Scientific Assessment of Climate Change and Its Effects in Maine

EXECUTIVE SUMMARY

MAINE CLIMATE COUNCIL

SCIENTIFIC AND TECHNICAL SUBCOMMITTEE

Scientific Assessment of Climate Change and Its Effects in Maine 2024 Update

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

EXECUTIVE SUMMARY

Susie Arnold[1], Stephen Dickson[2], and Ivan Fernandez[3]
(EDITORS AND CO-CHAIRS)

Jessica Reilly-Moman
(CONSULTANT[32, 34])

SCIENTIFIC AND TECHNICAL SUBCOMMITTEE MEMBERS AND CO-AUTHORS (ALPHABETICALLY):
Linda Bacon[4], Hannah Baranes[5], Andrew Barton[6], Sean Birkel[7], Damian Brady[8], Lily Calderwood[9], Gail Carlson[10], Alexandra Contosta[11], Amanda Cross[12], Adam Daigneault[19], Phillip deMaynadier[14], Muhammad Drammeh[15], Susan Elias[16], Alison Gardner[17], Andrew Goode[8], Caleb Goossen[18], Daniel Hayes[19], Glenn Hodgkins[20], Cindy Isenhour[21], Andrew Johnson[4], Eileen Johnson[22], Joe Kelley[7], Mark King[4], Glen Koehler[9], Jason Lilley[9], Rebecca Lincoln[23], Pamela Lombard[20], Bradfield Lyon[7], Katherine Mills[5], Todd Ontl[24], Nichole Price[25], Kristen Puryear[26], Darren Ranco[27], Nicholas Record[25], Jonathan Rubin[28], Rachel Schattman[29], Peter Slovinsky[2], Alyssa Soucy[30], Sally Stockwell[31], Kanae Tokunaga[5], Richard Wahle[32], Aaron Weiskittel[19], Carl Wilson[33]

Author Affiliations

1. Island Institute
2. Maine Geological Survey
3. University of Maine, School of Forest Resources, Climate Change Institute, School of Food and Agriculture
4. Maine Department of Environmental Protection
5. Gulf of Maine Research Institute
6. University of Maine at Farmington
7. University of Maine, Climate Change Institute, School of Earth and Climate Sciences
8. University of Maine, School of Marine Sciences
9. University of Maine Cooperative Extension
10. Colby College, Environmental Studies Department
11. University of New Hampshire, Earth Systems Research Center
12. US Fish and Wildlife Service
13. University of Maine, School of Forest Resources
14. Maine Department of Inland Fisheries and Wildlife
15. University of Maine, School of Earth and Climate Sciences (Maine Youth Rep)
16. MaineHealth Institute for Research
17. University of Maine, School of Biology and Ecology
18. Maine Organic Farmers and Gardeners Association
19. University of Maine, Center for Research on Sustainable Forests, School of Forest Resources
20. US Geological Survey, New England Water Science Center
21. University of Maine, Climate Change Institute, Department of Anthropology
22. Bowdoin College, Environmental Studies
23. Maine Center for Disease Control and Prevention
24. US Forest Service
25. Bigelow Laboratory for Ocean Sciences
26. Maine Natural Areas Program, Maine Department of Agriculture, Conservation and Forestry
27. University of Maine, Native American Programs
28. University of Maine, Margaret Chase Smith Policy Center, School of Economics
29. University of Maine, School of Food and Agriculture
30. University of Maine, Ecology and Environmental Sciences Program (Maine Youth Rep)
31. Maine Audubon
32. University of Maine, School of Marine Sciences, Darling Marine Center
33. Maine Department of Marine Resources
34. Klima Consulting

Citation:

MCC STS. 2024. *Scientific Assessment of Climate Change and Its Effects in Maine - 2024 Update*. A Report by the Scientific and Technical Subcommittee (STS) of the Maine Climate Council (MCC). Augusta, Maine. 268 pp.

Acknowledgements

The authors additionally wish to recognize the many individuals who generously provided input to the development of this report, some of whom are recognized below.

Tiago Biló, National Oceanic and Atmospheric Administration
Allison Bistline-East, Maine Climate Science Information Exchange
Theresa Burnham-Knight, University of Maine
Parker Gassett, Maine Climate Science Information Exchange
Adam Kemberling, Gulf of Maine Research Institute
Ryan Gordon, Maine Geological Survey
Richard Kersbergen, University of Maine Cooperative Extension
Stacy Knapp, Maine Department of Environmental Protection
Nathan Robbins, Maine Department of Environmental Protection
Amalia Siegel, Governor's Office of Policy Innovation and the Future
Nicole Spaulding, Maine Climate Science Information Exchange
Ana Trueba, University of Maine, School of Earth and Climate Sciences
Val Watson, Maine Climate Science Information Exchange
Nicholas Whiteman, Maine Geological Survey

***Editors' Note:** This assessment offers analysis on a broad spectrum of climate topics by experts from a wide background of scientific disciplines. The findings included herein reflect the work product of these expert authors, not necessarily the organization they represent, the Scientific and Technical Subcommittee, the Maine Climate Council, or the Governor's Office of Policy Innovation and the Future.*

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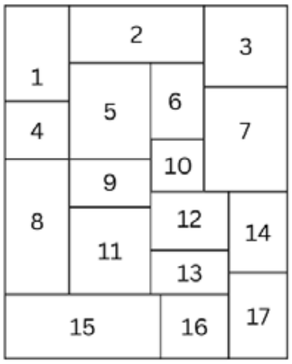

1. A rainbow over the Wyman's Center for Wild Blueberry Research and Innovation. Experimental wild blueberry plots will receive simulated temperature and precipitation treatments in 2024-2028, allowing a team of researchers to explore how this unique crop is likely to be affected by climate change. The project lead PI is Rachel Schattman.

   Photo credit: Kylie Holt, UMaine Agroecology Lab

2. Maine Natural Areas Program (MNAP) Ecologist Kristen Puryear takes readings from a Rod-Surface Elevation Table (RSET) at a State of Maine tidal marsh sentinel site. RSET readings track high resolution (millimeters) changes in the soil surface. Coupled with marker horizon readings and vegetation transects, these data are collected every year to monitor how the marsh platform and plant communities are responding to sea level rise and can indicate whether and at what rate the marsh is "keeping up" with higher water levels. MNAP and the Maine Coastal Program have partnered to establish and monitor 33 of these sentinel sites from York to Lubec.

   Photo credit: Emily Carty, Maine Natural Areas Program

   Courtesy: Kristen Puryear, Maine Natural Areas Program, Maine Department of Agriculture, Conservation and Forestry

3. Dr. Hannah Baranes, coastal scientist at the Gulf of Maine Research Institute, installing a Hohonu tide gauge on the Fore River pedestrian bridge in Portland. The team is improving flood forecasting for Maine's coastal communities by installing low-cost tide gauges and organizing community (citizen) science programs.

   Photo credit: Gulf of Maine Research Institute

4. Benthic young-of-year lobster retrieved from a vessel deployed bio-collector. Annual monitoring of newly settled lobsters provides an early warning of lobster year class strength. Monitoring is conducted through the American Lobster Settlement Index collaborative, a partnership of lobster producing states and provinces in New England states and Atlantic Canada.

   Photo credit: Richard Wahle

5. Dr. Lily Calderwood's Extension and Research team studying the impact of solar array installation on an existing wild blueberry field in Rockport. The project team works closely with the farmer to understand field management costs and adjustments required to farm under panels in addition to the impact of shading on the wild blueberry crop and changes to pest populations.

   Photo credit: UMaine Extension

6. Laura Lalemand, research assistant and student from University of Maine at Farmington, measuring understory light with a digital camera equipped with a fish-eye lens. These measurements were part of a project (PI, Andrew Barton, University of Maine at Farmington) to assess the dynamics and role of fire in ridgetop pitch pine woodland in The Nature Conservancy's Basin Preserve, Phippsburg peninsula.

   Photo credit: Andrew Barton, University of Maine at Farmington

7. Site of climate change research by Old Town High School students with their teacher, Ed Lindsey, in collaboration with Alix Contosta from the University of New Hampshire and the University of Maine. Students are measuring air temperature, relative humidity, snow depth, soil temperature, and soil moisture, plus a camera for tracking vegetation phenology in the forest shown in this photo.

   Photo credit: Ivan Fernandez

8. Research Associate Holly Hughes from the University of Maine checking environmental monitoring instruments at the top of a 27-m tower at Howland Research Forest, a core site of the AmeriFlux monitoring network. The primary measurements on the tower include meteorology and carbon dioxide (CO_2). These systems allow for the rare opportunity of direct measurements of carbon exchange between the atmosphere and the ecosystem, often only able to be estimated by measuring carbon stock changes over time.

   Photo credit: David Hollinger, USDA Forest Service

   Courtesy: Shawn Fraver, University of Maine

Contributor Contact: Ivan Fernandez, ivanjf@maine.edu

9. Neuston net under tow to collect lobster larvae off Boothbay Harbor for research supported by NSF and NOAA Sea Grant to evaluate climate effects on larval lobster trophic interactions in the pelagic foodweb.

   Photo credit: Richard Wahle

10. An unoccupied aerial vehicle (UAV) carrying a thermal camera flies over the University Forest in Old Town, Maine, capturing imagery of the tree canopy. The UAV image acquisitions were flown as part of a class demonstration in remote sensing at the University of Maine's School of Forest Resources.

    Photo credit: Adam Küykendall, University of Maine Division of Marketing and Communications

    Contributor: Daniel Hayes

11. Maine Geological Survey (MGS) Marine Geologist Peter Slovinsky on the MGS Nearshore Survey System (NSS) collecting nearshore bathymetric data near Camp Ellis Beach in Saco. The RTK-GPS antenna and narrow-beam depth sounder work at 10 Hz to map the underwater beach. A waterproof screen displays tracklines and collected data in real time between the handlebars while a navigation computer is stowed in the watertight bow compartment. MGS has been collecting nearshore bathymetric data in the vicinity of federal beach nourishment projects for two decades to keep track of the beneficial reuse of dredged sediment.

    Photo credit: Stephen Dickson, Maine Geological Survey.

12. Photo taken during a stakeholder engagement workshop focused on food waste (including policy to prevent food waste and the associated emissions). The workshop was led by the Materials Management Research Group at the Senator George J. Mitchell Center for Sustainability solutions and included participants from food producers (farmers); waste generating organizations (grocers, hospitals, schools); food waste managers (haulers, composters, landfillers, digesters); food recovery and hunger relief organizations (food banks, gleaning operations).

    Contributor: Cindy Isenhour

13. Senior Research Scientist David Fields of Bigelow Laboratory for Ocean Sciences talks with a Sea Change Semester student while on a research cruise along the Damariscotta River estuary. Bigelow Laboratory's Sea Change Semester gives students the chance to live at the nonprofit institute's coastal Maine campus and get hands-on research experience while working alongside leading researchers that study the foundation of global ocean health.

    Photo credit: Bigelow Laboratory

    Contributor: Nicholas Record

14. Bigelow Laboratory scientists and Sea Change Semester students take oceanographic samples along the Damariscotta River estuary. Over the course of the semester-in-residence program at Bigelow Laboratory, Sea Change students get access to emerging technologies at the frontiers of ocean science (from AI to environmental DNA), as well as the tried-and-true techniques that are used in professional labs and on research vessels worldwide.

    Photo credit: Bigelow Laboratory

    Contributor: Nicholas Record

15. A Gouldsboro community resilience workshop, May 2023, at the Gouldsboro School. With a grant from the Maine Coastal Program, Gouldsboro map to identified important shellfishing access points and identified roads and infrastructure that are climate vulnerable, helping the town prioritize where to focus their resilience efforts moving forward. As a result of the workshop, the project team heard how interconnected resilience efforts need to be and expanded their focus to include resiliency needs such as broadband connectivity and food security. The town now has a climate committee and joined the state Community Resilience Partnership.

    P*hoto credit: Bill Zoellick*

    Courtesy: Melissa Britsch, DMR

    Photo contact: Jessica Reilly-Moman, Klima Consulting

16. Gladys Adu Asieduwaa, a PhD Student in the University of Maine Agroecology Lab, measures out a plot of corn in an interseeding trial. Interseeding is the practice of planting cover crops, in this case rye and red clover, in between standing cash crops. Gladys's goal is to better understand the effects of different seeding timings and planting methods on cover crop establishment and corn performance. The experiment took place at Rogers Farm, part of the Maine Agricultural and Forestry Experiment Station (MAFES) in Stillwater, Maine. The project lead PI is Jason Lilley, University of Maine Extension; Co-PI is Rachel Schattman, University of Maine School of Food and Agriculture.

    Photo credit: Charlie Cooper

17. Maine Department of Environmental Protection (MDEP) biologist Emily Zimmermann surveying subtidal eelgrass in Casco Bay. The MDEP team dives during the summer to assess eelgrass health, by measuring density, size and amount of leaves, and light levels. This data allows characterization of conditions experienced by eelgrass, and allows documentation of short- and long-term changes to eelgrass meadows.

    Photo credit: Angela Brewer

    Contributor: Nathan Robbins

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 it charged the newly created 39-member Maine Climate Council (MCC) with developing an integrated Maine Climate Action Plan by December 1, 2020. In support of the work of the MCC, the law also established six working groups with various areas of focus that included transportation, coastal and marine systems, infrastructure, housing, natural and working lands, energy, community resilience, public health, and emergency management, all within an overarching framework of equity and economic development. The working groups were charged with developing draft strategy recommendations for the MCC that formed the basis for MCC deliberations in the development of the initial comprehensive Maine Climate Action Plan Maine Won't Wait in 2020, and subsequent quadrennial updates thereafter.

In addition, the 2019 law established the Scientific and Technical Subcommittee (STS) to support the work of the MCC 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 is primarily composed of scientists with a broad array of expertise on climate change globally and in Maine who are committed to supporting the work of the MCC with the best available science to inform decision-making. In 2020, the STS released its initial comprehensive report Scientific Assessment of Climate Change and Its Effects in Maine to support the deliberations of the working groups and the MCC in the development of *Maine Won't Wait*. The following year, the STS released the short report Maine Climate Science Update 2021. These reports were preceded by Maine's Climate Future assessment reports in 2009, 2015, and 2020, led by the University of Maine.

This report, ***Scientific Assessment of Climate Change and Its Effects in Maine—2024 Update*** builds on the existing body of work by the STS to provide an up-to-date scientific assessment for working groups and the Maine Climate Council in the development of a science-informed quadrennial update of *Maine Won't Wait* by December of 2024. The authorship of this report includes members of the STS and additional contributors noted in the title page, as well as others who were generous with their expertise, some of whom are recognized in the Acknowledgements.

As we have noted in prior reports, but warranting reiteration here, are 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 does not presume to have fully addressed all possible subject matter. The STS members are highly regarded scientists with an expertise and passion about Maine across many key sectors of our state, and drawn from academic institutions, non-governmental organizations, and state and federal agencies. The STS also includes bipartisan membership of both the Maine House and Senate. In addition, our work in scientific assessment is only meaningful if it provides guidance within the relatively short timeline of the MCC process. Thus, our work has been carried out within the practical constraint of available time but received and included feedback on key issues from the working groups during our process.

EXECUTIVE SUMMARY

Climate

Maine's climate is getting warmer. The past four years in Maine (2020-2023) have ranked among the ten warmest on record. Across the globe, record high temperatures were set by a large margin in 2023. Even when factoring in El Niño and the effects of increasing greenhouse gas emissions, predictions for global temperature leading into 2023 failed to account for the exceptional warming.

Maine's climate is getting wetter, with more high-intensity precipitation. Maine's climate is getting wetter overall and drought has not increased in the historical record. Precipitation (rain and snow) variability is increasing due to intensification of the hydrologic cycle, meaning that water cycles faster through the atmosphere, land, the oceans, freshwater, and glacial ice in response to warming. Maine now receives 1–2 additional days per year with 2+ inches of precipitation, and 2–3 more days per year with 1 inch of precipitation. Storm events with high one-hour intensities have prompted adaptive actions.

Maine is experiencing more extremes, from hourly and daily weather to monthly and seasonal climate. Dry periods will continue to become drier and wet periods will continue to become wetter. Precipitation variability between years is increasing and has recently produced impactful seasonal extremes; for example, the 2020 growing season was the driest on record, and summer 2023 was the wettest.

As temperatures rise, the warm season is getting longer as the winter season shortens and snow and ice declines. Winter in particular has warmed 5°F compared to a century ago and is the fastest warming season. In projected trends of winter indicators in the Northeast, current snow cover is reduced and there are fewer freezing days in both winter and the shoulder seasons. The average warm season for the recent period 2010–2023 is about two weeks longer, and winters are about two weeks shorter, in comparison to a 1901–2000 historical climate baseline. Similarly, there has been a two-week increase in the average length of the growing season since 1950. Maine's warm season is lengthening more towards late summer and early fall, which may be associated with Arctic summer sea ice decline delaying the arrival of cold air masses to New England.

A series of weather extremes in 2023 worldwide and in Maine were associated with record high global temperatures. In addition to the second warmest calendar year and first wettest summer, Maine experienced a series of weather extremes in 2023 reflective of the anomalous conditions worldwide. An unusually active weather pattern developed in mid-December 2023 against the backdrop of record warm wintertime ocean temperatures in the North Atlantic, and with a strong El Niño event influencing worldwide weather.

Winter storms are projected to become more intense, but their frequency remains uncertain. Recent "southeaster" storms in December 2023 and January 2024, in addition to major wind storms in fall 2017 and 2019, have generated significant concern for future extratropical storm trends. "Extratropical" refers to storms that are usually between 30° and 60° latitude from the equator (Maine sits at 45°North), and they are often associated with cold air. Most climate models project more intense cyclones (lower central pressure and increased heavy precipitation), but with an overall decrease in the number of storms as the climate warms. However, future storm frequencies remain uncertain because of model disagreement on average future positions of North Atlantic storm tracks. These changes reflect high rates of warming in the Arctic that decrease the differences between Arctic and equatorial temperatures, so are important for steering the movement of storms.

Temperature projections for Maine are for 2–4°F increase by 2050 and up to 10°F by 2100. Temperature projections worldwide and for Maine are based on modeled Representative Concentration Pathways, RCPs, which define a range of possible greenhouse emissions based on estimates of future energy use and development worldwide. The different trajectories, written as numbers such as 4.5 (intermediate emissions) and 8.5 (high emissions), reflect societal decisions to control greenhouse gas emissions. Temperature projections reported in the 2020 STS report continue to represent a reasonable spread of potential warming outcomes for Maine through the end of this century.

Human Health

Maine is vulnerable to increasing Illnesses and deaths stemming from extreme weather–especially heat, cold, and storm impacts such as flooding. Maine is projected to experience more periods of extreme heat, and Maine's population is likely to be vulnerable; currently, certain groups (men, middle-aged adults, and those working outdoors) experience higher rates of heat-related illness and may be at higher risk. Even as heat risks increase, Maine experiences more cold-related illnesses. Extreme weather events can cause significant injuries and fatalities, such as four confirmed deaths due to injuries and floodwater-associated drownings in Maine's December 2023 storm.

Adverse mental health impacts of climate change are well-documented and vary significantly depending upon how much a person is exposed to climate impacts, underlying burdens of adverse mental health conditions, quality of and access to emergency response and mental health services, and social and cultural support systems. In Maine and around the world, populations that may be at particular risk for the mental health impacts of climate change are children and adolescents, women, and Indigenous peoples. Like other regions, Maine has a significant gap in available mental health services for those in need.

Deer tick populations have stabilized in southern Maine but are increasing in northern counties, which is reflected in the high and increasing rates of Lyme disease in the state. Climate variations, such as increased precipitation or warmer winters, can cause decreases and increases in deer (blacklegged) tick populations, respectively. Warmer temperatures year round are likely to support increasing deer tick prevalence in northern Maine, and establishment (the consistent presence) of Lone star tick populations in southern and coastal Maine. Lyme disease incidence in Maine is consistently in the top five among U.S. states and has been increasing over time, in part reflecting range expansion of deer ticks in Maine. Deer ticks transmit the agents of multiple diseases such as Lyme disease, anaplasmosis, babesiosis, Powassan encephalitis virus, and relapsing fever.

Incidences of diseases associated with lone star ticks, such as red meat allergy, are increasing. Lone star ticks, which can transmit the agents of diseases such as ehrlichiosis and tularemia, and can cause alpha-gal syndrome (red meat allergy), are not established but increasing.

Mosquito-borne diseases are increasing in Maine, including a second veterinary outbreak of eastern equine encephalitis virus (EEEV) in 2023. Increased precipitation and longer growing seasons may prolong the active biting season of mosquitoes, which increases the potential for more outbreaks of eastern equine encephalitis virus (EEEV) in Maine. West Nile Virus and Jamestown Canyon Virus (JCV) were reported in Maine in 2023, with a JCV human fatality in Maine reported in 2022.

Smoke from wildfires in Canada and the Western U.S. and increased aeroallergens such as pollen are impacting air quality in Maine. Although large-scale wildfires have been more common in the Western U.S. and Canada than in the Northeast in recent decades, wildfire smoke can be transported to the East Coast and cause significant exposures and associated health outcomes. Climate change is making aeroallergens (airborne allergens) like pollen in the air worse, and the trend is for this problem to continue to increase with a changing climate.

Climate change threatens food security. Food insecurity affects ten percent of Maine's population, and is exacerbated by high prices driven in part by climate change. Indigenous food supplies are threatened by climate change in Maine; preserving traditional food systems and food sovereignty can support food security in the face of climate change.

Social and Economic Systems

Maine homeowners will see the second largest home insurance rate increase in the country in 2024. While Maine's homeowners insurance rates remain low compared to the rest of the country, the record increase is driven largely by increased storm severity and associated damages. Changing insurance rates are an example of an economic signal of changing incentives and opportunities for households, businesses, governments, and institutions. Research predicts higher demand on government systems: civic institutions should prepare to see existing programs used more intensively or in new ways as populations cope with climate change.

The social cost of carbon is higher than previously calculated, and federal guidance changed to better account for ecosystems and cultures when providing funds for disaster recovery. Comprehensive evidence implies that the social cost of carbon, which measures the dollar value of the damages to society caused by an incremental metric tonne of carbon dioxide (CO_2) emissions, should be significantly higher than its current value. Updated Federal Guidance on Benefit-Cost Analysis (BCA), which is used to determine whether a disaster recovery project is funded, accounts for ecosystem services and addresses benefits and costs that cannot be monetized. Frequently the value of physical infrastructure has been prioritized in BCA calculations, entrenching existing inequities (such as providing funding to areas with high property values but not to areas with lower property values given the benefit-cost ratios).

Climate change impacts the supply and demand of tourism, affecting how tourists plan their Maine travels. Tourism, an $8.6 billion dollar industry in Maine that supports over 150,000 jobs, depends on the quality and management of natural and cultural resources, particularly the complex relationship between climate hazards, risks, tourism demand, and tourism experience. Research in Maine shows Maine tourists perceive that climate change is impacting the environment they visit and the built infrastructure they use; their decision to travel depends on how they evaluate their potential exposure to climate-related risks at their destination.

Mainers particularly vulnerable to climate change include rural, older and lower-income residents, as well as those people and places with economies tied to climate-sensitive resources. Mainers experience different levels of vulnerability, and climate-vulnerable communities in Maine come from across the state, especially those whose economies are particularly sensitive to climatic change (such as lobstering or timber harvesting). Rural communities can be particularly vulnerable because local governments are challenged by constrained financial and human resources and consequently have lower levels of adaptive capacity to plan for and respond to climate-related natural disasters. Older, isolated, and lower-income residents may experience more harm from climate impacts such as power outages and flooding. Finally, cultural identities, such as the values and activities tied to various regions of Maine, are at risk from climate impacts. Intangible resources that support well-being, such as community cultural practices, can be impossible to replace once lost. For example, a cultural dependence on natural resources and systems makes

Wabanaki citizens particularly vulnerable. However, Wabanaki citizens can be uniquely resilient to climate change, as cultural traditions help to process change.

When municipalities are able to put time and resources into vulnerability assessments and engage meaningfully with the public in that process, this increases municipal climate resilience in Maine. Maine research shows that vulnerability to negative climate change impacts can be reduced through participation and engagement in climate adaptation. This includes building municipal capacity (such as having adequate funding for municipal employees to build relationships, apply for grants, and acquire needed skills to engage meaningfully with the community) to assess community vulnerability. This highlights the importance of creating opportunities for community involvement in local and state vulnerability assessments.

Climate Resilience

In Maine, resilience to climate change depends on relationships: this includes a strong sense of community among residents, solid connections between the economy and healthy natural systems, and maintaining ties to heritage. In Maine, partnerships, collaboration and funding for climate project implementation were identified as key municipal needs for enhancing resilience. In municipalities where coastal community comprehensive plans include social resilience, many 1) emphasize a strong sense of community and a desire to maintain a rural character; 2) focus on shoreline erosion and flooding; and 3) recognize the relationship between healthy natural systems and a healthy economy. Maine can improve climate resilient development by building on important aspects of Maine's culture, such as reuse and thrifting.

Tribal sovereignty enables climate resilience for Native nations. Building research relationships with Wabanaki nations requires slowing down, centering Wabanaki diplomacy and methods, and creating rhythms of collaboration. Both federal and state interference in Tribal sovereignty can limit the ability of Tribes to develop, fund and implement culturally appropriate climate adaptation plans and activities. When conducting sustainability science in Indigenous homelands of Penobscot, Passamaquoddy, Maliseet, and Mi'kmaq, researchers found that 1) centering Wabanaki diplomacy and Indigenous research methods; 2) a multi-perspectives, recurrent engagement; 3) slowing down; and 4) supporting Wabanaki students as leaders and researchers could begin to address tensions between Western and Indigenous ways of knowing. Traditional ecological knowledge is not another form of "data" to be folded into existing Western governance structures; practices around data sovereignty, in which Native nations control and maintain their personal and environmental data, begin to address this.

Housing security for low income and rural Maine residents may be stressed by high fuel and electricity costs, along with climate migration to Maine. Rural residents are not adequately supported by unstable funding for heating oil, such as funding provided in the Low Income Home Energy Assistance Program (LIHEAP). Longer term and more cost effective solutions to high heating costs include improvements in building insulation and energy efficiency.

Individual renewable energy systems can provide reliable power during extended outages. Solar panels with battery storage can meet individual homeowner basic backup power needs during extended power outages, and storage (such as batteries) can meet most of the critical heating and cooling needs during outages. In 2023, Vermont instituted a program now underway to test "solar+storage" to improve grid resiliency.

Resilience metrics should measure baseline conditions, assess both process and outcomes, engage and enable communities early and often, and address equity. When assembling resilience metrics, a critical question to ask is "resilience for whom, at what cost to whom else?" Indicators of resilience can be singular or composite, often mix qualitative and quantitative approaches, and measure an initial baseline. Involving communities in creating and using metrics allows them to steer conversations towards neglected social needs and exert influence and control in the adaptation process, increasing the likelihood of long-term effectiveness of a project to meet its resiliency goals.

Ensuring power, access and standing for public participants in climate decision-making builds trust and leads to better outcomes. When done well, public participation in decision-making improves legitimacy, builds capacity, leads to better environmental and social outcomes, and enhances trust and understanding among parties. Five key principles help to bring together science and the public in decision-making: 1) transparency of information and analysis; 2) giving explicit attention to facts *and* values; 3) addressing assumptions and uncertainties; 4) including independent review; and 5) allowing for iteration with new information. Maine research shows that commitment to community agency (the combination of access, standing, and influence that gives a community real power in a process) helps build trust and has proved locally successful in implementing renewable energy projects.

Sea Level Rise and Coastal Storms

Sea level is 7.5 inches higher than in early 20th century Maine, and the rate of sea level rise has nearly doubled in the past 30 years. Over the past 30 years, the rate of sea level rise was 1.4 inches per decade, while the previous rate was 0.7 inches per decade. Sea level rise rates in Maine remain similar to the global averages for both short- and long-term rates.

Record-high sea levels were measured along the coast in 2023 and 2024. 2023 set a new record-high annual average sea level at all three of Maine's long-term tide gauges, and also set numerous new monthly average sea level records. In 2023, the record for highest monthly average water level was broken at all long-term gauges for at least six months out of the year, with all remaining months except one falling within the top three highest levels for each month.

Rising sea levels have caused recent increases in coastal flooding, such as the record-breaking storm events of January 2024. The combination of high tide and storm surge (called storm tide) on January 10 and 13 were not historically unprecedented, but coming on top of a rising sea level is what caused the events to break records. This increase in sea level on top of high tides and storm surge, contributed to severe coastal flooding during the back-to-back January 10 and January 13, 2024, storms. Sea level rise has caused coastal flooding to occur about three times more often since 2010 in Portland compared to the past century. The frequency of minor high tide flooding will increase over the next decade, driven by sea level rise and an increasing tidal range induced by a lunar cycle.

Maine's "commit to manage" sea level rise targets (1.5 feet by 2050 and 4 feet by 2100) remain unchanged from the 2020 STS report. Maine's "commit to manage" sea level rise scenario (1.5 feet by 2050 and 4 feet by 2100, relative to 2000 average or "mean" sea level) remains within the statistically likely range of the equivalent sea level rise scenario in updated projections.

The timing of the "prepare to manage" targets (3 feet by 2050 and 8.8 feet by 2100) should be shifted to two decades later. Updated projections indicate that the timeframe of Maine's "prepare to manage" sea level rise scenario (3 feet by 2050 and 8.8 feet by 2100, relative to 2000 mean sea level) should be shifted two decades later, to 3 feet by 2070 and 8.8 feet in the 2120s.

Due to a possible large increase in the rate of sea level rise at the end of this century, Maine needs to extend planning horizons beyond 2100. Sea level is currently rising about 1.2 inches per decade in Maine. In 2100, this rate would increase to 8.4 inches per decade under the Intermediate (RCP 4.5) scenario and 1.2 feet per decade under the High (RCP 8.5) scenario. This possible order-of-magnitude increase in the rate of sea level rise by the end of the 21st century may cause physical impacts that outpace planning and adaptation efforts, highlighting the need for planning beyond 2100. Beyond 2050, when the different carbon emissions scenarios begin to diverge, the major driver of uncertainty in sea level rise projections is continental ice sheet melting, which in turn depends on emissions.

Catastrophic tropical storm surges are unlikely for Maine; winter storms will continue to be the main threat for severe flooding. It is unlikely that Maine would experience a tide-and-surge combination that would drive flooding multiple feet above the historical record. Instead, sea level rise and variability (such as astronomical or lunar-driven tides) drive severe flooding, as was the case for the January 2024 storms. In Maine, extratropical (originating between 30-60° latitude, usually cold-season) storms are the primary cause of flooding, and maximum wind speeds for these storms are less than half of hurricane maximum wind speeds. Tropical (originating in the tropics, usually within the warm seasons) cyclone intensity has increased in the North Atlantic, but this increase has not been connected with increasing surge intensity in the Gulf of Maine. There is also evidence for future changes in extratropical cyclone activity globally, but there is no evidence that storm surges will become larger or more frequent with future warming in the Gulf of Maine. However, as sea level rises, the same surges superimposed on higher sea levels will make coastal flooding and inundation more frequent and severe.

Marshes are not building elevation fast enough to keep up with sea level rise and need room to migrate upland, but coastal development restricts their ability to move, especially in southern Maine. Salt marshes in Maine currently store more carbon than salt marshes in all other states except Massachusetts, but are threatened by sea level rise.

Much of Maine's salt marshes are building elevation at a slower rate than sea level is rising: 75% of the Northeast's marsh area could be lost to inundation unless the habitat is able to migrate landward into undeveloped natural areas. There is six times less marsh migration space available south of Penobscot Bay than north of the Bay. Coastal bluff stability and landslide hazard maps, published by the Maine Geological Survey (MGS) in the early 2000's, need to be updated due to changing conditions. New maps from the MGS depict the full extent of coastal sand dune systems that are highly vulnerable to sea level rise.

Marine

The Gulf of Maine is warming faster than 97% of the world's ocean surface and is experiencing near-constant ocean heat waves. In 2022, sea surface temperature met the heatwave criteria for 353 days, or 97% of the year. Research indicates that the northward shift of the Gulf Stream and the deflection of the Labrador Current led to rapid warming and a "regime shift" in the Gulf of Maine beginning around 2008, in which the base of the food web was altered by warm water, sending a cascade of impacts up through iconic species such as Atlantic cod, North Atlantic right whales, and Atlantic puffins, a shift that has persisted.

Increased ocean temperature has decreased the size and quality of the food source that supports the marine food web, causing species to shift, become less abundant, grow faster but mature at smaller sizes, and results in species changes in the Gulf of Maine. Declines in primary production, or the rate at which organisms photosynthesize to build organic matter, have meant a fundamental change in the size and quality of the phytoplankton which supports food webs. The signature subarctic zooplankton species, which is the primary food for young lobster, has declined in the Gulf of Maine. Climate-driven changes in the planktonic community have the potential to influence maritime activities, including fishing, aquaculture, and tourism, as well as ecological communities. The biomass of certain groups of marine organisms has declined, and many fish and invertebrate populations shifted their spatial distributions, such as wild kelp populations that are disappearing from southern Maine, yet were still affected by warming: most species have grown faster at early life stages but plateaued at smaller body sizes. Research has found increased species diversity and "tropicalization" of the fish community. Certain species are being particularly affected by warming ocean temperatures and associated ecosystem changes, such as Atlantic cod, Atlantic herring, northern shrimp, Atlantic puffins, and North Atlantic right whales.

Warming is affecting the timing of food availability and migrations of iconic and endangered species. Significant shifts are occurring in the Gulf of Maine in the timing of ecological processes. The migration of certain diadromous fish, including Atlantic salmon and alewife, have advanced to earlier in the year, while other events are occurring later: these include spring and fall phytoplankton blooms, fledging of Atlantic puffin chicks, and the appearance of certain species of larval fish. These changes include the increasingly mismatched timing between larval lobster and their primary food source.

Maine's lobster harvest in 2022 declined by 26% in volume from its historic highs in 2016. The Maine lobster industry provided 18,000 jobs and $464 million in revenue in 2023. Lobsters are being directly impacted by warming waters as well as climate-driven changes to the zooplankton community, effects that have important implications for the future of Maine's lobster industry. While lobster appear to be relatively resistant to ocean acidification effects compared to other commercially valuable shellfish, climate-related changes in the reproductive performance of lobsters and the supply of planktonic foods have contributed to declines in lobster settlement over the past decade. Additional climate-related issues facing the lobster industry include an over-dependence on the fishery, anticipating sea level rise and storm damage to working waterfronts, minimizing interaction between the North Atlantic right whale and lobster fishing, and offshore wind energy development.

Under the highest emissions scenario (RCP 8.5), the Gulf of Maine will experience ocean acidification conditions that are unfavorable for shell growth for most of the year by 2050. Additional species, including invertebrate pelagic species, have been identified since 2020 as vulnerable to ocean acidification. Rising atmospheric CO_2 will lead to more acidic (lower pH) conditions in the Gulf of Maine.

Increasing hypoxia (low oxygen) events in the Gulf of Maine, which have resulted in lobster die-offs, have attracted research to understand the environmental causes and drivers of these conditions and to predict them in advance. Seaweed aquaculture can remediate localized low dissolved oxygen as well as low seawater pH, particularly with sugar kelp. However, a lack of genetic knowledge around kelp biodiversity limits the expansion of kelp aquaculture. Aquaculture systems in cold water environments face global change challenges, but can be adapted with investment into infrastructure, strain selection, and emergent species.

Accounting for carbon and removing it is a burgeoning area of marine research. Maine is at the forefront of research and policy by attempting to include coastal carbon sequestration in the 2023 Maine Carbon Budget. New guidelines to responsibly conduct marine carbon dioxide removal research stress the need for caution and development of Measurement, Reporting, and Verification Tools (MRV) to ensure claims about carbon burial and sequestration from seaweeds in particular are evidence-based.

Communities that are heavily invested in one fishery (such as lobster) face resilience planning challenges. Different lobster fishing business models, such as the inshore single-operator fishermen versus more capital intensive multi-crew operations, may experience differential impacts from climate change. Socioeconomic indicators of resilience in Maine's lobster fishery include profitability, coastal accessibility, community change, and physical and mental health, but more data are needed to quantify specific impacts. Co-management of fisheries and ecosystems are increasingly important.

In Maine, using nature to protect infrastructure and environments, or "nature-based solutions," can provide climate risk reduction, habitat, and social benefits, but planners need streamlined planning and regulation supported by a network of interagency partnerships to have solutions be effective at scale. Nationally, the effectiveness of nature-based solutions to meet coastal adaptation needs is well-documented but depends on a wide range of conditions, knowledges and capacities, with the bottlenecks for implementation similar to those found in Maine: governance (such as regulatory streamlining), communication (such as social proof from neighbors implementing projects), and equity (such as attention to who sees value from projects).

Agriculture

Weather variability is reducing crop yields, causing economic impacts to farms, and mental and physical health impacts to farmworkers in Maine. Maine has over 7,600 farms, 96% of which are family farms, on 1.3 million acres. The industry generates $3.6 billion and 27,000 jobs. Producers report concern about reduced crop yields and quality, poor crop and cover crop germination, and increased labor needs associated with irrigation. Survey respondents noted that extreme weather, such as an overabundance of rain, makes field access more difficult, increases soil erosion, and has negative effects on farm viability and farmworker health and wellbeing. Crop insurance policies designed for diversified farms have low utilization rates by the Maine farmers, but the industry has new opportunities with climate-related crop insurance policies that are becoming available.

New opportunities and both positive and negative impacts for Maine agriculture are likely with warmer temperatures and longer growing seasons. Longer growing seasons allow new insect pests, diseases, or weeds to become established or allow existing species to have additional generations. Longer and warmer growing seasons can increase the frequency and intensity of stress to crops, livestock farmworkers and water demand. Earlier spring warmup can lead to damage to perennial plants if the date of spring cold temperatures does not shift earlier at the same rate. Higher winter temperatures can also allow agricultural pests that are not currently able to overwinter in Maine to persist year-round. The benefit of longer, warmer growing seasons that permit a wider range of crop options and higher productivity could be curtailed or even eliminated if the increase in growing degree days is not synchronized with a matching shift in the dates of spring and fall frosts, or if heat waves, droughts, or other extreme weather events degrade productivity.

Updated USDA plant hardiness zones show average annual minimum temperatures increasing by about 20°F between 2005 and 2085. By 2085, under the highest emissions scenario (RCP 8.5), average annual minimum temperatures in central Maine will resemble current (2024) conditions in central New Jersey; and northern Maine will be similar to current conditions in Connecticut.

Climate change poses a substantial risk to U.S. agricultural yields. Using corn and soybeans as model crops, climate change is expected to have negative impacts on crop production nationally. Studies are not specific to Maine, but given that Maine imports 90% of its food, the national market directly impacts Maine food pricing and security.

Effective agricultural adaptation requires decades to implement and faces constraints, but can be highly effective if warming remains under 2.7°F (1.5°C). Agricultural and water management adaptation options are on average 90% effective in reducing risks up to 2.7°F of warming, but with increased warming above 2.7°F, effectiveness declines across all options and regions. More broadly, the U.S. and Canada were ranked as having higher constraints to adaptation than countries in western and southern Europe when using indicators such as GDP per capita, governance, education, and gender inequality.

Agriculture accounted for approximately 2% of total Maine statewide emissions in 2019. From 2010-2021, total emissions from Maine agriculture decreased. In 2021, livestock accounted for more than 86% of Maine's agricultural emissions, primarily from methane. Enteric methane emissions (from ruminant digestion) have been on a slow but steady decline since 1996. Conversely, methane emissions from manure have increased over that same period. Globally, livestock methane emissions represent the largest agricultural contribution to climate change. Livestock emissions can be reduced through feed additives, and research suggests that methane emission from beef and dairy cattle can be reduced by 50%. Over half of Maine's organic dairy producers surveyed were familiar with, and a third were using, red seaweed as a feed supplement to reduce enteric methane emissions.

Mitigation in agriculture can come from biochar and adding renewable energy to farms. Evidence suggests that biochar, a form of charcoal, can enhance soil carbon sequestration and improve soil health with appropriate management. Maine farmers are installing renewable energy infrastructure on agricultural land to increase farm economic viability and contribute to greenhouse gas mitigation goals.

There are multiple challenges and constraints for effective soil carbon sequestration, including ecological and socioeconomic factors, lack of standardized soil carbon monitoring and measuring methods, and documentation of sustainability and permanence. While there is a great deal of enthusiasm for the potential of soil carbon sequestration globally, recent studies have pointed to the ecological, biogeochemical, and socioeconomic challenges of achieving enhanced, sustained, and demonstrable carbon sequestration in soils. Research on mechanisms of soil carbon sequestration indicates that crushed rock mineralization, also known as enhanced silicate weathering, could theoretically remove billions of tons of CO_2 per year if implemented on a global scale.

Biodiversity

The globe experienced its first documented climate-driven extinctions of this era, along with widespread localized extirpations: a quarter of all species on earth are at risk of extinction. Climate change has been identified as the cause of at least two species extinctions. An additional 5% of currently living species are at risk for climate-driven extinction with 3.6°F (2°C) warming and 16% at 7.7°F (4.3°C) warming. Research shows that one million species, or 25% of all the world's known species, are threatened with extinction due to other reasons alone or in conjunction with climate change. Climate change is causing local species extinctions, often driven by increases in annual high temperatures.

Eight new wildlife species were added to the Maine State List of Endangered and Threatened Species in 2023, many of which are additions driven in full or part by climate change. New species are the Saltmarsh Sparrow, Bicknell's Thrush, Blackpoll Warbler, Marginated Tiger Beetle, Cliff and Bank Swallows, the Tricolored Bat, and Ashton's Cuckoo Bumblebee. Maine's Beginning with Habitat program identifies areas where a disproportionate concentration of at-risk species and habitats are located. Additional species not listed but vulnerable to climate change include additional bats, amphibians, turtles, salmonid fish and moose. A quarter of Maine's at-risk butterflies are threatened by climate change.

Climate warming is expected to facilitate the establishment and spread of more invasive species in the Northeast, and Maine's biodiverse river shores and floodplains are particularly vulnerable. Many of Maine's species have already been impacted by climate-driven changes to climate niche space and ecosystem structure. This includes the loss of eelgrass and kelp beds, and the loss of forest understory plant diversity due to invasive species. In Maine, the range of invasive Common and Glossy Buckthorn, for example, has expanded due to warming temperatures, contributing to the loss of native species through overcrowding in the forest understory and shading out natural regeneration, decreased carbon sequestration, and increases in invasive earthworms.

Climate change impacts on biodiversity are expected to increase, but are currently less impactful than habitat loss. Species distribution in the Northeast depends more on precipitation than temperature. While temperatures are important limits to species distributions, research identified physical habitat factors, such as soil and geological factors, as well as precipitation to be slightly more important than temperature for defining distributions. Research projects a loss of at least 6% (386 species) of current species by 2100 under the highest emissions (RCP 8.5) scenario.

Almost all birds are declining and shifting their ranges; wetland bird populations have benefited from adaptive management and long-term wetland protection. Maine birds are expanding or shifting their ranges, which can lead to decreased nesting success. While resident bird species in the Northeast are projected to increase as more southern species move northward, about two-thirds of short-distance migrant birds, such as Hermit Thrush, and a third of long distance migrants, such as the Rose-breasted Grosbeak, are projected to decrease. Residents that will decrease are culturally important species such the Black-capped Chickadee (the Maine state bird). Species reliant on high-elevation forests, such as Bicknell's Thrush, are especially vulnerable because such forests are limited in their ability to move upslope with warming.

Due to climate change, insects will alter their flight periods, and amphibians will be impacted by changes in seasonal events and hydrology. Many of Maine's insects, foundational to most ecosystem food webs, will respond to climate change by altering their flight periods. Changes in precipitation and hydrology, especially of ephemeral or vernal pools, are likely impacting the state's amphibians. Along with changes in seasonal emergence, highly variable late winter and spring freeze-thaw events are impacting regional amphibians.

Maine is not on track to add approximately 200,000 acres of conserved land per year to reach the national and state goal of 30% of land conserved by 2030. Though Maine's overall conserved area (22%) is low relative to most states in the Northeast, rates have recently increased. At present, the state is projected to reach 30% land conserved in 2047 and would need to triple the current rate of conservation to meet the 2030 goal. Although state ownership makes up the largest proportion of conservation lands, lands held in conservation easement (primarily as working forest) are the predominant form of conservation (54% of conserved lands), followed by state ownership (23%).

Old growth forests are the best forest type for sequestering carbon, and young forests sequester carbon quickly. Old growth forests (older than 170 years old) support the largest carbon pools of all Northeast forest conditions while concurrently supporting the highest biodiversity. Severe disturbances (such as clearcutting or infestation by invasive insects) have the potential to convert forests from carbon sinks to sources at least temporarily depending on the severity and frequency of the disturbance. Young forest stands (younger than 15 years) sequester carbon quickly and provide important habitat for species that rely on early successional forests.

Freshwater

Maine's wetlands are a bright spot for biodiversity and carbon storage, with some of the highest quality and quantity of these types of ecosystems across New England, but remain at risk from poorly planned development and climate impacts. Maine has lost up to 20% of its wetlands since the 1780s, but has some of the most intact and extensive floodplain forests remaining in the northeastern U.S. Conservation plays a critical role in maintaining these ecosystems. Maine hosts an exceptional number and diversity of peatlands such as bogs and fens, which store the most carbon of all wetland types, but are at risk of switching from a sink to a source with climate warming, because wetlands only store carbon when they are wet. Although wetlands are recognized for their important role in carbon sequestration and storage, accurate assessments of their carbon sequestration ability are limited.

In Maine's streams and rivers, intense flooding and increased temperature will impact fish species. Increased frequency and greater magnitude of floods can erode stream banks, reshape stream channels, accelerate the spread of invasive species, and increase sediment deposition in other parts of a river system. In addition to affecting stream and river geomorphology and habitat quality, intense floods can directly impact aquatic life by killing some organisms and washing others downstream. Significant rain events in late winter and early spring on frozen ground can increase stream scouring when larval Brook Trout and Atlantic Salmon are sac fry in the loose gravels and cannot evade these conditions. A key problem for Brook Trout and Atlantic Salmon is likely to be range expansion of introduced non-native species as waters warm. Maine's Eastern Brook Trout population is especially important for long-term conservation of the entire species because Maine is predicted to be a regional stronghold for suitable habitat.

For coldwater fish species, earlier onset of ice-out conditions means a longer open water season, more opportunity for water temperature increase and a longer duration of stressful or lethal summer temperatures. This is exacerbated in drought years that would already stress coldwater fish species. Lake conditions are changing to the advantage of warmer water species moving northward, often to the detriment of smaller resident and native forage species, such as rare minnows. Overnight recovery of water temperatures in lakes and streams from extreme high temperatures are reduced when overnight temperatures remain at or near the thermal tolerance limits for coldwater species.

Climate change, changes in air quality, and human impacts interact to drive regional changes in lake water quality in Maine. Climate change and land use (particularly road salt), as well as rising concentrations of dissolved organic carbon attributed to climatic warming and recovery from acid rain, are changing lake chemistry and decreasing lake clarity, with demonstrable impacts on lake biology including zooplankton as an indicator of ecological health.

Annual peak streamflows have increased in magnitude in Maine's rivers and streams over the last century, while the length of warm low-flow periods may increase. Future changes in larger, less-frequent peak flows (such as the 100-year peak flow) are uncertain but may increase with increased precipitation or decrease with increased temperatures and decreased snowpacks. In the last 50 to 100 years, snowpack depths have decreased in late winter and snowpack densities have increased. Groundwater levels and low stream flows have increased in recent years or not changed significantly. However, there may be an increase in the length of the warm low-flow season in the future for high-emission scenarios. Competing water demands in some Maine watersheds during low-flow periods have the potential to become more problematic during future droughts. Increased cyanobacteria blooms and cyanotoxin production continue to threaten drinking water and recreational uses.

The potential inland reach of saltwater intrusion has not been systematically studied in Maine. Inundation of the land surface during coastal storm surges or higher tides from sea level rise can contaminate an aquifer with salt from above or laterally through rock fractures. From below, sea level rise can permanently replace freshwater volume in a coastal aquifer with salt water.

Mapping vulnerable waters, determining their hydrological thresholds, and engaging in adaptive management can support watershed resilience. Freshwater resources can be supported with planning that encompasses climate, human activities, uses, economies, and lake characteristics. Building resilience into watersheds can be supported with risk assessments, integrative implementation, and monitoring.

Forests and Forestry

Treelines, the growing season, and foliage timing in Maine's forest are all shifting; peak fall foliage is now occurring almost two weeks later than 1950. Future climate projections predict that the timing of peak fall foliage will occur between October 30 and November 2 by 2060. Treelines are shifting upslope due to climate change, and some treelines are shifting faster. Among the climate impacts to Maine forest management, warming winters and increased frequency of winter freeze-thaw cycles is disrupting forest harvesting.

Elevated atmospheric carbon dioxide (CO2) has had a strong and consistently positive effect on wood volume, growth, and yield. CO2 fertilization is the dominant driver of the observed forest biomass increase over recent decades, increasing forest biomass accretion by over 50% in forests studied. The positive effect of CO2 fertilization may slow down and eventually reach saturation in the future, potentially reducing the forest ecosystem's contributions to achieving carbon neutrality. Future CO2 fertilization could increase total forest carbon by 0.8% to 5.1%, and could increase harvest volumes by up to 20% compared to the no-CO2 fertilization scenarios.

Maine's forestry industry has the highest vulnerability in the rural northern and western parts of the state, where forest industry activities are most prevalent. The Maine forestry sector is a heritage industry worth $8 billion per year and over 17,000 direct jobs. Reduced forest sensitivities and an increased capacity to adapt to a changing climate have the potential to decrease overall vulnerability in many parts of the state. Forest management would benefit from improving communication strategies to get relevant research to land managers and decision makers; providing funding sources for research that better match the needs of forest managers and decision makers; and creating a conservation landscape that embraces the value of both actively managed and unmanaged forests.

Climate change, coupled with increased pressure from non-native pathogens, insect pests and invasive species, will change Maine forests. Some tree species that occur south of Maine today are likely to migrate into the state, creating novel forest types. Certain tree species are also especially vulnerable to pests that target only one or a few tree species (such as the emerald ash borer). Cedar and fir may be particularly sensitive to future temperature and precipitation changes. Modeling found that the most sensitive seasonal climate variables for cold-adapted species included colder temperatures and preferences for wet weather concentrated in the winter months.The arrival and spread of invasive earthworms in Maine forests also poses a risk to forest carbon stocks and forest resilience to climate change.

Nationally, the future of the land carbon balance will be strongly influenced by the geographic extent of drought and heat stress, but projections show that socioeconomic factors are a greater driver of harvest and carbon stocks than climate change. The western U.S. is showing negative productivity trends while the eastern U.S. is showing positive productivity trends, strongly influenced by climate change.

Maine's extensive wildland-urban interface makes Maine vulnerable if a large wildfire were to occur. Projections for the Northeast predict intensification of conditions conducive to wildfire: warmer temperature, more variation in precipitation, more lightning, and longer periods of high-fire risk. Models predict an earlier fire season and more than a doubling of fire probability in the state. Maine has many houses in the wildland-urban interface (WUI), and 19% of the state's more than 17 million forest acres are considered WUI. These patterns make Maine particularly vulnerable if a large, severe wildfire were to occur. While large-scale, catastrophic wildfires are unlikely in Maine for a range of future climatic conditions, some Maine forests have characteristics that are similar to the Canadian Acadian forests that recently burned. The record-breaking 2023 wildfire season in Nova Scotia was driven largely by extreme short-term drought in May and June, and provided a glimpse of future fire risk in Maine. Increased fire risk in Maine's future can potentially be reduced by efforts to minimize human ignitions, employ prescribed fire where appropriate, and increase wildland fire-fighting preparedness.

Maine forests and wood products are a net carbon sink and are the largest contributor to the state's carbon neutrality target. Forests and wood products are estimated to have acted as a net sink between 2017 and 2021, offsetting about 101% of Maine's total gross GHG emissions. Carbon sequestration could be greatly increased by managing forests using a 'triad' approach consisting of harvesting to create uneven age continuous cover, intensive plantations, and permanent set-asides. In addition, optimally implementing forest management practices can increase carbon storage by 20% or more. Achieving forest carbon objectives requires attention to the choice of species cultivated, overall species diversity, and a mix from uneven age continuous cover to intensive plantations.

Hope (the science)

Hope theory can be a framework for action in the face of climate change. Hope theory is made up of three primary components: (1) goal setting (having a personally meaningful goal), (2) agency thinking (having the knowledge and determination to achieve the goal), and (3) pathways thinking (having a plan and a willingness to tweak the plan). Hope theory provides specific and systematic actions that can reduce anxiety and increase well-being.

Hope-based science communications are urgently needed. Maine-based physicians report that climate change is worsening the mental health and well-being of their patients. Climate anxiety, particularly in young people, can be alleviated through the creation of social outlets, agency, and providing avenues for meaningful action. In addition, hope increases the likelihood of individual success.

Having an accessible roadmap, such as Maine Won't Wait, is a key strategy for nurturing hope. Hope helps people cast a vision of what future success will look like. Every success is an opportunity to show that the future we want is possible.

maine.gov/future/climate/council