitive groups include people with lung disease such as asthma, older adults, children and teenagers, and people who are active out- doors.	Sensitive groups: *Reduce* prolonged or heavy outdoor exertion. Take more breaks, do less intense activities. Watch for symptoms such as coughing or shortness of breath. Schedule outdoor activities in the morning when ozone is lower. People with asthma should follow their asthma action plans and keep quick relief medicine
151 – 200 (86-105 ppb)	Unhealthy	Everyone	Sensitive groups: *Avoid* prolonged or heavy outdoor exertion. Schedule outdoor activities in the morning when ozone is lower. Consider moving activities indoors. People with asthma, keep quick-relief medicine handy. Everyone else: *Reduce* prolonged or heavy outdoor exertion. Take more breaks, do less intense activities. Schedule outdoor activities in the morning when ozone is lower.
201 – 300 (106- 200 ppb)	Very Unhealthy	Everyone	Sensitive groups: *Avoid all* physical activity outdoors. Move activities indoors or reschedule to a time when air quality is better. People with asthma, keep quick-relief medicine handy. Everyone else: *Avoid* prolonged or heavy outdoor exertion. Schedule outdoor activities in the morning when ozone is lower. Consider moving activities indoors.
301 – 500 (≥ 201 ppb)	Hazardous	Everyone	Everyone: *Avoid all* physical activity outdoors.

Updated on May 10, 2016

Figure 8. Air Quality Index for Ozone, with parts per billion mapped to Advisory level (American Lung Association, 2019).

cardiovascular effects and aggravated asthma. This can lead to hospital and emergency room visits and premature deaths; the elderly, children, and those with chronic illnesses are most vulnerable to these pollutants (Nolte et al., 2018).

Ozone

Hazard: Ozone (O_3) is a gas composed of three oxygen atoms. At ground-level, ozone is created by a chemical reaction between oxides of nitrogen (NO_x) and volatile organic compounds (VOC) in the presence of sunlight. Breathing ozone can trigger a variety of health problems including chest pain, coughing, throat irritation, and congestion. Ozone can exacerbate bronchitis, emphysema, and asthma, reduce lung function and inflame the linings of the lungs, and repeated exposure may permanently scar lung tissue. According to the Maine lung association, there are 18,000 children with pediatric asthma, >108,000 adults with asthma, and >74,000 adults with COPD (American Lung Association, 2019).

Exposure: Ozone formation depends on nitrogen oxides (NO_x), a combination of nitrogen monoxide (NO) and nitrogen dioxide (NO_2); methane (CH_4); volatile organic compounds (VOCs); and carbon monoxide (CO). In Maine, NO_x is the biggest factor driving formation of ground ozone (Martha Webster, Air Bureau, DEP, personal communication 1/11/2020). Emissions of NO_x arise primarily from fossil fuel combustion, with vehicle exhaust, maritime shipping, and power plant energy production contributing the largest amounts (Nolte et al., 2018).

A significant amount of air pollution is transported into Maine from large metropolitan areas and emission sources west and southwest (transport region) of Maine. Regional and local air quality controls have significantly reduced NOx and VOC emissions in Maine and in the transport region, resulting in a significant reduction of ozone levels in Maine. Ozone alert days (maximum daily 8-hour ozone average greater than 70 parts per billion (ppb), i.e., in the Moderate or yellow zone with Air Quality Index up to 100, Fig. 8) in Maine are occurring less frequently and primarily occur along Maine's coastal counties. Figure 8 maps Air Quality Index to advisory levels. The average number of ozone alert days during the latest five-year period (2015-19) was 3.6 days compared with 22.8 days during the 2001-05 five-year period. In 2019 there was only one ozone alert day experienced in coastal York and Hancock (only at the summit of Cadillac Mountain) counties. The last year in which there was an ozone alert day experienced in any inland county was 2013. Background ozone levels are highest during the spring months before full leaf out. An emergency episode alert is triggered when 8-hour ozone levels reach 116 ppb and that level has not been reached in Maine since 2002. Recent historical trends show that ozone levels have not increased due to increased temperatures in the region primarily because significant reductions in ozone precursor emissions are currently dominating changes in ozone levels in Maine (Tom Downs, Bureau of Air Quality, Maine DEP, email communication 2/14/2019).

Two studies that included Maine data demonstrated tangible negative health consequences of increased air pollution (particularly ozone). Palu and Smith (2008) found a 7 percent increase in asthma-related ED visits per 10-ppb increase in ozone averaged over 4 days in Maine patients, and risk was concentrated among females aged 15 to 34 and males younger than 15. In Portland, Maine an increase in SO2 (sulfur dioxide) was associated with a 5% increase in all respiratory ER visits, a 6% increase in asthma visits and an increase in ozone was associated with a 5% increase in ER visits (Wilson et al., 2005).

Health Impacts from Climate Change: Paulu and Smith (2008) and Wilson et al., 2005) indicate we can expect measurable negative health outcomes if ground-level ozone increases in response to higher temperatures in Maine. However, in Maine emissions of ozone precursors are expected to decrease in the near term due to reductions in fossil fuel use and expected regional and local controls (Martha Webster, Bureau of Air Quality, Maine DEP, email communication 2/14/2019). Environmental data on ground ozone is more robust compared to data on exposures, which in turn is more robust than data associating ozone exposures with climate change.

Particulate Matter

Hazard: PM2.5 refers to very small particulate matter less than 2.5 micrometers in diameter. PM includes sulfate, nitrate, organic and black carbon, mineral dust, and sea spray. At a local level in Maine, PM is highly variable and dependent on global and local weather patterns, precipitation and drought, location of fires ranging from large fires in California and Canada to small, local fires, including wood smoke from wood stoves used to heat homes. Hot, sunny days and stagnant weather conditions may result in high concentrations of particulate matter (PM). Even a spell of clear, cold, calm weather with snow on the ground will result in the build-up of PM (Martha Webster, Air Bureau, DEP, personal communication 1/11/2020).

Exposure: The size of particles plays a role in how they affect the lungs. PM 2.5 and smaller are “respirable” and PM 2.5 to PM 10 are “inhalable” (Don Darling, Air Bureau, DEP, personal communication 2/13/2020). The inhalable particulate fraction includes inhaled airborne particles that can be breathed into the nose or mouth; the respirable particulate fraction refers to even smaller particles that can penetrate beyond the terminal bronchioles into the gas-exchange region of the lungs (Brown et al., 2013). The primary annual average National Ambient Air Quality Standard for PM2.5 is 12 $\mu g/m^3$. U.S. counties with design values of 12 or lower receive a grade of “Pass.” Counties with design values of 12.1 or higher receive a grade of “Fail.” (American Lung Association, 2019).

Exposure to high concentrations of PM2.5 can result in serious health impacts, including adverse birth outcomes and premature death. As with ozone, Maine’s PM levels have dropped over the past 30 years thanks to national and regional air quality controls (Maine Department of Environmental Protection, 2019). Wildfires (and prescribed fires) are major sources of PM (and contribute to ozone formation), contributing 40% of directly emitted PM2.5 in the United States in 2011 (Nolte et al., 2018). Exposure to wildfire smoke increases the risk of respiratory disease and mortality (Nolte et al., 2018). In Maine, PM2.5 can be an issue due to forest fire smoke from western US and Canadian forest fires and with many residential wood burning stoves (Tom Downs, Bureau of Air Quality, Maine DEP, email communication 12/20/2019, 2/14/2020).

Health Impacts from Climate Change: Although Maine’s PM levels have dropped over the past 30 years, PM levels could be worsened through climate-mediated air stagnation, droughts, and wildfires (Nolte et al., 2018). Wildfires are growing in intensity and frequency and merit attention. Climate scientists have correlated the growing incidence and intensity of wildfires with rising global temperatures; recently Alaska and the American northwest, southwest and southeast have had massive wildfires. In federally managed forests in the western U.S. today, wildfires larger than 1,000 acres have become nearly five times more frequent and burned areas 10 times as large as in the 1970s (Westerling et al., 2014). Smoke from these fires is transported east. For example, on August 14, 2018 smoke from western U.S. fires moved into Maine (NWS 2018). Thus, even while holding air quality controls steady, climate change-mediated wildfires have the potential to offset reductions in emissions of PM2.5 precursors (Nolte et al., 2018). That said, downbursts of smoke in Maine from distant fires may not last long, typically 1-2 hours (Martha Webster, Air Bureau, DEP, personal communication 1/11/2020).

It is very difficult to assess whether regional or local increases in PM will occur, given national and regional air quality controls in place. Also, increased amounts and frequency of rainfall in Maine may reduce likelihood of forest fires in Maine (Tom Downs, Bureau of Air Quality, Maine DEP, email communication 2/14/2020). Maine has experienced a 30% increase in average precipitation for 2005–2014 (13 inches per year) compared to previous decades, with this increase due mostly due to more 1-inch and 2-inch events (Fernandez et al., 2020). Environmental data on PM are more robust compared to data on exposures, which in turn are more robust than data associating PM exposures with climate change.

Aeroallergens/Pollen

Common aeroallergens causing disease are pollens and house dust mites, mold and spores and particulate matter produced by combustion. This section focuses on pollen.

Hazard: Pollen is the coarse powdery substance made up of pollen grains; it comes from flowering plants and is key to plant reproduction. Wind dispersal brings pollen into contact with nasal passages, causing allergic reactions in some individuals. Ragweed causes hayfever in late summer and fall. Airborne allergen (aeroallergen) exposure in the United States begins with the release of tree pollen in the spring (Nolte et al., 2018). Common sources of tree pollen in Maine are pine, oak, and birch trees.

Exposure: Higher total pollen levels and increases in specific types of pollen negatively impact respiratory conditions. Elevated pollen exposure leads to increases in asthma and rhinitis visits to health care providers and to emergency departments, asthma inpatient hospitalizations and asthma deaths (especially in persons over 64), increased use of over-the-counter medications, and lost school and work time (Anderson et al., 2013). However, there are no air quality standards for pollen (Andy Johnson, Air Bureau, DEP, conference call, 1/11/2020).

Rising temperatures and increased CO_2 concentrations can increase the duration of the pollen season and increase the amount of pollen produced by plants. The allergenic pollen seasons of representative trees, weeds and grass during 2001–2010 across the contiguous United States have been observed to start 3 days earlier on average than during 1994-2000, with the average peak value and annual total of daily counted airborne pollen increased by over 40% (Zhang et al., 2015). Severity of allergies can be reduced if treatment occurs ahead of the pollen season (Harvard Health Letter, 2017). Pretreatment requires good pollen monitoring and forecasts.

Trends and patterns in current and past pollen exposure in Maine are unknown, because several pollen collection surveillance programs have been discontinued, and because there was no statewide, coordinated mechanism for publicly reporting data from these stations. Pollen monitoring requires collection equipment at long-term collecting sites, and experts in pollen identification (or advanced equipment to automate collection, speciation, and counting). At the time of preparation of this document the following information on these programs was gleaned:

- Biddeford: Southern Maine Medical Center ran a pollen surveillance program for several years in the 1980s (exact period unknown), having a roto-rod aeroallergen sampler and a space for counting pollen and mold spores; this program provided pollen data to Portland area TV stations (Andy Johnson, Air Bureau, DEP, email, 1/20/2020).

- Bangor: Affiliated Labs, Inc. (Northern Lights Laboratory as of Nov. 1, 2018) ran a pollen collection and identification program that lasted an estimated 20 years (approximately 1996-2016), but was ended due to aging equipment (replacement parts were unavailable) and staff shortages (Christine Henderson, Northern Light Laboratory, emails, 1/19/2020 and 1/27/2020). Data on paper were possibly provided to a contact at Maine Center for Diease Control and Prevention as well as to local TV stations and several local physicians (Christine Henderson, Northern Light Laboratory, emails, 1/19/2020 and 1/27/2020). Two of these physicians were allergists Dr. Paul Shapiro, and Dr. Leonard Bielory (Andy Johnson, Air Bureau, DEP, email, 1/20/2020), the former practicing in the Bangor area and latter now practicing in New Jersey.

- Farmington: Franklin Memorial Hospital briefly ran a pollen collection site that collected April - September 2011 and April - May 2012. The program was discontinued due to staff shortages and the fact that the program was not a revenue generator (Andrea Nurse, Climate Change Institute, University of Maine, email (3/23/2020).

- Presque Isle: Micmac Environmental Health Department (MEHD) ran a pollen collection program but as of this writing the collection and reporting periods are unknown (Andy Johnson, Air Bureau, DEP, email, 1/20/2020). MEHD data were not publicly disseminated, but may have been or are available on paper upon request. Dave Macek has been the person monitoring, counting, and reporting on pollen at MEHD.

At this time, pollen forecasts for Maine come from out-of-state monitoring stations. Weather.com (Weather.com, 2019) uses counts from Salem Massachusetts for reports from Kittery to Freeport and used Affiliated Lab's data for Brunswick to Maine's northern border; at the time of this writing their current source is unknown. Pollen.com (Pollen.com 2019) uses proprietary data, likely from Philadelphia. The American Academy of Allergy, Asthma & Immunology maintains a website (American Academy of Allergy, Asthma & Immunology, 2019) with pollen and mold reports for locations with volunteer-staffed pollen stations around the country, but with no pollen stations in New England.

Health Impacts from Climate Change: On a global basis, Nolte et al. (2018) predict with high confidence that the frequency and severity of allergic illnesses, including asthma and hay fever, are likely to increase as a result of a changing climate. Data on environmental hazards of pollen are well known, although exposure and health impacts due to pollen levels in Maine are not known. Still, by inference, impacts to human health from pollen due to longer growing seasons seem likely.

Health Impacts Mediated through Human Institutions

Mental Health

Exposure to extreme weather- or climate-related events, or their health consequences, can lead to mental health effects ranging from mild stress and symptoms of distress to severe anxiety, depression, post-traumatic stress disorder (PTSD), and suicidality (Dodgen et al., 2016). In the Northeast, the increasing likelihood of sea levels rise, flooding from extreme storms, and extreme precipitation events puts Mainers at risk of displacement and loss of property, which are associated with significant mental health effects. Exposure to life-threatening events such as severe storms, has been linked to a range of mental health impacts, including acute stress, PTSD, depression, and suicide within affected communities (Dodgen et al., 2016). Following Superstorm Sandy in 2012, residents who were displaced from their homes following flooding reported significant and long-lasting mental health impacts (Lieberman-Cribbin et al., 2017). Increases in interpersonal and domestic violence and high-risk coping strategies, such as alcohol abuse, have also been documented following extreme storms and flooding events (Clayton et al., 2014; Flory et al., 2009).

Significant mental health effects have also been documented in communities experiencing drought (Sartore et al., 2008; Hanigan, 2012) and extreme heat. In particular, extreme heat has been associated with decreased happiness, increased aggression and violence, and increased suicide rates (Noelke et al., 2016; Trombley et al., 2017; Burke et al., 2018). Exposure to more moderate heat has been associated with less severe mental health impacts, such as reduced cognitive function (Laurent et al., 2018) and disturbed sleep (Obradovich et al., 2017).

It is also important to note that those with existing mental health disorders are often some of the most vulnerable members of a community to other climate-related health effects, especially heat-related illnesses. Psychiatric medications can impair the body's ability to thermoregulate; some disorders can impair patients' ability to sense an increasing body temperature; and other cofactors in mental illness, such as poverty, substandard housing, lack of access to cool environments, isolation, and lack of community engagement can prevent those with mental illnesses from protecting themselves from heat-related illnesses (Chong and Castle, 2004; Martin-Latry et al., 2007). Taken together, these added risk factors put those with mental illness at much greater risk of heat-related illness during hot weather; one study found that pre-existing mental health conditions tripled the risk of death during a heat wave (Bouchama, 2007).

Veterinary Health and One Health

This summary on health impacts of climate change has focused on human health, but health impacts extend to wildlife, livestock, and pets. Impacts on wildlife are discussed in other sections of the working document, particularly in the Biodiversity section. Impacts of climate change on livestock and pets as they pertain to infectious disease have not been extensively developed in this working document, but are mentioned here.

Veterinary Health

The livestock industries are a major contributor to the economy of the northeastern United States (Hristov et al., 2018). Climate change may increase or decrease forage productivity depending on the crop, and may decrease protein content and forage digestibility. Heat stress will reduce fertility in milk production in dairy cattle, whereas climate change impacts on the beef industry are expected to be minimal. Broiler and layer production in the region may benefit from warmer winter and summer temperatures, if housing is appropriately insulated and ventilated. In the horse industry, land, forage and shelters may need to be managed differently to preserve health of working and competing horses (Hristov et al., 2018).

Large animal and companion animal health can be impacted through the same pathways as human health, such as displacement from natural disasters, heat illness, and vector-borne disease. Dogs suffer from Lyme disease, although a vaccine is available for dogs. The same is not the case for horses, which can become very ill from Lyme disease and for which treatment is quite expensive. Heartworm and eastern equine encephalitis virus (EEEv) are mosquito-borne diseases. Maine had its first veterinary EEEv outbreak in 2009 (Lubelczyk et al., 2013) in which fifteen horses and one llama died of infection with EEEv. During 2008–2014, there were 25 veterinary deaths due to EEEv in 5 of 7 years, compared with only two cases in 1 year during 2001–2007 (Elias et al., 2017).

One Health

The One Health concept is that human and veterinary health depend on the health of the environment. Zoonotic disease spillover that affects humans may also affect pets and livestock. As mentioned above, the bacteria that cause Lyme disease can cause debilitating illness not just in humans, but also dogs and horses (Johnson et al., 2004; Imai et al., 2011).

To safeguard human and veterinary health, One Health encourages cross-disciplinary collaborations among physicians, veterinarians, and scientists from a wide range of specialties. Over 60% of emerging human pathogens can be traced to wildlife origins (Karesh et al., 2012), so surveillance and health management that unite human and animal health and landscape ecology will have a greater benefit compared to a human-only focus (Daszak et al., 2007). This is never more evident than in 2020 as the world is impacted by a global pandemic (COVID-19) representing a human pathogen of wildlife origin. One Health approaches to emerging disease surveillance and management (EDSM) have been found to be more economical than systems that focus on humans only (Suijkerbuijk et al., 2018). Sentinel animal species can forecast human exposure to risk.

In Maine, vector ecologists, veterinarians, Maine CDC, and IDEXX collaborated on canine serosurveys for an antibody to the agents of Lyme and anaplasmosis. The studies revealed transmission of tick-borne pathogens in Maine in advance of human disease (Rand et al., 1991, Stone et al., 2005, Rand et al., 2011). Deer and moose serosurveys for antibody to mosquito-borne Eastern Equine Encephalitis virus (EEEv) showed a statewide distribution of EEEv though human and veterinary cases of EEEv so far have been restricted to southern and central Maine (Mutebi et al., 2015; Lubelzcyk et al., 2014). Climate change will likely aid range expansion of vector ticks and mosquitoes in Maine (see sections on tick- and mosquito-borne disease), so emerging disease surveillance and management through a One Health framework may be more adaptive than a human-only framework.

As stated by Zinsstag et al. (2018) on the topic of One Health: "The cost of outbreaks of emerging vector-borne zoonotic pathogens may be much lower if they are detected early in the vector or in livestock rather than later in humans. Therefore, integrated community-based surveillance of zoonoses is a promising avenue to reduce health effects of climate change."

Description of Priority Information Needs

Temperature Extremes

- Enhanced and up-to-date projections for extreme heat in Maine, and in particular, the number of days projected to exceed a daily maximum heat index of 95°F (35°C), for all major population centers.
- Research to quantify the additional impact of prolonged heat events (that is, longer than 1 day) on all-cause and cause-specific emergency department visits and deaths in Maine.
- A better understanding of groups of Mainers who may be vulnerable to extreme heat and where they are located.
- A better understanding of key locations such as schools and long-term care facilities without air conditioning around the state.
- A better understanding of effective approaches to protecting populations from extreme heat that are alternative to cooling centers – especially in rural areas.
- Up-to-date projections for the frequency of extreme cold days in Maine under various warming scenarios.

Extreme Weather Events

- Projections for the future frequency and severity of winter and windstorms.
- Better understanding of the broader short- and long-term health effects of power outages, aside from carbon monoxide poisoning and foodborne illness.

Tick-Borne Diseases

Current active and passive tick surveillance and tick testing in Maine is supported (in part) by U.S. Centers for Disease Control and Prevention funding through the Maine Center for Disease Control and Prevention. Funding should be at least maintained, but ideally expanded.

Active Tick Surveillance. Active tick surveillance entails collection of ticks from vegetation and host animals such as deer, moose, birds, mice, chipmunks, voles, and squirrels. Program expansion will improve coverage of the northern part of the state, which has been under-sampled yet where winters are warming faster, allow monitoring of the impact of moose (winter) ticks (*Dermacentor albipictus*) on moose mortality, and preparation for the anticipated colonization of Maine by the lone star tick (*Amblyomma americanum*). For a discussion of the moose tick please see the section on Biodiversity.

Until 2019, active tick surveillance has not been standardized or routine across the US. In 2019 the U.S. Centers for Disease Control and Prevention released a document titled "Surveillance for *Ixodes scapularis* and pathogens found in this tick species in the United States" (www.cdc.gov/ticks/resources/TickSurveillance_Iscapularis-P.pdf), providing guidance to standardize sampling for and test of deer ticks. Specifically, at the spatial scale of U.S. counties, CDC aims to: 1) classify county status for *I. scapularis*: established, reported, or no data available; 2) classify county status for presence of specific pathogens in *I. scapularis* ticks: present or no data. The CDC program asks that a minimum of two sites per county per season (nymph, adult) be sampled, with multiple collections per season 2-3 minimum). This has been achievable for all but the more northerly counties.

Cooperating institutions such as University of Maine Fort Kent, UM Presque Isle, UM Machias, UM Farmington, and UM Augusta have contributed to active surveillance in northerly and westerly counties such as Aroostook, Washington, Piscataquis, and Franklin. The deer tick and the diseases they transmit are well-established in the southern tier of the state but emergent in the northern tier. This is compelling because the northern tier is where climate change is allowing deer tick populations to grow but where policy actions have a prophylactic effect.

Passive Tick Surveillance. Passive tick surveillance involves submissions of ticks to tick identification programs. Maine has a rich temporal and spatial extent of passive surveillance data from which to draw, including a series collected by the Maine Medical Center Research Institute running from 1989-2013 and by the University of Maine Cooperative Extension Service's Tick Lab since 2014. The UMaine Tick Laboratory is ideal for tracking range expansion of ticks and the pathogens they carry, particularly in northern Maine. UMaine's Tick Lab has become vital to Maine's response to this growing risk.

Tick Testing. Current laboratory capacity for statewide tick surveillance and testing includes the Maine CDC, the Maine Health and Environmental Testing Laboratory, the Maine Medical Center Research Institute, and the University of Maine.

Case surveillance. Vector-borne disease tracking should be conducted in a manner that allows public health staff to devote resources not just to Lyme disease, which is established in Maine, but also to tracking trends in emerging tick-borne diseases, such as anaplasmosis, babesiosis, and Powassan (deer tick) virus encephalitis. Due to high volume in Lyme-endemic states, Lyme disease case-counting is burdensome to public health staff (Cartter et al., 2018). In Maine, case reports are derived from either Lyme disease testing results from laboratories, or from clinician reports that must be collected by Maine Disease Control and Prevention staff. At this time, Maine is the only New England state that still counts individual cases. Due to the overwhelming nature of this task, Maine may follow other Lyme-endemic states that have moved to other estimation systems, for example case-counting on the basis of laboratory tests only (S. Robinson, Maine CDC, personal communication 1/30/2020). Another challenge to precise quantification of Lyme disease is that case definitions have changed over time (https://wwwn.cdc.gov/nndss/conditions/lyme-disease). Also, clinician/patient awareness and diagnostic tests are improving (e.g., Elias et al., 2020b). Thus, consumers of Lyme disease case data should be aware of these challenges when interpreting data.

Clinical, ecological, and human dimensions research. A human Lyme disease vaccine (currently undergoing clinical trials) could ease the burden of Lyme disease in Maine. However, deer ticks carry at least four other pathogens in Maine, and the lone star tick, which is advancing north, will bring with it a host of pathogens as well as red meat allergy. Anti-tick vaccines, some of which are in research development, would provide the best defense against tick-borne diseases. Maine is well positioned as a site for clinical research in tick-borne disease. Maine has a long history of research in ecological studies pertaining to the ecology of deer ticks and an emerging body of research in human dimensions of tick-borne disease. Research is still needed in tick biology and ecology, pesticide resistance, and new Integrated Tick Management (ITM) options. However, given there are already a number of effective tools in the ITM toolbox, the greatest need is for comprehensive policy.

Policy. Currently Maine has no comprehensive policy plan to support tick control efforts of communities and towns, and no way to unify these efforts across the landscape. The lack of comprehensive, state- and/or regionwide policy means that long-term, landscape-scale integrated tick management has not yet been paired with short-term, personal, yard- and community-scale tick management strategies. State-scale, coordinated removal of tick-associated invasive plant species is not yet a reality. Since the early 1990s the Maine Disease Control and Prevention has run Vector-borne Disease Work Group (VBDWG) meetings which has produced a document outlining response to mosquito outbreaks, but there is not yet a comparable document outlining comprehensive policy to address tick control . For more on recommendations for tick control please see the Public Health subgroup's draft recommendations at https://climatecouncil.maine.gov/strategies/resilience.

Mosquito-borne Diseases

In Maine, the burden of mosquito-borne disease (MBD) is currently less than the burden of tick-borne disease (TBD), but the Zika outbreak of 2014 resulted in a broader awareness that the US has been under-prepared for arboviral (mosquito-borne virus) outbreaks. This resulted in expanded U.S. Centers for Disease Control and Prevention funding to states to expand capacity for mosquito surveillance and testing in all US states. The climate conditions that support *Aedes* mosquitoes (*Aedes aegypti* and *Aedes albopictus*) that transmit dengue, chikungunya, Zika and yellow fever are expanding northward (Ryan et al., 2019). It is still too cold for these *Aedes* species in Maine, but as human trade moves mosquitoes into Maine and a favorable climate envelope shifts north, ongoing surveillance and response planning is Maine's best defense. Years of low arboviral activity should not lull us into a state of under-funding and under-staffing.

The Maine Disease Control and Prevention in consultation with other state agencies, and health professionals, and vector ecologists have prepared guidance for Maine towns and communities Arboviral (Mosquito-Borne) Illness Surveillance, Prevention, and Response Guidance for Maine Towns and Communities, last reviewed June 2019.

Needs:

- Continued and expanded surveillance including mosquito, wildlife, and veterinary testing to detect hotspots of arboviral activity prior to outbreaks.

- Research in mosquito/arboviral biology and ecology to understand how MBD agents are amplified based on weather, habitat, and host conditions.
- Pesticide resistance.
- Mosquito control districts
- Emergency outbreak planning, preparedness, and response
- Ongoing public health education.

Food- and water-borne infections

Improved surveillance is needed for water-borne and food-borne disease outbreaks, including gathering more complete information on consumption of well water, shellfish, and other exposure pathways mitigated by climate change.

Harmful Algal Blooms

Human health tracking of harmful algal blooms is currently a knowledge gap although systems are now in place to gather health data, e.g., CDC's NORS (National Outbreak Reporting System) and OHHABS One Health Harmful Algal Bloom System (OHHABS). HAB metrics placed into various tracking networks would allow exploratory data analysis. Citizen scientists and volunteer groups can be enlisted to expand monitoring in the near-term.

As time goes on, we can expect more data to accrue from U.S. Centers for Disease Control and Prevention and NORS (2020c,d), and the National Institute of Environmental Health Sciences (2020). NIEHS and the Woods Hole Oceanographic Institution Center for Oceans and Human Health in collaboration have developed the Environmental Sample Processor, which can continually test a water body for HABs. This will allow rapid early detection of HABs to permit early warnings, water treatments, and studies of long-term health effects of HABs in low doses.

Maine needs to increase freshwater and marine HAB monitoring capacity including phytoplankton and shellfish sampling, improve predictive modeling of HABs to guide industry and management decisions, [such as those for red tide in coastal Maine (Grasso et al., 2019)], invest in research to develop best management practices when HABs impact the fishing industry, invest in technology to depurate biotoxins from shellfish, establish regional working groups to communicate and strategize response to morbidity/mortality events of aquatic species (e.g. Maine's Aquatic Animal Health Technical Committee, since ~2001; NOAA's New England Marine Mammal Working Group, since 2017) (Kohl Kanwit, Maine Department of Marine Resources; Mike Plaziak, Maine Rural Water Association, email communication, 1/9/2020). For more on marine HABs information needs please see the Marine Ecosystems chapter, "Description of Priority Information Needs" section of this report.

Air Quality

Ozone and Particulate Matter

Maine is currently attaining all ambient air quality standards, but needs include:

- Continued monitoring by Maine DEP, Micmac Environmental Health Department (MEHD), and the Passamaquoddy Tribe in Sipayik, Pleasant Point; monitoring stations should be in every county: Franklin, Lincoln, Piscataquis, Somerset, and Waldo do not have monitors according to the American Lung Association (2019): https://www.lung.org/our-initiatives/healthy-air/sota/city-rankings/states/maine/.

- Increased air quality monitoring: satellite monitoring is useful for areas not covered by surface monitoring, and useful for assessing above-surface particle pollution, nitrogen dioxide, sulfur dioxide and carbon monoxide levels; NASA has a number of current and future satellites that can help fill in gaps in the ground based monitoring networks and support air quality management (Tom Downs, Bureau of Air Quality, Maine DEP, email communication 5/13/2020).

- Tracking (syndromic surveillance) of ED visits and hospitalizations associated with timing and amount of ozone and PM

Aeroallergens/Pollen

The health burden of past, and anticipated future pollen increases due climate change in Maine are unknown, because Maine currently lacks all components of a systematic pollen monitoring progam. A spatially distributed network of pollen collection stations is absent, but a minimum of four could be put to use through resurrection of stations and establishment of new stations (e.g., the Micmac Lab in Presque Isle, UMaine in Orono, UMF in Farmington, and USM in Portland or Gorham (or other college campuses) with the the best and most efficient technology available. A centralized pollen identification laboratory in Maine is lacking, but could be implemented in Maine (e.g., at the University of Maine Climate Change Institute) or a central U.S. lab. There is no data archiving infrastructure to digitize, preserve, and provide past and future Maine pollen data to Mainers. The Maine Tracking Network (Maine Center for Disease Control and Prevention, 2020) have data on blacklegged (deer) tick abundance and mosquito abundance, and the DEP has air quality data on ozone and PM trends, but there is no such database for pollen. Without a pollen database, it follows that a centralized reporting and forecasting mechanism in Maine is not possible, but a reporting and forecasting system could be implemented, as has been done in New York (Anderson et al., 2013). Currently we have no way to correlatee ED visits and hospitalizations with timing, amount, and species of pollen, and include interactions with temperature and air quality. To advance the science, Maine needs to plan for and implement all components of a pollen monitoring progam.

These efforts should dovetail with the national framework being developed by the Council of State and Territorial Epidemiologists (CSTE) Climate and Respiratory Health Workgroup https://www.cste.org/page/ClimateResp?&hhsearchterms=%22aeroallergen%22. A review of Anderson et al., 2013 is strongly recommended. In 1977, U.S. State Agricultural Experiment Stations (SAES) organized a project, later titled the National Atmospheric Deposition Program (NADP), to measure atmospheric deposition and study its effects on the environment. The purpose of the NADP's Aeroallergen Monitoring Science Committee (AMSC) is to engage multi-disciplinary stakeholders in advancing the science of aeroallergen monitoring, including identifying emerging technologies, evaluating methods to ensure data quality, coordination of monitoring stations, and possibly serving as a repository of long-term aeroallergen monitoring data. Efforts in 2016-17 to establish a nationwide pollen monitoring network were not successful, but with renewed effort, the AMSC could provide the supporting infrastructure for a nationwide pollen monitoring program (Andy Johnson, Air Bureau, DEP, conference call, 1/11/2020). It is understood that climate change is leading to longer and heavier pollen seasons (e.g., Sierra-Heredia et al., 2018). Canada has a pollen forecasting system that can predict with 80% accuracy the first day of the pollen season (Andy Johnson, Air Bureau, DEP, conference call, 1/11/2020).

Mental Health

- Better understand threats to mental health from exposure to other climate change impacts besides storms, floods, droughts, and extreme heat.

- Delineate best practices for supporting population mental health during and after all types of extreme weather- and climate-related events.

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APPENDIX – HEALTH IMPACTS

Deer Tick-Transmitted Diseases in Maine

Lyme disease. Lyme disease is caused by the bacterium *Borrelia burgdorferi* and rarely, *Borrelia mayonii*. Symptoms include fever, headache, fatigue, and a characteristic skin rash called erythema migrans (bulls-eye rash). If left untreated, infection can spread to joints, the heart, and the nervous system (https://www.cdc.gov/lyme/index.html). Symptoms persist in some patients after treatment (https://www.cdc.gov/lyme/postlds/index.html).

Anaplasmosis. Anaplasmosis is caused by the bacterium *Anaplasma phagocytophilum*. Symptoms include fever, headache, chills, and muscle aches. Can be more severe in the immune compromised (https://www.cdc.gov/anaplasmosis/stats/index.html).

Babesiosis. Babesiosis is caused by *Babesia microti*, a protozoan parasite that infects red blood cells, and can cause flu-like symptoms, such as fever, chills, sweats, headache, body aches, loss of appetite, nausea, or fatigue; can be severe and life-threatening in the immune compromised and elderly https://www.cdc.gov/parasites/babesiosis/index.html

Powassan Encephalitis. Powassan encephalitis is caused by Powassan encephalitis virus or a variant known as deer tick virus. Though rare it is usually a serious viral infection of the brain that leaves half its victims with permanent neurological damage and is fatal for 10%-15% (https://www.cdc.gov/powassan/index.html). Maine has recorded five cases, including the first fatality in 2014 (Cavanaugh et al.,2017).

Tickborne relapsing fever (TBRF). TBRF is caused by *Borrelia miyamotoi*. Common symptoms include fever, chills, headache, body and joint pain and fatigue. Rash was uncommon, with fewer than 1 in 10 patients developing a rash (https://www.cdc.gov/relapsing-fever/miyamotoi/index.html).

Mosquito-Transmitted Diseases in Maine

Eastern equine encephalitis virus (EEEv). EEEv infects the brain, causing encephalitis; approximately 30% of people with EEE die and many survivors have ongoing neurologic problems (https://www.cdc.gov/easternequine-encephalitis/index.html).

West Nile virus (WNv). WNv is the leading cause of mosquito-borne disease in the continental United States. About 1 in 5 infected people develop a fever and other symptoms and 1 of 150 develop a serious or fatal illness (https://www.cdc.gov/westnile/index.html). **Jamestown Canyon virus (JCv).** JCv causes fever, headache, and fatigue and rarely severe disease including encephalitis and meningitis (https://www.cdc.gov/jamestown-canyon/index.html).

MAINE'S ECONOMY AND CLIMATE CHANGE

Photo: Paul Cyr

HIGHLIGHTS

Climate change will affect all sectors of Maine's economy from tourism, agriculture and forestry to transportation. The state has, and will likely experience more, economic losses in some sectors that *may* be offset in others. Warmer temperatures, more rain, and sea-level rise will increase the incidence of flooding, damage to coastal property and infrastructure. The responses that we make to mitigate and adapt to climate change will determine, in part, the economic and social costs to Maine's economy. The extent of the costs to Maine are also dependent on how climate change will impact people and businesses, net population flows, tourism and our imports and exports.

Economic opportunities from the response to climate change include the growing renewable energy industry including land and ocean-based wind power, solar, and biofuels. Growing renewable energy production and use also means fewer imports of fossil-based energy supplies of which Maine has none.

Of particular concern are changes that impact traditional industries such as lobsters and shellfish harvesting, other commercial fishing and the forest products industry. The share of Maine's gross domestic product (GDP) coming from forestry and paper product manufacturing has shrunk considerably in the last decade. Today, Maine's economy is dominated by service industries such as finance, insurance, and real estate (EIA, 2019).

Warmer temperatures may extend seasons for tourism activities such as cruise ships and boating while reducing the seasons for skiing and snowmobiling. Longer growing seasons will permit farmers to expand the range of crops and animals in Maine agriculture. The forest products industry, which has been adapting to changing species mix and market demand, will experience more variable impacts due to a longer growing season but increased occurrence of drought. The agricultural sector will also likely have a longer and warmer growing season. In addition, while some recreational experiences (e.g., snowmobiling) may be degraded by increasing temperatures, parts of Maine tourism industry may still benefit if Maine's climate remains superior to the climate in competing regions.

DISCUSSION

Maine's GDP and GHG Emissions

The state's annual greenhouse gas emissions (GHGs) increased from 1990 to 2002, peaking at about 27 million metric tons CO_2 equivalent (MMTCO2e) (ME DEP, 2018). GHGs then decreased through 2012 and remained relatively steady at around 19 million metric tons CO2e through 2015. From 1997 -2018, Maine's real (inflation adjusted) GDP has increased from $43 to $57 Billion dollars per year, representing a 33% total or 1.5% per year annual growth rate.[1] Over the same period, Maine's GHG emissions *per dollar of real GDP* have declined from about 535 tCO2e per million dollars GDP to about 355 tCO2e per million dollars GDP. This finding indicates that the Maine economy has reduced its GHGs emissions relative to income. This is primarily due to the use of lower carbon emitting fuels in the electricity and residential sectors, more efficient equipment, and a relative increase in industries/sectors that are less GHG intensive per dollar of GDP produced (ME DEP, 2018). This decoupling can be seen in Figure 1.

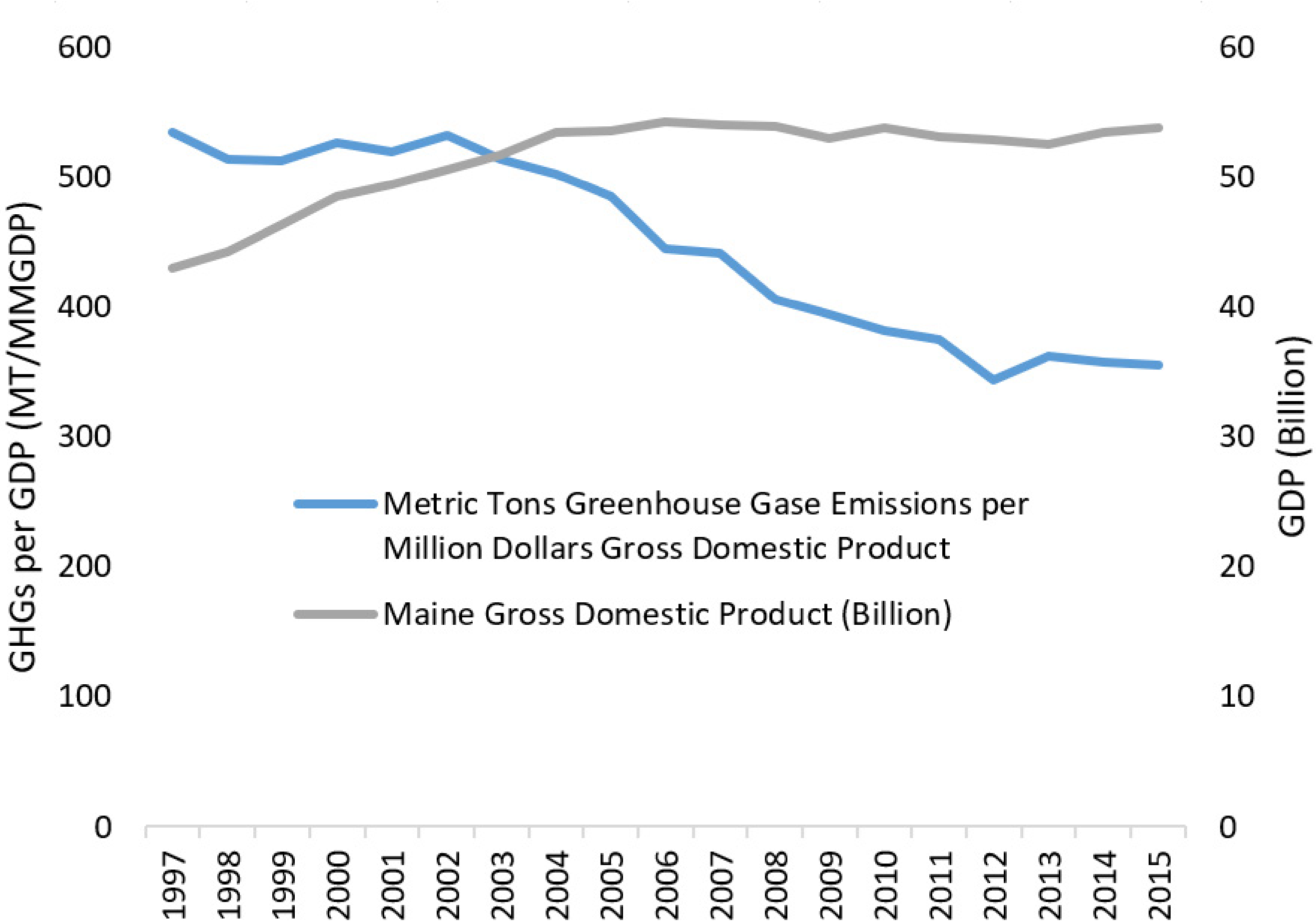

Figure 1. Maine's GDP and GHG emissions per million dollars GDP, 1997-2015.

1 BEA, SAGDP9N, chained real dollars, 2012 base year, earlier years use a different index.

Sector-level Economic Impacts of Climate Change

Energy

Data from the US Department of Energy shows that about two-thirds of Maine households use fuel oil for home heating, the highest level of dependency in the US. In terms of total energy use, petroleum products provide the largest share of Maine's primary energy and accounts for about half of all energy used in the state. At the same time, Maine has one of the least carbon intensive electricity generation mixes with 75% of Maine's net electricity generation coming from renewable sources including 31% from hydroelectricity, 22% from biomass, and 21% from wind[2]. Maine's wind generation places it sixth in the nation for share of wind-powered electricity generation[3]. We note that Maine's low carbon electricity sector provides opportunities to lower carbon emissions through fuel switching or "beneficial electrification" in other sectors including transportation (electric vehicles) and structural heating (air and ground heat pumps). We provide a summary of Maine's energy sector in Appendix B.

Transportation

Currently, the transportation sector accounts for 53% and 52% of Maine's carbon dioxide and greenhouse gas emissions, respectively (ME DEP, 2018). On a per-capita basis, Maine's transportation sector is about average for the nation (rank 21 out of 51). More than 90% of Maine's transportation energy comes from petroleum (ME DEP, 2018). Reducing transportation-related petroleum demand and emissions will benefit Maine's economy. This can be achieved by increasing vehicle efficiency, switching to alternative fuels (e.g., electricity, biofuels) that have lower emissions per mile, and by reducing the demand for motorized transportation. Reducing transportation emissions can have other benefits by improving air quality and reducing congestion. It can also reduce the expense of importing gasoline and diesel fuel into Maine and providing increasing opportunities for active mobility such as biking and walking. The impacts of switching to electric vehicles needs to consider Maine's cold climate. Losses from extreme weather (very hot or very cold) can reduce plug-in electric vehicle range by 25% (US DOE, 2020).

Future climate is expected to have negative impacts on pavement, bridge, and culvert durability. Higher temperatures can decrease pavement life and require earlier road repair. Additionally, more freeze-thaw cycles can increase bridge fatigue and higher frequency of extreme precipitation events could lead to more culvert washouts (see the Climate chapter in this report for more information). The estimated impacts to these components of the transportation sector will likely need to be made at the sub-regional level within the state.

Tourism & Recreation

Tourism is one of the largest industries in the state of Maine, generating over $6 billion in direct expenditure per year (Maine Office of Tourism 2019). Tourism in Maine relies heavily on outdoor and recreational activities, most of which are significantly influenced by the temperature and precipitation (e.g., snow). Climate change will lengthen the season for some recreational activities, while decreasing the number of days available for enjoying others (snow skiing, snowmobiling). While some recreational experiences (e.g., snowmobiling) may be degraded by increasing temperatures, Maine tourism industry may still benefit overall if Maine's climate remains superior to the climate in competing regions. However, tourists who visit Maine to fish or view wildlife may seek recreation elsewhere if desirable species migrate north as a result of climate change. Results from a recent study indicated that warmer temperatures increased tourism spending in Maine during the summer and fall but had more varying results in the winter (Wilkens et al. 2018). This suggests that tourism businesses in Maine could capitalize on potential gains in warmer months, while cold-weather ventures may have to adapt more to negative impacts of a changing climate.

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2 https://www.eia.gov/state/?sid=ME

3 https://www.eia.gov/state/?sid=ME, June 20, 2019

Forest Products

Forests currently cover nearly 89% of Maine's land area and sequester over half of the state's annual emissions (see the Forestry chapter in this report for more information). The forest products sector is statewide, multi-faceted, and provides around $8 billion in economic impacts to Maine. As the world's population grows larger and wealthier, pressure will increase on forest resources for sustainable building materials, furniture, paper, and energy. A significant factor affecting the industry will be the rate and magnitude of climate change, and how these changes influence the adoption of new technologies and resulting species and product mix. Forest productivity will likely be more variable with some portions of the state seeing greater growth due to a longer growing season and more favorable climate, while other areas will decline due to the increased occurrence of drought (Duveneck and Thompson 2019). Harvest operations are likely to become more expensive due to less consistent winter conditions, thereby reducing stand accessibility. The forest response to climate change will be complex and difficult to predict given the range of conditions and species present in Maine's current forest as well as variation in future management. Continued development pressure reduces the land base available for Maine's natural resource industries, limiting their ability to expand and adapt. Land use change to development can also reduce carbon stored on the landscape in forests, wetlands, and other ecosystems, adding to greenhouse gas emissions.

Adequately quantifying the impacts to Maine's natural and working lands requires sophisticated understanding of how the weather and climate will change, and how ecosystems and the people who manage them will respond as a result. This is of particular importance because climate can have an important effect on the carbon uptake and removal ("sequestration") rate of forests and other natural ecosystems, which are expected to have a major role in helping Maine achieve its 2045 carbon neutrality target.

Agriculture

Maine is considered to have one of the largest and most diverse agricultural economies in New England. The state has nearly 8,000 farms that generate more than $1 billion per year in economic output (USDA 2019; Farm Credit East, 2015). The plant hardiness zones used by farmers and gardeners have shifted north, allowing Mainers to grow crops, plants, and flowers previously available only in warmer climes. Warmer temperatures will give farmers and the horticulture industry continued access to new crops and livestock. Farmers and gardeners can expect a greater need for irrigation, particularly for high value crops, to offset increased soil moisture loss through evaporation and transpiration. Increasing temperatures will also negatively affect confined livestock in the state. New pests, invasive plants, and pathogens will increasingly encroach into Maine, threatening plants, animals, and humans, and making management more difficult. Farmers are already adapting to climate change by investing in infrastructure like new high tunnels and irrigation systems and using cover crop and other soil health strategies to manage the risks of heavy precipitation and drought (White et al. 2018). For more details about how climate change is expected to affect Maine agriculture, see the Agriculture chapter of this report.

Marine Fisheries and Aquaculture

Maine's commercial fish harvest was valued at about $637 million in 2018 (ME DMR, 2019). About two-thirds of that value is attributed to Maine's lobster fishery. Other important commercial species harvested in recent years include elvers, Atlantic Herring, softshell clams, sea urchins, and scallops. Nearly 30,000 people are employed in the state's commercial fishing industry. Oremus (2019) provides empirical evidence that fluctuations in regional climate reduced county-level fishing employment in New England by an average of 16% between 1996 and 2017).

Population and Workforce

Maine's population has a median age of 45 years and is the oldest in the US (Rector, 2019). Moreover, Maine's population of 25-64 year olds (prime working age) is projected to decline, while the number of residents 65 and older is projected to increase. Maine's rate of total population increase ranked 34th and the rate of total net migration ranked 19th in the U.S. (Rector, 2019). The top sending and receiving states – in terms of population flows – were our New England neighbors as well as Texas, Florida, and California (Rector, 2019). How climate change impacts these states' economies and the desirability to live there will impact Maine's population, workforce and economic vibrancy.

Opportunities from Mitigation & Adaptation

The need to mitigate and adapt to climate change presents Maine with several economic opportunities. These include ideas covered in more detail elsewhere in this report, such as developing markets for Maine forests to be used for carbon sequestration and bioproducts (see the Forestry chapter), or modifying crops and farm practices to take advantage of changing market conditions (see the Agriculture chapter). Expanding on this, a recent analysis based on Fargione et al (2018) estimated that Natural Climate Solutions (NCS) implemented on up to 1.3 million acres of Maine's natural and working lands could reduce net annual GHG emissions (i.e., gross emissions less carbon sequestration) by 0.3 to 3.4 $MtCO_2e$/year. According to the study, the bulk of the mitigation (75%) would come from afforestation, which may or may not be widely accepted by the public due to the loss of some agricultural land (which the study found to have limited mitigation potential). Related to this, Daigneault et al. (2020) released an initial analysis of land-based mitigation opportunities in Maine (Figure 2). They estimated that more than 4.0 MtCO2e/yr in additional sequestration could be achieved in Maine's forests through changes in forest management and afforestation at costs of $10-20/tCO2e. Furthermore, they estimated that farmers could collectively amend their soil with biochar, reduce their tillage intensity, plant riparian buffers, and construct and utilize anaerobic digesters to manage dairy manure waste, thereby mitigating up to 0.78 MtCO2e/yr in GHG emissions or about double the sector's current annual emissions at a cost of about $34/tCO2e.

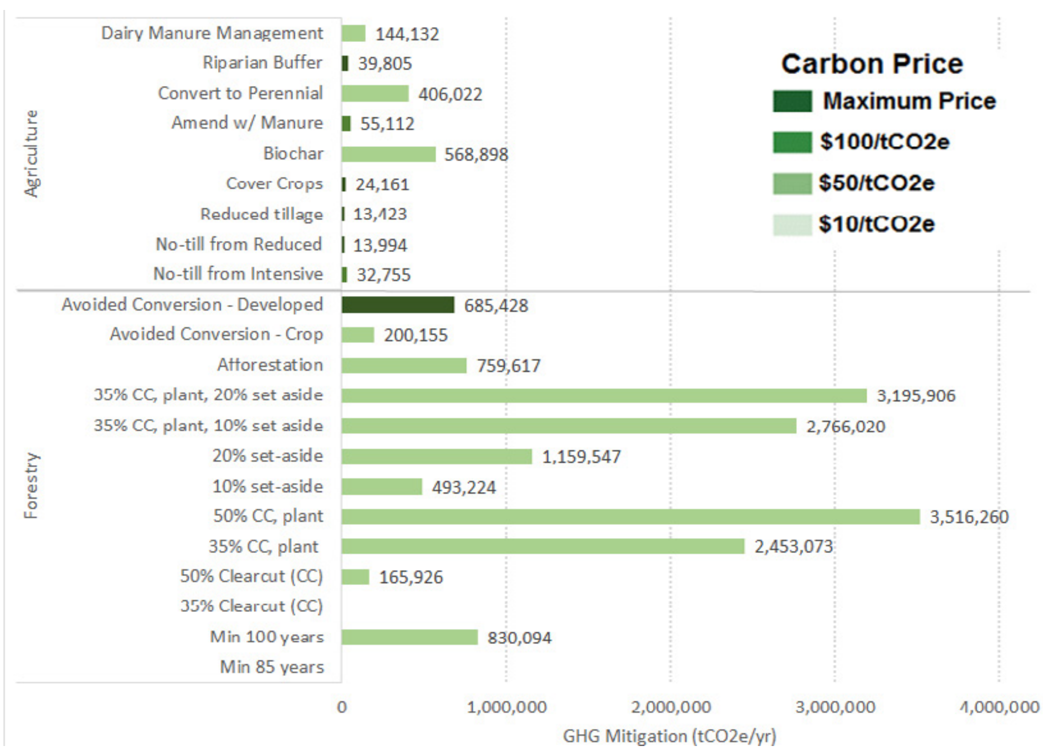

Figure 2. Maine natural climate solutions mitigation potential ($MtCO_2e$/yr). for varying carbon prices (source: Daigneualt et al., 2020)

Maine has other economic opportunities associated with adopting climate change mitigation and adaptation policies. For example, there has already been significant investment and planning in alternative energy generation, particularly on- and off-shore wind power. In addition, transitioning the state to a low-emissions economy can lead to public health benefits through the development of new infrastructure like more walkable neighborhoods and improved air and water quality that can promote more healthy lifestyles. Other potential opportunities include developing new tourism and recreation ventures, harvesting new or different aquatic species, improving public health and disaster response infrastructure, and enhancing energy efficiency of residential housing.

Description of Priority Information Needs and Recommendations

Consistently Quantifying the Costs and Benefits of Climate Change Impacts, Mitigation, and Adaptation

One difficulty with responding to climate change is that the costs of mitigation and adaptation are borne today while the impacts of climate change on our ecosystems and economy are projected to increase over time.

Perhaps one of the most difficult questions is how to weigh the short-term costs and benefits of climate action against the long-term impacts of climate change. This comparison is typically done by discounting, that is valuing or weighing the monetary and non-monetary, impacts (positive and negative) relatively less in the future than those which are expected to accrue closer to today (i.e., present value). The *rate* by which we discount these future impacts should reflect society's values. This decision can be informed by looking at how society makes these choices for other long-term decisions such as building bridges, dams and power plants where costs are borne today but have decades-long impacts. Choosing a discount rate to use is one of the most important factors in determining the monetary costs and benefits of climate change damages, mitigation costs and expenditures on building resiliency. We have two high-level recommendations with respect to discounting:

- The Climate Council should choose several different discount rates to evaluate future benefits and costs. We recommend 2.5% 3% and 5% based on the U.S. Government Technical Support Document to Executive Order 12866 (2016). Trump administrative guidance calls for 3% and 7% (Executive Order 13783, 2017). That said, the final choice should reflect the values and judgment of the Council.

- The Climate Council should insure that all working groups - and any work commissioned to evaluate the monetary benefits and costs on behalf of the Climate Council - use the chosen discount rates. Studies used to support the decisions of the Climate Council that do not use these rates require expert judgment to interpret their finding and should be used with caution.

We provide an extensive bibliography on this topic in Appendix A.

Other Recommendations and Questions

Quantifying Maine's Sector-level GHG Emissions

Maine's GHG emissions are determined from the US EPA's State Inventory Tool (MDEP, 2018). The State Inventory Tool consists of 11 estimation modules applying a top-down approach to calculate GHG emissions, and one module to synthesize estimates across all modules. The SIT gives users the option of applying own state-specific data or using default data pre-loaded for each state. It would be helpful for ME DEP to provide guidance to the STS and Climate Council on which sectors use Maine-specific data and where additional effort should be taken to collect or develop data for the SIT model to improve confidence in its accuracy. Future work should include clarifying if the

GHG emissions estimated by the SIT model are full cycle or only end-use. This is very important for some fuels and pathways such as natural gas that, depending on how it is produced, may have significant upstream methane emissions 60% above existing US EPA estimates (Alvarez et al. 2018).

Employing Best Practices for Economic Analysis

Studies commissioned or adopted for use by the Climate Council ought to use consistent assumptions on key economic variables such as the cost of capital, the lifetime of projects, the statistical value of lives saved—across all sectors considered (e.g., forestry, fisheries, transportation infrastructure and other). The USEPA's National Center for Environmental Economics (2014) provides guidance and best practices for economic analyses.

Impacts of Current and Future Climate Policy

Maine is currently a part of regional climate policies and initiatives that aim to reduce the state's GHG emissions. For example, CO_2 emissions from the state's electrical power sector are capped through the Regional Greenhouse Gas Initiative (RGGI)[4] (Maine DEP, 2018). Maine has been observing the Transportation and Climate Initiative (TCI)[5] and is also part of the (non-legally binding) United States Climate Alliance (USCA)[6] of states committed to reducing greenhouse gas emissions consistent with the goals of the Paris Agreement. These TCI and USCA are both focused on developing state and regional approaches to mitigate climate change. Many public institutions and private enterprises across the state also have established climate change-related policies. However, these policies are not necessarily linked, have an unspecified timeframe, and are focused on specific sectors of the economy. As a result, more could be done to evaluate the efficiency and effectiveness of the current policy approach relative to what could be implemented in the future.

Other Considerations for Quantifying Impacts to Maine's Economy

1. Linkages to national/international drivers, policies, etc.

2. Expectations for the future absent CC

3. Rates of changes/drivers of sectors versus static snapshots of current status

4 https://www.rggi.org/
5 https://www.transportationandclimate.org/content/about-us
6 http://www.usclimatealliance.org/

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APPENDIX B

Maine Energy Overview

Mariya Pominova and Jonathan Rubin
School of Economics Staff Paper # 636

Energy Sources

The U.S. Energy Information Administration (EIA) defines primary energy as energy that can be accounted for in a statistical energy balance without undergoing any transformation. There are two groups of primary energy sources: renewable and non-renewable (Table 1).

NON-RENEWABLE ENERGY SOURCES	RENEWABLE ENERGY SOURCES
Oil and Petroleum Products	Solar Energy
Hydrocarbon gas liquids	Geothermal Energy
Natural Gas	Wind Energy
Coal	Biomass
Nuclear Energy	Hydropower

Table 1: Main Primary Non-Renewable and Renewable Energy Sources (U.S. Energy Information Administration, 2018)

Renewable energy sources, such as hydropower and wind energy, are non-depletable whereas non-renewable energy sources, such as coal or natural gas, have a finite amount (U.S. Energy Information Administration, 2018). A note on energy sources and GHGs: biomass energy sources, while renewable, are considered carbon/GHG neutral if an equal amount of carbon is replaced through the growth of trees or other plants, a process which may take years to decades. Nuclear energy, while non-renewable, does not emit carbon dioxide or other GHGs as a result of producing energy.

There are four major **end-use energy consuming sectors:** *industrial, transportation, residential, and commercial*. Electricity is a secondary energy source and can be produced through burning fossil fuels, nuclear reactors, or renewables.

Maine Energy: Maine is the northernmost state in New England and highly rural. Furthermore, Maine's economy is highly dependent on forestry and wood-products, such as production of biofuel, tying in the industrial sector as well (EIA 9/2/2020).

DESCRIPTION	MAINE	US
Resident population[7]	1.33 million	0.4% (Share US)
Real GDP[8]	$55.6 billion	44 (Rank US)
Total Energy Consumption[9]	**392 trillion BTUs**	**44 (Rank US)**
→Per Capita	294 million BTUs	27 (Rank US)
→Per dollar real GDP	7.05 thousand BTUs	
Total Energy Production	153 trillion BTUs	0.2% (Share US)
Total energy expenditures	$5,624 million	40 (Rank US)
Per capita	$4,213	11 (Rank US)
Total energy average price	$18.15 per million BTUs	

Table 2 - Maine Energy Snapshot (2016). Source: EIA Maine Energy Overview

EIA Quick Facts:

- Maine's households have the highest dependence on oil in the US, with approximately two-thirds of households reliant on fuel oil as the primary energy source for home heating.
- In 2018, 75% of Maine's net electricity generation was obtained from renewable sources: 31% from hydroelectricity, 22% from biomass, and 21% from wind.
- In 2017, about 49% of all Maine's end-use energy consumption came from petroleum product sources.
- The share of Maine's gross domestic product (GDP) from forestry and paper product manufacturing has shrunk considerably in the last decade. Today, Maine's economy is dominated by service industries such as finance, insurance, and real estate.
- Maine is a New England leader and sixth in the nation for share of wind-powered electricity generation.

Source: EIA Maine Energy Overview, (https://www.eia.gov/state/?sid=ME,) June 20, 2019)

Energy Production in Maine

The EIA defines primary energy production as the transformation of energy from fossil fuels, and renewable and nuclear sources[10]. Primary energy production in Maine is 100% renewable, i.e., Maine does not produce oil, gas, coal or nuclear energy. Maine is a leader in New England in renewable energy production (Figure 3).

7 Including armed forces; Source: Bureau of Labor Statistics (2016)
8 Inflation adjust with 2009 as base year; Source: Bureau of Economic Analysis (2016)
9 Source: Energy Information Administration (2016)
10 This includes harnessing energy from sources such as the sun, wind, and water for the generation of electricity but does not include the use of already harvested energy, such as coal, for electricity production.

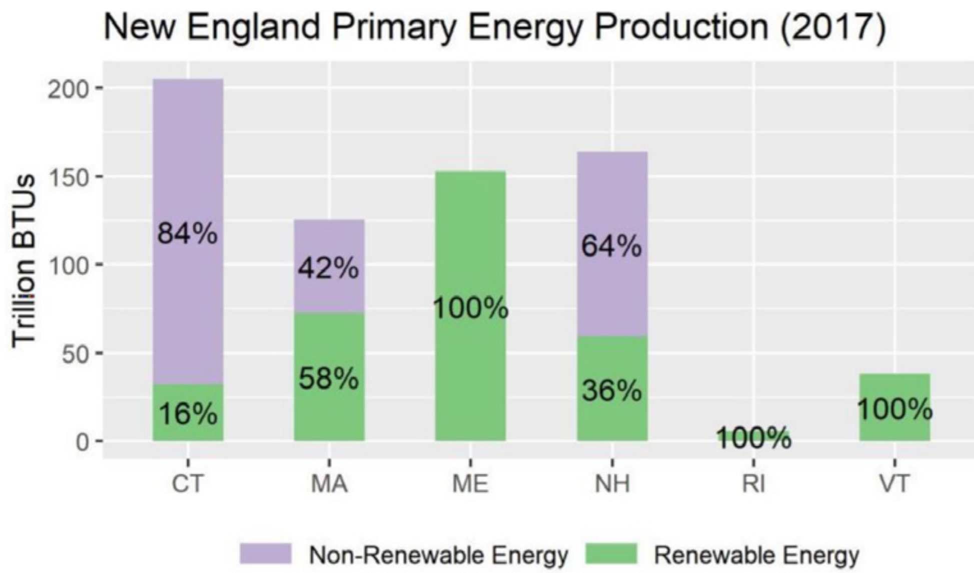

Figure 3: Maine Energy Production by Source (Source: EIA State Energy Data System (SEDS): 2017)

The majority of primary energy production in Maine is from hydroelectricity and wood and wood products, but recently electricity production from primary energy resources wind and solar has begun to increase. Maine is a New England leader and sixth in the nation for share of wind-powered electricity generation (EIA Maine Energy Overview 2019).

Maine has significantly decreased use of fossil fuels for the production of electricity in the last two decades, with 75% of all electricity production coming from renewable sources (Figure 4).

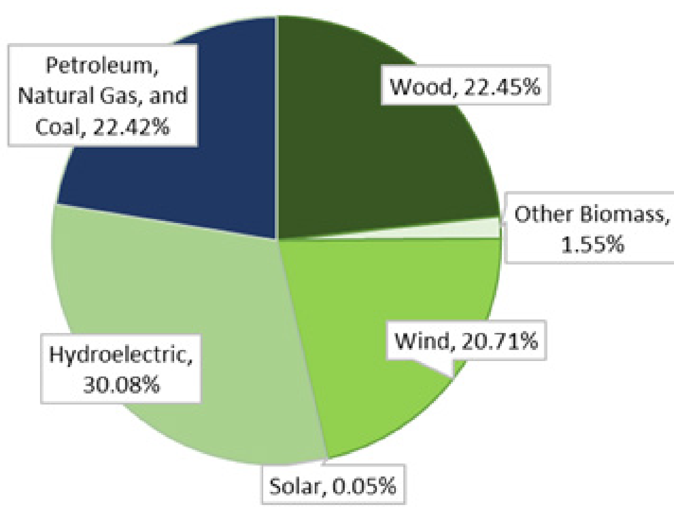

Figure 4: Maine Net Electrical Generation by Energy Source
(Source: EIA State Energy Data System (SEDS): 2017)

Energy Consumption in Maine:

On a per-capita basis, Maine consumes the most energy per person in New England (Figure 5).

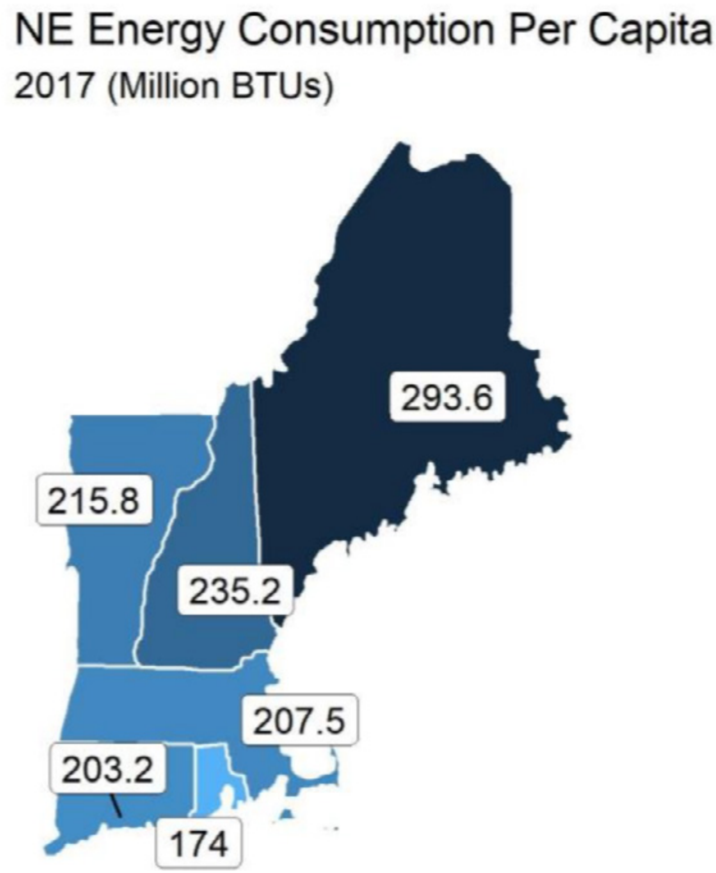

Figure 5: New England Total Energy Consumption by State (Source EIA SEDS: 2017)

The majority of energy consumption in Maine is non-renewable, with three of the four energy consumption sectors using a majority of non-renewable energy (Figure 6).

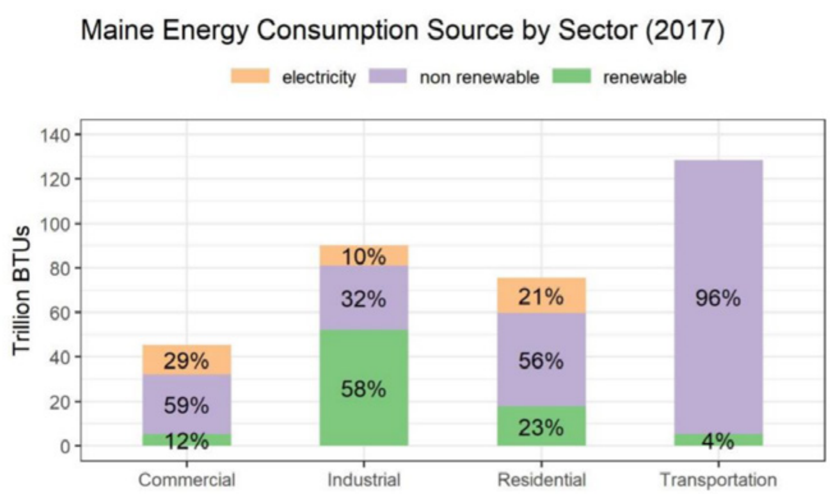

Figure 6: Maine Total Energy Consumption by Source and Sector (Source: EIA SEDS 2017)

Energy consumption in Maine has been steadily decreasing for the last two decades (Figure 7). In this time, there has been a shift in the proportions of total energy consumption held by each sector. In 2000, 46% of all energy consumption was in the industrial sector. In 2017, this number dropped to 26%. The transportation sector, on the other hand, increased by 7 percentage points. The industrial and transportation sectors make up over 50% of the end-use energy consumption in Maine.

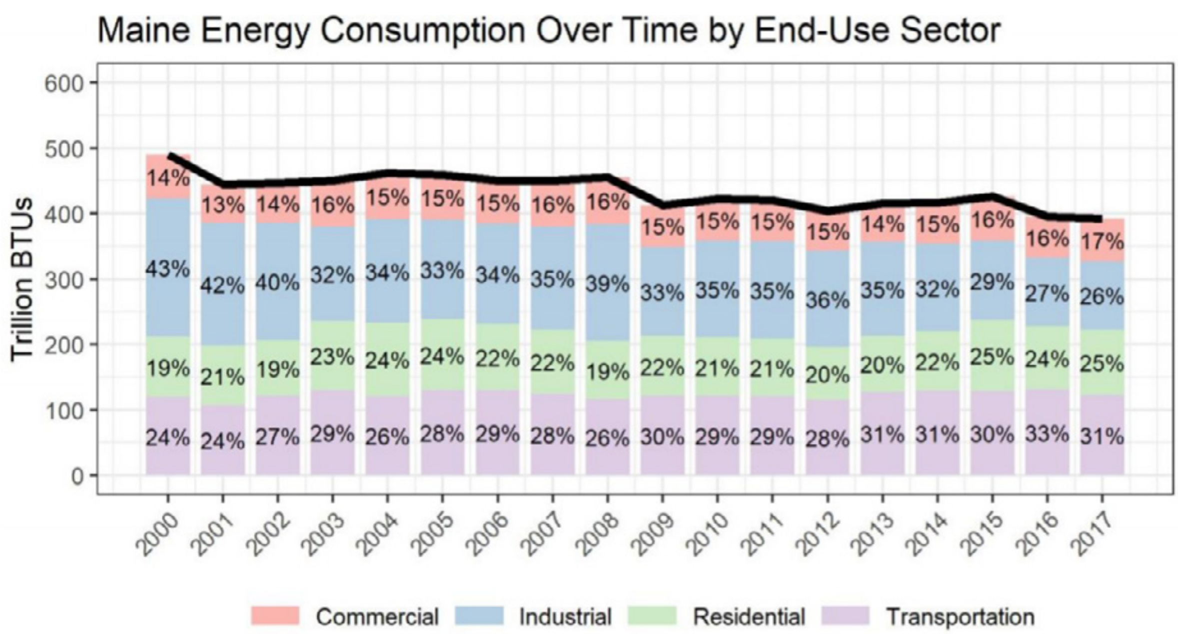

Figure 7: Maine Total Energy Consumption over time(Source EIA SEDS 2000-2017)

Energy Prices and Expenditure in Maine

The lowest priced energy source in Maine is wood and biomass waste. The next cheapest is natural gas. Coal is an inexpensive input but only makes up 1% of energy consumption in Maine (Table 3).

ENERGY SOURCE	CONSUMPTION (%)	PRICE ($USD/ MILLION BTU)
NON-RENEWABLE		
Coal	1%	$4.29
natural gas	12%	$6.42
all petroleum products	49%	$17.19
RENEWABLE		
wood and biomass waste	25%	$2.91
SECONDARY		
electricity sales	10%	$37.51
TOTAL ENERGY		$16.71

Table 3: Maine average energy price by source in 2017 (Source: EIA SEDS 2017)

Energy Expenditure in Maine

Since 2000, Maine energy expenditure increased by over 50% (Figure 8). The transportation sector has seen the most growth in this time and accounts for the greatest proportion of expenditure in the state (Figure 9).

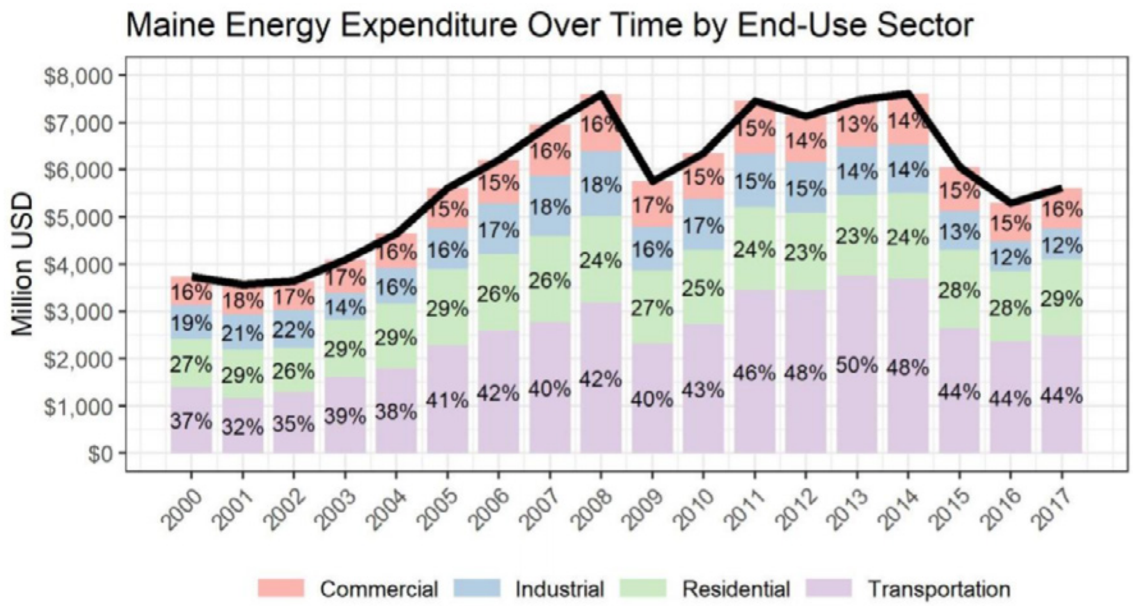

Figure 8: Change in Maine Total Energy Expenditure by End-Use Sector Over Time (Source: EIA SEDS 2000-2017)

Maine's greatest expenditure is in petroleum products, for transportation and heating, and electricity, with nearly half of the Residential sector and 100% of the transportation sector expenditure used on petroleum products. Maine is the most petroleum-dependent state for home heating and has the highest per-capita petroleum consumption in New England, with approximately two-thirds of households reliant on fuel oil as the primary energy source for home heating. Only 10% of Maine households use electricity for home heating, despite the state having the lowest electricity prices in the New England region. (EIA Maine Energy Overview, 2019).

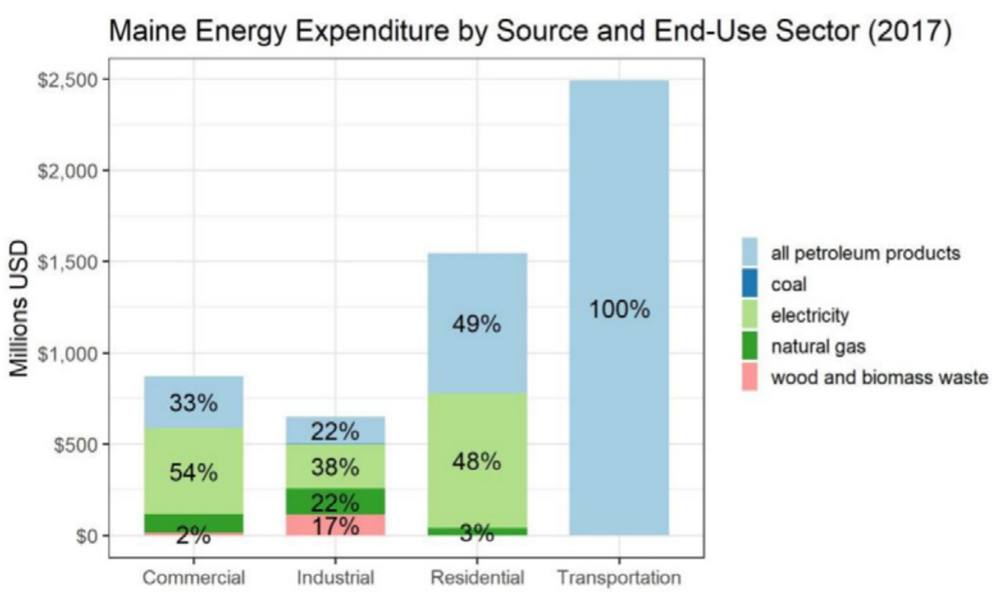

Figure 9: Maine Total Energy Expenditure by Source in 2017 USD (Source: EIA SEDS 2017)

Given its high per-capital energy use, Maine also has the highest energy expenditure per capita in New England (Figure 10).

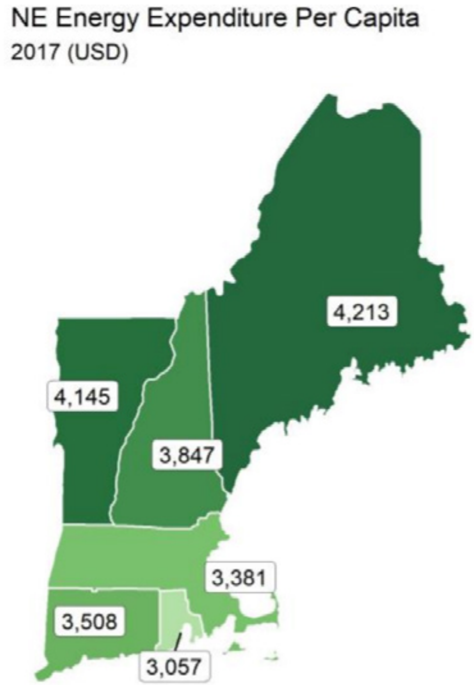

Figure 10: New England Total Energy Expenditure Per Capita in 2017

Maine's high per-capita expenditure can be largely explained by high energy consumption relative to the population size (Figure 10). Much of these high costs can be explained through comparable proportions to consumption (Figure 11).

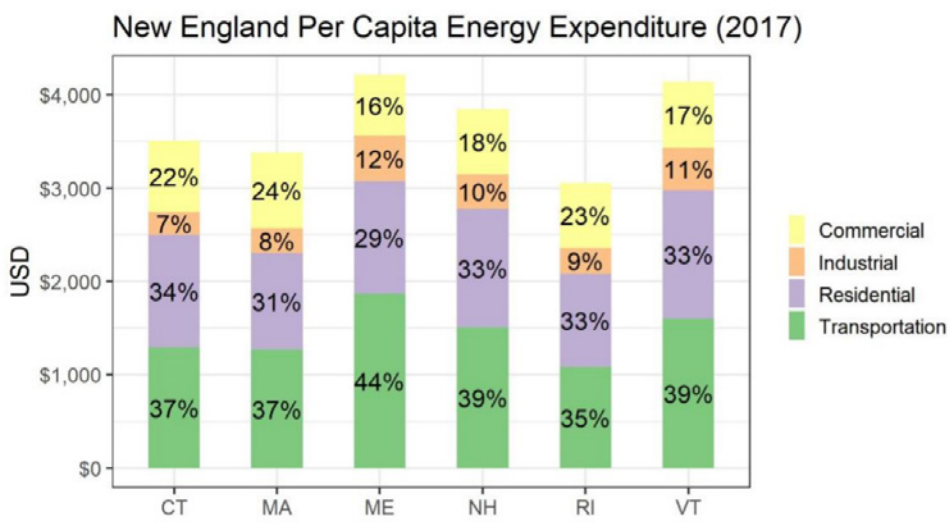

Figure 11: New England Per-Capita Total Expenditure per Sector in 2017 USD (Source EIA SEDS 2017)

Figure 11 shows the energy expenditure per-person in each state by sector. Transportation accounts for 44% of Maine's per capita expenditure, over 5% greater than the other states. This, again, is largely explained by the size of the state and its rural nature.

Conclusion:

The state of Maine is a regional leader in renewable energy production and highly ranked nationally in proportion of renewable energy consumed. Maine is 3rd in the nation for highest percentage of renewable energy consumption as a share of state total (Maine State Energy Profile 2019). However, 61% of all primary energy consumed in Maine in 2017 was from non-renewable sources, about half of which were petroleum products (Table 3). Because Maine does not have oil and natural gas reserves, it is reliant on oil and natural gas imports. This causes Maine to be subject to the volatility of national and world oil and natural gas prices. Striving towards developing the state's renewable energy resources, such as offshore wind and solar, may help alleviate some of that volatility and drive down expenditure costs.

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APPENDIX C

Maine Energy Overview: Consumption in New England by state, sector, and source (2017) – Billion BTUs.

SECTOR AND SOURCE	CT	MA	ME	NH	RI	VT
Commercial sector						
natural gas	54,014	112,741	9,247	9,356	11,684	6,391
coal	-	-	-	-	-	-
all petroleum products	14,828	19,235	17,585	11,732	3,493	6,173
wood and biomass waste	1,029	2,531	5,000	2,671	247	2,428
electricity sales	42,088	88,603	13,364	14,978	12,294	6,744
geothermal energy	-	807	-	-	-	-
hydroelectric power	-	36	-	-	-	-
solar thermal and photovoltaic energy	1,445	8,342	131	237	247	366
wind	-	193	-	-	66	-
total energy	188,139	401,606	65,554	70,080	44,591	24,642
Industrial sector						
natural gas	25,259	48,408	18,337	9,790	8,812	2,257
coal	-	103	465	-	-	-
all petroleum products	18,843	30,104	10,058	11,469	8,279	9,247
wood and biomass waste	4,262	7,456	48,694	4,016	134	396
electricity sales	11,067	23,404	9,070	6,674	2,476	4,857
hydroelectric power	-	54	3,353	-	-	-
solar thermal and photovoltaic energy	194	649	-	50	-	16
wind	-	15	-	-	-	-
total energy	79,275	154,862	103,705	45,858	23,037	18,603
Residential sector						
natural gas	49,815	124,802	2,847	7,556	18,983	3,614
all petroleum products	54,102	79,033	39,324	33,770	11,568	17,040
electricity sales	42,239	65,981	15,827	15,154	10,332	6,904
geothermal energy	21	52	72	29	57	29
solar thermal and photovoltaic energy	3,087	5,343	395	588	302	737
wood	5656	8386	17138	11275	1356	12400
total energy	229,922	409,530	99,557	99,843	56,517	43,325
Transportation sector						
natural gas	5,591	8,939	706	309	3,040	13
all petroleum products	221,786	445,760	122,481	101,404	56,466	48,210
electricity sales	604	1,188	-	-	94	-
total energy	229,054	458,156	123,187	101,713	59,726	48,223

SECTOR AND SOURCE	CT	MA	ME	NH	RI	VT
Electric power sector						
natural gas	111,655	167,889	13,989	26,738	52,231	13
coal	2,507	12,304	1,704	3,617	-	-
all petroleum products	1,626	2,877	1,703	866	453	87
wood and biomass waste	13,061	19,982	28,524	23,591	1,950	6,152
total energy	306,755	274,914	110,331	176,590	56,761	57,038
hydroelectric power	3,060	9,468	27,867	13,022	22	11,796
solar thermal and photovoltaic energy	360	7,197	50	-	130	910
wind	117	1,936	21,493	3,792	1,306	2,814
nuclear electric power	172,570	52,788	-	104,493	-	-
Total of all sectors						
natural gas	246,334	462,781	45,127	53,748	94,751	12,288
coal	2,507	12,407	2,168	3,617	-	-
all petroleum products	311,185	577,010	191,151	159,241	80,259	80,757
biomass	36,917	62,219	104,855	47,645	6,899	23,864
wood and biomass waste	24,008	38,355	99,357	41,553	3,687	21,376
electricity sales	95,998	179,175	38,261	36,806	25,196	18,506
geothermal energy	21	859	72	29	57	29
hydroelectric power	3,060	9,558	31,221	13,022	22	11,796
solar thermal and photovoltaic energy	5,086	21,532	577	875	679	2,029
wind	117	2,143	21,493	3,792	1,372	2,814
total energy	726,389	1,424,156	392,002	317,495	183,872	134,794

APPENDIX D

Maine Energy Overview: New England Expenditure by State, Sector, and Source (2017) – Million Dollars

SECTOR AND SOURCE	CT	MA	ME	NH	RI	VT
Commercial sector						
natural gas	488	1,112	101	106	128	44
all petroleum products	251	319	284	178	59	101
wood and biomass waste	4	7	13	8	1	9
electricity sales	1,981	4,138	475	650	548	289
total energy	2,725	5,576	873	943	736	443
Industrial sector						
natural gas	159	377	144	86	73	11
coal	-	1	2	-	-	-
all petroleum products	294	512	146	173	119	129
wood and biomass waste	2	4	112	2	0	1
electricity sales	425	952	245	241	106	145
total energy	880	1,846	649	503	298	286
Residential sector						
natural gas	676	1,614	40	107	258	50
all petroleum products	1,112	1,566	765	709	235	404
electricity sales	2,512	3,879	741	853	555	358
total energy	4,322	7,092	1,613	1,713	1,053	860
wood	22	33	67	44	5	48
Transportation sector						
natural gas	0	6	-	2	1	-
all petroleum products	4,590	8,665	2,491	2,032	1,137	1,000
electricity sales	19	22	-	-	5	-
total energy	4,610	8,693	2,491	2,034	1,143	1,000
Electric power sector						
natural gas	395	623	53	114	194	-
coal	11	53	7	16	-	-
all petroleum products	19	30	18	11	6	1
wood and biomass waste	29	44	63	92	4	14
nuclear electric power	123	40	-	75	-	-
Total of all sectors						
natural gas	1,718	3,732	338	415	654	104
coal	11	54	10	16	-	-
all petroleum products	6,265	11,092	3,703	3,105	1,557	1,636
wood and biomass waste	57	87	255	147	11	72
electricity sales	4,938	8,991	1,460	1,744	1,213	792
total energy	12,536	23,206	5,624	5,193	3,229	2,589

APPENDIX E

Maine Energy Overview: Energy Prices in New England by State, Source, and Sector (2017) - Dollars per million BTU

SECTOR AND SOURCE	CT	MA	ME	NH	RI	VT
Commercial sector						
all petroleum products	14.62	14.83	13.62	12.88	14.42	13.83
coal	0	0	0	0	0	0
natural gas	8.55	9.2	10.32	11.03	10.83	6.47
electricity sales	46.16	45.72	35.42	42.3	43.6	42.62
wood and biomass waste	5.73	3.17	3.37	4.26	5.73	5.41
total energy	23.97	24.55	19.06	23.61	26.16	20.02
Industrial sector						
all petroleum products	14.7	15.85	13.06	15.22	12.96	13.23
coal	0	5.24	5.21	0	0	0
natural gas	5.91	7.18	7.46	8.34	8.44	5.08
electricity sales	37.55	39.2	26.26	36.16	39.52	29.97
wood and biomass waste	3.24	2.29	2.96	1.13	1.59	2.72
total energy	15.36	17.45	8.38	17.17	14.45	17.27
Residential sector						
all petroleum products	17.95	17.91	17.17	19.66	18.18	20.96
coal	0	0	0	0	0	0
natural gas	12.56	12.09	13.42	13.83	13.39	13.82
electricity sales	58.65	55.69	46.38	53.87	54.56	50.9
total energy	27.98	24.84	22.04	26.24	25.14	23.02
Transportation sector						
all petroleum products	18.43	17.17	18.07	17.92	18.01	18.43
coal	0	0	0	0	0	0
natural gas	12.19	14.17	10.32	13.4	13.08	6.47
electricity sales	31.78	17.41	0	0	54.85	0
total energy	18.47	17.17	18.07	17.91	18.07	18.43
Electric power sector, fuel consumption						
all petroleum products	8.53	6.5	7.73	8.99	9.76	9.76
coal	4.07	4.07	4.07	4.07	0	0
natural gas	3.58	3.2	3.22	4.07	3.39	2.97
wood and biomass waste	2.32	2.32	2.32	3.98	2.32	2.32
Electric power sector, net generation						
nuclear electric power	0.71	0.67	0	0.71	0	0
Total of all sectors						
all petroleum products	17.91	17.06	17.19	17.68	17.34	17.98
coal	4.07	4.08	4.29	4.07	0	0
natural gas	6.54	7.52	6.42	6.9	6.94	8.38
electricity sales	50.54	48.3	37.51	45.88	47.71	42.39
wood and biomass waste	2.99	2.98	3.11	4.11	3.39	4.23
total energy	21.89	20.65	16.71	21.03	21.17	19.87

APPENDIX F

Energy Prices in New England by State, Source, and Sector (2017) - Dollars per million BTU

SECTOR AND SOURCE	CT	MA	ME	NH	RI	VT
Commercial sector						
all petroleum products	14.62	14.83	13.62	12.88	14.42	13.83
coal	0	0	0	0	0	0
natural gas	8.55	9.2	10.32	11.03	10.83	6.47
electricity sales	46.16	45.72	35.42	42.3	43.6	42.62
wood and biomass waste	5.73	3.17	3.37	4.26	5.73	5.41
total energy	23.97	24.55	19.06	23.61	26.16	20.02
Industrial sector						
all petroleum products	14.7	15.85	13.06	15.22	12.96	13.23
coal	0	5.24	5.21	0	0	0
natural gas	5.91	7.18	7.46	8.34	8.44	5.08
electricity sales	37.55	39.2	26.26	36.16	39.52	29.97
wood and biomass waste	3.24	2.29	2.96	1.13	1.59	2.72
total energy	15.36	17.45	8.38	17.17	14.45	17.27
Residential sector						
all petroleum products	17.95	17.91	17.17	19.66	18.18	20.96
coal	0	0	0	0	0	0
natural gas	12.56	12.09	13.42	13.83	13.39	13.82
electricity sales	58.65	55.69	46.38	53.87	54.56	50.9
total energy	27.98	24.84	22.04	26.24	25.14	23.02
Transportation sector						
all petroleum products	18.43	17.17	18.07	17.92	18.01	18.43
coal	0	0	0	0	0	0
natural gas	12.19	14.17	10.32	13.4	13.08	6.47
electricity sales	31.78	17.41	0	0	54.85	0
total energy	18.47	17.17	18.07	17.91	18.07	18.43
Electric power sector, fuel consumption						
all petroleum products	8.53	6.5	7.73	8.99	9.76	9.76
coal	4.07	4.07	4.07	4.07	0	0
natural gas	3.58	3.2	3.22	4.07	3.39	2.97
wood and biomass waste	2.32	2.32	2.32	3.98	2.32	2.32
Electric power sector, net generation						
nuclear electric power	0.71	0.67	0	0.71	0	0
Total of all sectors						
all petroleum products	17.91	17.06	17.19	17.68	17.34	17.98
coal	4.07	4.08	4.29	4.07	0	0
natural gas	6.54	7.52	6.42	6.9	6.94	8.38
electricity sales	50.54	48.3	37.51	45.88	47.71	42.39
wood and biomass waste	2.99	2.98	3.11	4.11	3.39	4.23
total energy	21.89	20.65	16.71	21.03	21.17	19.87

PRIORITY INFORMATION NEEDS

HIGHLIGHTS OF PRIORITY INFORMATION NEEDS

During the deliberations of the Scientific and Technical Subcommittee (STS), numerous information needs emerged and many have been captured in Appendix A. The STS did not deliberate on these comprehensively in the time-frame of our work in late 2019 and 2020, with our highest priority being the assessment of climate change evidence in Maine, the effects of these changes, and what we expect in the future. We did not focus on solutions, but rather on providing the science in support of the Working Groups charged with recommending solutions. Here we present the most critical aggregate research/monitoring needs based on the information in Appendix A. These information needs are not intended to encompass the scope of work of the Maine Climate Council Working Groups which are identifying their own priority information needs, although there will be overlap. Unless otherwise noted, all needs identified are about conditions *in* Maine or *for* Maine.

Why do we need this information? First, we need high quality data to support science-informed decision-making. This takes the form of filling gaps in data where we have little or none (e.g., ocean acidification, air-borne pollen), increasing the density of data to improve our understanding of variability and uncertainty, improving the scale of available data in support of local decision-making, or data to encompass emerging conditions requiring new measurements (e.g., invasive species, disease). Second, we need research to continuously advance our understanding of the problems in ways that allow us to develop better solutions. These kinds of information needs include understanding the changing ecology of a rapidly warming Gulf of Maine, understanding carbon cycling in Maine as a framework for greenhouse gas goals, and developing new technologies to improve adaptation and mitigation options. There are also certain themes for information needs to assure that our response to climate change is effective. These include benefit/cost analyses to assure that climate actions are successful investments in Maine's future. Life-cycle analyses will assure that our actions are effective and do not merely displace greenhouse gas sources to other places or result in unintended consequences. We need research on social equity to assure Maine develops a climate response that minimizes social injustices. In addition, as we do this work in 2020, it is clear that the COVID-19 pandemic has exposed some of the same strengths and weaknesses that apply to our climate response, and we must learn from this experience.

BASIC AND APPLIED RESEARCH PRIORITIES

A. Cross-cutting Priorities

- Continued analysis of historical and predicted extreme weather events and impacts for Maine. Determine alternative future pathways for climate conditions.
- Determine the vulnerability of Maine species and habitats and identify priority areas for conservation, especially climate refugia.
- Conduct comprehensive product Life-Cycle Analyses to determine the carbon footprint, mitigation potential, and social and economic viability of renewable energy strategies for:
    - » Important marine fisheries and aquaculture,
    - » Forest practices and bioproducts,

    - Agricultural and food systems.

    - Conduct a comprehensive Maine carbon cycle analysis (pools, sources, rates, and sinks) to include communities, coastal ecosystems, forestlands, farmlands, and wetlands (inclusive of green and blue carbon, soil carbon, and uncertainty analyses).

    - Benefit/cost assessments of climate mitigation and adaptation strategies for all sectors of the economy including impacts on equity.

B. Targeted Priorities

- Improve riverine flood maps and predictions.

- Determine climate change impacts on marine coastal flooding, including:

    - Impacts of the intensification of precipitation,

    - Impacts of storm tracks, sea-level rise, storm surge, and wave height on coastal erosion and flooding.

- Study the response of foundational (e.g. kelp, *Calanus finmarchicus*, alewife) and economically important (e.g. lobster, scallops) species to multiple stressors (e.g., temperature, ocean acidification, pH, oxygen) and their adaptive capacity to determine the relative importance of each.

- Enhance research on the development of traditional and new products from Maine forests including nanocellulosics, cross-laminated timber (CLT), and biofuels that contribute to Maine's mitigation objectives.

- Assess Maine's vulnerabilities (e.g., on-farm, supply chain) for agricultural operations and food systems, vulnerability to disruptions, food waste and food insecurity.

MONITORING PRIORITIES

- Enhanced snowpack monitoring, air quality monitoring (increased density of pollen monitoring stations), water- and food-borne disease monitoring, and continued disease vector surveillance.

- Improved freshwater and marine water quality monitoring including riverine water quality and surface water Harmful Algal Blooms (HABS).

- Continue, improve and expand measurements on marine conditions including the NERACOOS/University of Maine mooring array, monitoring sea level rise and nuisance flooding, and developing enhanced warning systems along the Maine coast.

- Continue and improve beach and bluff change monitoring and analysis due to storms and sea level rise. Expand from coastal beaches (2% of Maine's shoreline) to include unconsolidated bluff shorelines (40% of Maine's shoreline) using remote sensing and field stations.

- Establish a robust, long-term program of monitoring for temperature, oxygen and ocean acidification including the infrastructure to utilize the data in the development of management support tools and models of change out to 2050.

- Evaluate current, and identify critical improvements needed, in long-term ecological monitoring of Maine's coastal ecosystems, forestlands, farmlands, freshwater ecosystems and wetlands to support sector-based and comprehensive mitigation and adaptation strategies. This includes identification/utilization of ecosystem 'health' indicators to achieve goals that rely on traditional empirical and remote sensing methodologies.

- Comprehensive monitoring of food waste incidents in Maine.

- Consistent economic data collection to evaluate changes in consumer and producer behavior, including monitoring changes in key industries and sectors in other states and nationally.

Appendix A - Table of STS Priority Information Needs

This appendix represents a collection of information needs identified by STS during the process of developing the chapters of this report. The information here reflects the organization of this document and the composition of the STS. This is not the product of a comprehensive assessment of information needs on climate change that would require a separate process unto itself. This also was not an attempt to encompass information needs that may be identified in the documentation developed by the various Working Groups of the Maine Climate Council.

Subject		Name	Priority	Description
Climate and Drought		**BASIC AND APPLIED RESEARCH**		
	1.	Analysis of historical and future-predicted extreme weather events and associated impacts	High	Heat waves, cold waves, and intense storms with heavy rain, snow, ice, or high wind can impact Maine's civil infrastructure, economy, and environment. Robust identification of extreme events, impacts, and trends over the past several decades can help inform future projections and lend to insights and better preparedness for the future.
	2.	Historical drought characterization	Medium	Research the historical 1) frequency, geographic variation and persistence characteristics of drought, including seasonality and return period; 2) linkages between meteorological drought (deficient precipitation) and both soil moisture and hydrology (low stream flow and groundwater levels); and 3) relationship between statewide drought indicators and local drought conditions.
	3.	Examining drought in a warming world	Medium	Explore how 1) a warming climate will influence the character of drought in Maine (e.g., increasing atmospheric demand for water reduces the effective precipitation which affects soil moisture); and 2) increasing precipitation may not directly translate to improved soil moisture or groundwater if there is greater runoff associated with heavier rainfall events.
		MONITORING		
	1.	Improved real-time drought information	High	Includes gathering existing data and conducting new monitoring for precipitation, streamflow, groundwater, soil moisture, snowpack/snow water equivalent, and temperature.
	3.	Expand winter lake monitoring to include ice-on	Medium	The duration of ice cover on Maine lakes has important climatological, ecological, recreational, and economic implications. While the Bureau of Parks and Lands currently monitors ice-out dates for an array of lakes across the state, there is not yet a concerted effort to monitor ice-on. An expanded monitoring program that documents both ice-on and ice-off dates in perpetuity would help to better characterize broader changes in Maine's winter climate.
Hydrology		**BASIC AND APPLIED RESEARCH**		
	1.	Riverine flood maps	High	Develop flood inundation maps for areas of recurring riverine flooding in order to develop mitigation actions. We need to better understand the current flooding problem before we can consider the impact of climate change on flooding in these locations.
	2.	Watershed models for winter/spring flooding	Medium	Build targeted watershed models to better understand and manage water contributed to winter and spring floods by snowmelt runoff. This includes installing multiple monitors in each basin for precipitation and snowpack.
	3.	Impact of changing summer precipitation on low streamflows	Medium	Initiate studies to understand the impact of summer precipitation on summer/fall low flows, both historical and projected.
		MONITORING		
	1.	Riverine water quality monitoring network	High	Establish long-term riverine monitoring stations for climate-relevant water quality variables, especially temperature.
	2.	Full-season snowpack monitoring	High	Expand statewide snowpack monitoring network for better temporal and spatial coverage in order to better predict current and future snowmelt runoff.
	3.	Streamflow on headwater streams	Medium	Expand riverine streamgaging network to include streamflow monitoring on more small headwater streams to better understand potential loss of habitat for macroinvertebrates and other biota. Baseline data is needed to understand changes related to climate change.
Freshwater: Quality		**BASIC AND APPLIED RESEARCH**		
	1.	Accurate spatial characterization of intense storms across state	High	Intense, localized storms result in stream crossing washouts and other highly erosive events. Proper crossing resizing and stabilization is critical to prevent washouts and silt/nutrient delivery to rivers, streams, lakes & wetlands, which impairs water quality, fuels algal growth, and increases the risk of Harmful Algal Blooms (HABs).
	2.	Evaluate effectiveness of statewide standards (Shoreline Zoning, NRPA, Site Location of Development, others) for protecting freshwater resources from erosion related to stormwater runoff	High	Erosion results in silt & nutrient delivery to rivers, streams, lakes and wetlands. Most of the current development standards originated 30-45 years ago under much different climate conditions and likely need to be adjusted to current conditions to protect water quality in freshwater and downstream marine waters.
	3.	Ecosystem modeling of freshwater species' ranges and temperature tolerances, and, eDNA characterization of current species assemblages	Medium	Species shifts are expected as a result of warming temperatures. Knowing which species are where, as well as their temperature tolerances will allow accurate modeling to predict changes in the geographic range of species and prioritize regional waters for protection.
		MONITORING		
	1.	Establish permanent monitoring stations on a range (size, depth, relief) of each water type, across the entire state	High	A few permanent monitoring stations exist in a few water types, but the parameters measured are limited. A more extensive network, with coordinated data acquistion will allow for a better understanding of long-term changes in our freshwater resources.
	2.	Expand agency and citizen monitoring of rivers, streams, lakes and wetlands	High	Current agency and citizen monitoring needs to be expanded to allow for a more comprehensive understanding of changes in water quality in Maine. Citizen scientists provide an effective front-line means of tracking changes in our freshwater systems. Programs designed specifically for citizens, specific to each water type using low-cost measures and sensors, have the potential to provide critical information to researchers.
	3.	Implement regular use of satellite imagery and aerial imagery to evaluate siltation events following intense storms	Low	Remote monitoring will provide insight into damage done to Maine waterways as a result of intense storms. Knowing where issues arise will help locate sites requiring stabilization to prevent future erosion events.
Freshwater: HABs		**BASIC AND APPLIED RESEARCH**		
	1.	Improved evaluations of lakes, rivers and streams to determine sensitivity to HABs	Medium	Identify parameters and characteristics of waterbodies that make them susceptible to HABs including nutrient concentrations, pelagic and benthic algal flora, sediment geochemisty and redox potential in lakes and wetlands, and, flow characteristics in rivers and streams.
	2.	Improved methods to evaluate algal toxin concentrations (microcystin, anatoxin, cylindrospermopsin, others)	High	Current technology is limited to lab-based ELISA techniques and multistep rapid ELISA tests. Simple, inexpensive, rapid tests are needed so that real-time conditions can be evaluated. Evaluate the effectiveness of passive samplers such as Solid Phase Adsorption Toxin Tracking (SPATT) devices, as well as the usefulness of eDNA/qPCR testing for determining if an algal population has the genetic capacity to produce toxins, is needed.
	3.	Evaluation of algal toxin movement through freshwater food chain	Medium	Research of this nature has only recently begun, for the most part outside of Maine. Determination of algal toxin concentrations in fish tissue will provide insight into consumption risk to humans and wildlife.
		MONITORING		
	1.	Expand capacity to characterize toxin (microtoxin, anatoxin) concentrations IN and effects FROM HABs	High	Maine needs to invest in technology to efficiently and effectively determine toxin levels in water, algal biomass, humans and pets. Standard reporting of human illness suspected to be related to ingestion of an algal toxin needs to be implemented. A free mail-in blood sample testing program for pets suspected of dying from toxin ingestion is also needed.
	2.	Expand monitoring of freshwaters for algal toxins	HIgh	Algal toxin concentrations should be evaluated at a regular frequency whenever pelagic bloom conditions or benthic mats of species are observed in Maine freshwaters. Results will allow identification of sites where algal toxins occur annually to better inform the public regarding risk.
	3.	Adopt Federal criteria or establish Maine criteria so public can evaluate risk	High	Presently Maine is applying Federal criteria to evaluate microcystin results. These criteria could be adopted by Maine or modified to reflect regional considerations. Swimming and drinking water risk communication through an advisory process will become more important as HABs increase.
Marine - SST		**BASIC AND APPLIED RESEARCH**		
	1.	Interaction between changes in precipitaton (timing, intensity, type) and ocean conditions	High	Climate projections for the Gulf of Maine have focused on surface heat flux and offshore forcing. This is adequate for understanding long-term changes, especially at the Gulf of Maine scale. Along Maine's coast, these drivers will interact with changes in precipitation to determine the temperature, salinity, water chemistry, and circulation.
		MONITORING		
	1.	Maintain NERACOOS/UMaine mooring array and expand inshore	High	The NERACOOS buoys operated by the University of Maine are a unique asset. The 20 year time series provides a valuable record of change that can now be used to develop forecast products for Maine's marine resources. There is also an opportunity to use newer, cheaper sensors to increase ocean monitoring along the coast. Expanded monitoring would help with the detection of unusual conditions and would support predictions that could help with short-term decisions and long-range planning.
		BASIC AND APPLIED RESEARCH		
	1.	Storm Tracks vs. Wave Height, Duration, Energy, Surge Level that Cause Coastal Erosion and Flooding	High	Storm track, intensity, forward speed all affect winds, waves, ocean circulation, and beach loss. Quantify met-ocean characteristics from 1980s-present and relate to coastal erosion and flooding. Model future changes in jet stream, tracks, intensity, wind field, and estimate revised meteorological-ocean impacts to beaches and flooding.
	2.	Model Erosion with Higher Sea Level & Stronger Storms	High	Develop dynamic geological models for inundation and subsequent beach and bluff erosion, sediment fluxes, and erosion rates at higher sea levels. Resolve sediment fate in intertidal environments such as mud flats, salt marshes, and beaches.

Marine - SLR	3.	Living Shoreline Designs for Rising Sea Level	Medium	Design transferable green and gray-green engineering plans to compliment traditional shoreline stabilization that can be modified or removed in a future of higher tides and flooding while minimizing environmental degradation. Build off of Living Shorelines in New England: State of the Practice developed by a working group from ME, NH, MA, RI, CT.
		MONITORING		
	1.	Ocean Level Monitoring, Trends, and Statistics	High	MGS continues to quantify sea level trends in Maine tide gauges at monthly and annual intervals set in a historical context and rank; recalculate rates and acceleration of sea level rise. MGS computes surge statistics, recurrence intervals, and temporal trends and duration of surges over time at Maine tide gauges. Compare and contrast trends along the coast. MGS and NWS collaborate to quantify nuisance flooding, locations, durations, and trends. Improve predictions to issue geographic warning areas along the coast. Create a database for frequency and damage analysis.
	2.	Establish a NOAA Tide/Meteorological Gauge in Penobscot Bay	High	Spatial coverage of tide gauges (Wells, Portland, Bar Harbor, Cutler, and Eastport) is good along the Maine coast, but there is a significant gap in Penobscot Bay. Reestablish and continue data collection at the Rockland NOAA CO-OPS tide gauge and meteorological station 8415490. NOAA should recalculate the National Tidal Datum Epoch for all Maine stations by 2021.
	3.	Beach and Bluff Change Due to Storms & Sea Level Rise	High	Continue monitoring coastal beaches (2% of Maine's shoreline) through MGS-led Maine Beach Monitoring Program by moving to state funding instead of NOAA CZM. Continue the Southern Maine Beach Profiling Program in partnership with Maine Sea Grant. Expand monitoring statewide to include unconsolidated bluff shorelines (40% of Maine's shoreline) using remote sensing and field stations.
Marine - OA		**BASIC AND APPLIED RESEARCH**		
	1.	Understand species response	High	Understand the response of critical marine species under multi-stressor (low pH, high temperature, low oxygen, limited food availability) and variable conditions (to more accurately reflect nature) and assess adaptive capacity to OCA through multi- generational studies to inform ecosystem management. Through this research, determine the relative importance of OA in comparison to other stressors.
	2.	Develop climate tolerant strains of commercially important species	Medium	Understand the natural variability in tolerance for key species. Encourage the development of research hatcheries for rearing of more species and selective breeding for climate change tolerant strains.
	3.	Continue remediation research	Medium	Build off of active research programs investigating potential applications of phytoremediation and buffering.
		MONITORING		
	1.	Establish a robust, long-term, coastal monitoring program	High	Establish a robust, long-term, spatially diverse, coastal monitoring program across many ecosystems that coordinates and supplements existing efforts. This will require reliable instrumentation and protocols, long-term funding, a data repository and management system, and the capacity to maintain and operate instrumentation and conduct meaningful data analysis. These data are essential to parameterization of models. Continue to train and expand the capacity of the citizen scientist network.
	2.	Develop a regional scale water quality model	High	A regional scale physio-chemical model will feed into a finer scale, state level water quality model and use monitoring to validate the models. We currently lack good predictive or diagnostic models for end users. These are needed for planning at different temporal scales- from diurnal shifts out to 2050 or beyond. These models should be accessible and usable by resource managers, wild caught, and aquaculture based fisheries.
	3.	Determine blue carbon potential of Maine coast	High	First, understand the specific species response to ocean and coastal acidification and other climate stressors (e.g. will these species be able to provide the same services in a warming ocean?), Estimate biomass of salt marsh, sea grass, eel grass, and intertidal and subtidal seaweeds in order to get a sense of blue carbon potential of the Maine Coast (funding needed for LD559- low altitude imagery used to map segments of coast for eel grass and potentially other species).
Marine - Ecosystems		**BASIC AND APPLIED RESEARCH**		
	1	Characterize food web structure, dynamics, and underlying processes for coast and Gulf of Maine	High	Understand how multistressors (low pH, high temperature, low oxygen, changing salinity, extreme precipitation) impact species interactions and distributions, population demographic rates, intra- and inter-specific diversity, community composition, and ecosystem services through experiments (e.g., common garden). Assess adaptive capacity via functional redundancy to inform ecosystem management.
	2.	Develop climate tolerant strains of commercially important marine species	Med	Understand the natural variability in tolerance for key species. Encourage the development of research hatcheries for rearing more species including multi-generational experiments and selective breeding for climate change tolerant strains.
	3.	Identify potential invasive and/or lucrative species that migrate polewards from the south	Med	Understand the natural variability in tolerance for key species. Use monitoring and citizen science programs to collect data that will lead to new commercial species or controlling outbreaks of invasive marine species
	4.	Focus habitat restoration and conservation efforts where climate 'refugia' (places that are changing at a slower pace either via ecosystem service feedbacks or due to unique geography/bathymetry) are located	High	Build off of active research programs investigating potential applications of phytoremediation and buffering as well as monitoring and surveillance efforts
	5.	Develop life cycle assessment for commercial marine species	High	Inventory cradle-to-grave CO_2eq for hatcheries, nurseries, aquaculture farm maintenance, wild-harvest, processing, packaging, and distribution of marine species balanced with carbon or nitrogen capture and GHG mitigation capacity and identify where renewable energy strategies are socially and economically viable
		MONITORING		
	1.	Establish robust, long-term, coastal biological monitoring programs	High	Establish robust, long-term, spatially diverse, coastal monitoring programs across many ecosystems that coordinates and supplements existing efforts and uses novel tools. This will require reliable protocols, long-term funding, a data and voucher sample and image repository and management system, and the capacity to conduct meaningful sample and data archiving and analysis. These data are essential to parameterization of models. Continue to train and expand the capacity of citizen scientist networks.
	2.	Develop a regional scale model for biology (e.g., food web EcoPath, HABs population) informed by a water quality model (e.g., physico-chemical)	High	Regional scale models will feed into a finer scale, state level biological models and use monitoring to validate the models. We currently lack good predictive or diagnostic models for end users. These are needed for planning at different temporal scales- from diurnal shifts out to 2050 or beyond.
	3.	Determine blue carbon potential of Maine coast and develop monitoring plan in alignment with verification processes for voluntary carbon (and/or nitrogen) markets	High	First, understand the specific species response to ocean and coastal acidification and other climate stressors (e.g. will these species be able to provide the same services in a warming ocean?), Estimate biomass of salt marsh, sea grass, eel grass, rockweed, and kelp in order to get a sense of blue carbon potential of the Maine Coast (funding needed for LD559- low altitude imagery used to map segments of coast for eel grass and potentially other species)
	4.	Report changes in carbon footprint per marine commodity		Verify which adaptation strategies and/or changes to business structure (e.g., vertical integration, up-scaling) have disproportionate impacts on GHG emissions or reductions
Biodiversity		**BASIC AND APPLIED RESEARCH**		
	1.	Determine amounts and configurations of existing conserved lands, connectors, and the extent of additional lands needed to protect existing and future species distributions; conservation in this context is broad and includes lands conserved by fee or easement as well managed and working lands that also support biodiversity	2	Models exist (e.g., Beginning with Habitat, Nature's Network, etc.) but these are built on current conditions rather than future and do not fully account for connections among conserved areas
	2.	Determine effects of climate change on vulnerable species and habitats	1	We have a lot of predictive information on this topic but limited research documenting changes and impacts. We need better information across species and habitats including vernal pools, moose, Canada lynx, pollinators, etc. and across seasons (e.g. changing winters and impacts to snowpack, temperature extremes in summer and stress on pollinators, etc.) to more fully understand and prepare for coming change and what that means for ecological systems and human interactions with fish and wildlife.
	3.	Downscale currently available regional climate refugia and habitat connectivity models to scales useful for local planning and decision making	3	Models exist (e.g., The Nature Conservancy's Resilient and Connected Landscapes), but these are often at scales that are not locally adaptable
	4.	Conduct long-term population studies on insects to determine if they are declining at similar rates to other parts of the world	4	There is very little long-term data on insect population trends in Maine, and because they are the base of many food chains, we need to have better information regarding both aquatic and terrestrial systems, and how a warming climate may be affecting them.
		Conduct research on differences in species composition and interactions in reserved areas and mature forests versus nonreserved and younger forests	5	Need to determine the role each of these forest scenarios play in securing biodiversity into the future, and if we need to rebalance the percentage of each across the landscape.
		MONITORING		
	1.	Monitor distribution, abundance, and health of climate vulnerable species, habitats, and food web dynamics	1	This applies across all taxonomic groups including birds, insects, mammals, amphibians, plants, etc.
	2.	Continue and expand monitoring of compounding stressors on climate vulnerable habitats	2	Examples include stream temperature monitoring, water quality, stream biodiversity, invasive species monitoring, etc.
	3.	Monitor the success of conserving and connecting habitats in facilitating species shifts and survival	3	It is crucial to determine if our conservation recommendations are actually effective
		BASIC AND APPLIED RESEARCH		
	1.	Full environmantal life cycle analysis for Maine forest and forestry products, emphasizing carbon and greenhouse gas impacts.	High	Efforts to support "natural climate solutions" need to be validated to determine the likely success in reducing greenhouse gas concentrations in the atmosphere. This is particularly important for issues such as additionality, leakage, and socioeconomic effects.
	2.	Improved forest management alternatives, updated BMPs, and research on the human element in forest adaptation	High	Research is needed to accommodate the changing climate and the impacts of forest management in a future with a changing forest. Assuming what worked well in in the last century will suffice in the future may often be inadequate.

Forestry	3.	Bioproducts development (e.g., nano, CLT, biofuels)	High	A high priority for Maine is the development of durable products that will benefit society, drive the Maine economy, and sequester carbon for long periods of time. Maine has abundant raw materials and the research capabilities to advance in this area.
		MONITORING		
	1.	Improved monitoring of forest health indicators, including empirical and remote sensing technologies, with an emphasis on ecosystem carbon.	High	Monitoring forest condition is essential to determine the role of Maine forests in the carbon cycle, and evaluate changing forest conditions and the impacts of our management on them. This includes improved empirical measures of forest condition that can document change and validation of advanced uses of remote sensing and real-time assessments of Maine forests.
	2	Better mapping of tree species distributions and change detection	Medium	Improved information on species distributions will be important in understanding the impacts of a changing climate combined with management on Maine's future forests.
Agriculture		**BASIC AND APPLIED RESEARCH**		
	1.	A review of the climate-related agronomic, horticultural, and verterinary production and market vulnerabilities and opportunities for Maine's primary agricultural products and production systems.	High	Maine agricultural products vary in their vulnerability to climate-induced changes on production and sale. And within a single commodity, scale and producer preferences will also affect those vulnerabilities. State agencies and higher education institutions, and especially UMaine as the Land Grant university, should cooperate to collect this information into a comprehensive yet digestible summary format suitable for use by the ag industry and policy makers. Understanding the opportunities and liabilities that come with realistic expectations for future climatic and weather conditions will be essential to identify and promote strategies to optimize adaptation and emission mitigation responses to those conditions. A comprehensive review of California's ag production with respect to what geographic shift would be required to relocate production to accomodate a changed climate provides a different but related approach. (See https://tinyurl.com/CA-AgShift). A parallel study could examine what out-of-state production would be well suited for future conditions in Maine, as conditions in their current production areas becomes less suitable.
	2.	Quantify sources for nitrous oxide emissions in Maine.	High	"The highest source of GHG emissions [in the Northeastern U.S.] is N2O from croplands" Tobin et al. 2015. Source specific amounts of N_2O emissions are needed to identify need for, and if needed strategies to achieve, N_2O emissions from Maine agriculutral sources.
	3.	Technical, economic, and policy infromation on the feasability of small scale anaerobic digesters for small scale dairy farms.	High	Anaerobic digesters to process dairy manure have been shown to provide a source of on-farm energy generation, reduce manure storage and handling costs, and reduce GHG emissions for large scale operations. Ongoing development may make them feasible for Maine dairies. Economic and technical information is needed to determine if anaerobic digesters are a viable option for the majority of Maine dairy farms which have smaller herds than the current break even point for anaerobic digesters. If feasible, then policy and programs to assist their adoption would be needed.
	4.	Economic analysis on technical support opportunities to reduce Maine agricultural GHG emissions.	Medium	Basic information on potentially useful tools such as manure presses to separate solids from liquids, better refrigeration options, and farm tool electrification is needed to support policy development towards these and other methods for GHG emission reduction.
	5.	Environmental effects and economic feasibility of biochar additions to Maine ag soils for carbon sequestration.	Medium-High	Information is needed about the energy and other costs, GHG emissions, feedstock supply, effects on soil carbon level, pH, and other soil property changes associated with the production and application of biochar made from Maine agricultural sources or for addition to Maine ag soils. Critical information needs exist to identify the crops with the highest potential to benefit from biochar amendments, and the market and cultural unknowns that currently hold back further development.
	6.	Production and economic informaton on the potential role of bioenenergy crops to reduce Maine GHG emissions.	Low	Bioenergy crops could be a new revenue stream for Maine agriculture, and could potentially contribute to GHG emissions reduction goals. But policies to incentivize this sector could have negative effects on other agricultural, social and environmental objectives. A basic understanding of bioenergy crop input and outputs is needed to evaluate these interactions.
Food Systems		**BASIC AND APPLIED RESEARCH**		
	1.	Measuring the the GHG contributions associated with Maine food choices.	Medium	Maine-specific data on possible state/national/internatonal policies and market-forces away from animal protein and towards plant protein-based diets would provide state-level policy makers information to understand and influence the economic, health and other impacts of those factors on
	2.	Food system network mapping.	Medium	The virus pandemic has made clear that operation of the Maine food system as an interconnected network is critically important to the well-being of Maine citizens. Understanding the food system has implications for being able to identify key inflexion points to optimize its GHG emissions. Current Maine policies may result in food system practices that unintentionally and unnecessarily increase GHG emissions. Identifying opportunities for food system optimization with respect to GHG emissions requires understanding the underlying physical, economic, and social infrastructure and functions of that system.
	3.	Identify food system operator priorities to build resilience to climate related challenges.	High	This is is similar to identifying vulnerabilities and opporutnities for food producers listed above for Agriculture, but in this case the target population is food system managers. They have unique insight into the how the Maine food system operates, and on how to improve its efficiency and resilience in response to climate change challenges. This is especially true with regard to state policies that directly and indirectly affect the food system.
	4.	Food insecurity mapping.	HIgh	MCC recommendations could create downstream effects on food pricing and availability and thus on food insecurity. A basic understanding of the food system with regards to how its functions relate to food insecurity is required in order to predict how policy recommendations may affect food insecurity. For example, to understand the effect of GHG emission policies on food pricing and food access for low income citizens requires knowledge about the scope and factors affecting food insecurity.
		MONITORING		
	1.	A monitoring system for large scale food waste incidents.	HIgh	A reporting system to track large food waste incidents would be a first step at directing those streams to better end uses than GHG-generating landfills. Identifying where, when and how large food waste discard events occur might make it possible to develop a rapid response system to capture those discards as an asset for other end uses. For example, a centralized depository could be established from which hog farmers, compost manufacturers, anaerobic digester operators etc. could retrieve discarded food. Other states may have relevant prototype models. National data indicate that food waste is a significant source of methane production. Reducing food waste can contribute to food security, agricultural viability and local production, and GHG emission goals.
Human Health		**BASIC AND APPLIED RESEARCH**		
	1	Enhanced projections for extreme weather that impacts human health	High	1) extreme heat in Maine, and in specific, the number of days projected to exceed a daily maximum heat index of 95°F (35°C), for all major population centers; 2) extreme cold days; 3) winter storm frequency, 4) windstorm frequency
	2	Vulnerability to weather extremes - physical health	High	Quantify the impact of prolonged heat events (>1 day) on all-cause and cause-specific emergency department visits and deaths in Maine; identify locations such as schools and long-term care facilities without air conditioning around the state; identify Mainers who may be vulnerable to extreme heat; quantify broader short- and long-term health effects of power outages, aside from carbon monoxide poisoning and foodborne illness.
	3	Vulnerability to weather extremes - mental health	High	Quantify threats to mental health from exposure to other climate change impacts besides storms, floods, droughts, and extreme heat; delineate best practices for supporting population mental health during and after extreme events. [Note: the onset of COVID-19 has dramatically increased the potential compounding effects of climate on mental health.]
	4	Harmful algal blooms (HABs)	Medium-High	See above section Freshwater: HABs
	5	Tick- and mosquito-borne disease research	Medium	Research in tick and mosquito ecology and molecular biology to understand how pathogens are amplified based on weather, habitat, and host conditions; also pestcide resistance
		MONITORING		
	1	Air Quality: Aeroallergens including pollen	High	1.a) establish a minimum of four pollen monitoring stations around the state: the MicMac Lab in Presque Isle, UMaine in Orono, UMF in Farmington, and USM in Portland or Gorham (or other college campuses) as the three additional monitoring sites (plus MEHD); b) use the best and most efficient technology available; 2. Centralize pollen identification by shipping samples to one lab. For example establish the Climate Change Institute at UMaine as the central processing laboratory for pollen collections (alternatively, ship samples to a central processing lab in the US if and when one becomes available); 3. Make data readily available to various reporting and forecasting entities. This is already being done in New York (Anderson et al. 2013). 4. Fund monitoring and correlate emergency department visits and hospitalizations with timing, amount, and species of pollen, and include interactions with temperature and air quality.
	2	Air quality: Ozone and particulate matter	Medium	Continued monitoring by Maine DEP, Micmac Environmental Health Department (MEHD), and the Passamaquoddy Tribe in Sipayik, Pleasant Point; surface monitoring stations should be in every county. Could be enhanced via satellite monitoring.
	3	Water- and food-borne disease outbreaks	Medium	Improved surveillance is needed for water-borne and food-borne disease outbreaks, including gathering more complete information on consumption of well water, shellfish, and other exposure pathways
	4	Harmful algal blooms (HABs)	Medium-High	See above section Freshwater: HABs
	5	Tick-borne disease surveillance	High	Current active and passive tick surveillance and tick testing in Maine is supported (in part) by CDC funding through the Maine CDC. Funding should be at least maintained, but ideally expanded.
	6	Mosquito-borne disease surveillance	Medium	Continued and expanded surveillance including mosquito, wildlife, and veterinary testing to detect hotspots of arboviral activity prior to outbreaks.
		BASIC AND APPLIED RESEARCH		
	1.	Climate mitigation cost and cost effectiveness	High	Mitigation costs for all sectors based on Maine-specific data (ideally) or via approximation from national data are necessary to identify the lowest cost methods to reduce GHG emissions in Maine. This is not a one time assessment, but on-going as technology and human behavior and settlement patterns change.
	1a	Equity Impact assessment of MITIGATION actions	High	Impact assessment of mitigation actions on different socio-economic sectors including: income, age, race and geographic location as well as on specific sectors of the economy including fishing, forestry, tourism and others should be identified, monitored and reported.

Economy	1b	Equity Impact assessment of ADAPTATION actions	Medium	Impact assessment of adaptation actions on different socio-economic sectors including: income, age, race and geographic location as well as on specific sectors of the economy including fishing, forestry, tourism and others should be identified, monitored and reported.
	2.	Identification of ancillary benefits	Medium	Implementaion of mitigation and adaptation strategies should identify and prioritorize actions that maximize ancillary benefits.
	3	Policy design for efficiency	Medium-High	Policy instruments should be evaluated for efficiency, cost effectiveness (e.g., $/ton) and include the full suite of options including: traditional prescriptiveregulation, technology or design standards, performance stands, market oriented approaches (tradable credits, emission fees, environmental subsidies, and tax-subsidy combinations (e.g., feebates)). Information tools (consumer education), information disclosures and volunatry mechanisms. Abundant research demonstrates that policy design can greatly affect the cost effectiveness of implementing mitigation actions.
		MONITORING		
	1.	Socio-economic data collection for decisionmaking	High	Consistent economic data collection is essential to accurately estimate changes in consumer and producer behavior from climate change and climate change mitigation. This requires knowing current travel, housing, spending patterns at the smallest practical level such as the town level. Much of this disaggregated data do not currently exist (e.g., household commute patterns at the town level, level of employment in specific industries at the town level) or is expensive and time consuming to collect.
	2.	Monitorning trends in economically important sectors	Medium	Monitoring changes in key industries and sectors in other states and the nation can inform decisionmaking in Maine. Examples includes trends in outdoor recreation in neighboring states, fish landings and interstate electric vehicle charging station availability.