2022
MASSACHUSETTS
CLIMATE CHANGE
ASSESSMENT

2022 Massachusetts Climate Change Assessment

December 2022

Volume II - Statewide Report

Executive Office of Energy and Environmental Affairs

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Letter from the Secretary

I am pleased to present the Massachusetts Climate Change Assessment, which provides the Commonwealth with a data-driven roadmap for the climate impacts that will affect Massachusetts communities most significantly, and where urgent action is needed. While efforts on the issues identified in this report are currently underway, the MA Climate Change Assessment will directly inform the Commonwealth's 2023 State Hazard Mitigation and Climate Adaptation Plan (SHMCAP) and serve as a critical guiding resource across the state as we work collectively to reduce risk and build resilience.

Strategic, comprehensive, and data-driven climate action has been central to the Baker-Polito Administration over the past eight years, as Massachusetts has led the nation in both decarbonization and resilience planning, partnerships, and implementation. In 2016, Executive Order 569 Establishing an Integrated Climate Change Strategy for the Commonwealth, was signed by Governor Baker to ensure a comprehensive approach to reduce greenhouse gas emissions, safeguard residents, municipalities and businesses from the impacts of climate change, and build a more resilient Commonwealth. Since then, the Administration has worked across agencies and communities to better understand and prepare for the impacts of climate change, including:

- Investing over **$1 billion in climate initiatives** through the Executive Office of Energy and Environmental Affairs (EEA) and its agencies in order to implement mitigation and adaptation efforts;
- Launching the **Municipal Vulnerability Preparedness Program**, which over 97% of communities representing nearly the entirety of the Commonwealth's population are enrolled in and have been awarded over $100 million since 2017, to support local climate resilience and adaptation projects;
- Creating the **Coastal Resilience Grant Program**, which is open to the 78 municipalities located within the Massachusetts coastal zone and has awarded $23 million;
- Implementing the **State Hazard Mitigation and Climate Action Plan (SHMCAP)**, which is a nation-leading effort to comprehensively integrate climate change impacts and adaptation strategies with hazard mitigation planning; and,
- Convening the **Resilient MA Action Team (RMAT**), an inter-agency steering committee responsible for implementation, monitoring, and maintenance of the SHMCAP. The RMAT has developed a climate resilience design standards online tool to facilitate the application of statewide climate data to the planning and design of capital projects, and has been applied annually across municipal grant infrastructure programs and the capital planning process.

Across state government, we continue to be focused on meeting the state's ambitious decarbonization goals while preparing for projected climate impacts. In 2021 and 2022, Governor Baker signed comprehensive climate change legislation that codifies into law the Administration's commitment to reach Net Zero emission in 2050 and furthers the Commonwealth's nation-leading efforts to combat climate change and protect vulnerable communities.

The Massachusetts Climate Change Assessment represents a continued commitment to improving the understanding of the impacts of climate change on the people, places, and resources of the Commonwealth, and making updated and improved information available. We will continue partnering with and supporting communities to build their resilience to climate change, and invest in the capacity and expertise needed to ensure the continued development, maintenance, and cross-government application of this information. We look forward to working with all of you to build a more resilient and equitable Commonwealth.

Sincerely,

BETHANY A. CARD

Secretary of Energy and Environmental Affairs

Acknowledgments

The 2022 Massachusetts Climate Change Assessment (Climate Assessment) was developed under the leadership of:

Charles D. Baker, Governor
Karyn Polito, Lieutenant Governor
Bethany A. Card, Secretary of Energy and Environmental Affairs
Kathleen Theoharides, former Secretary of Energy and Environmental Affairs
Gary Moran, Undersecretary of Environmental Policy and Climate Resilience
Judy Chang, Undersecretary of Energy and Climate Solutions

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- Woods Hole Group for their analysis of coastal hazards
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Climate Science Review Panel

An expert review panel consisting of Massachusetts academics with deep climate science and impact assessment backgrounds provided critical input to the use of climate projection data used in the Climate Assessment. The panel consisted of:

- Mathias Collins, National Oceanic and Atmospheric Administration
- Robert DeConto, University of Massachusetts Amherst
- Adam Schlosser, Massachusetts Institute of Technology
- Scott Steinschneider, Cornell University
- Stephen Young, Salem State University

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- Department of Energy Resources (DOER)
- Department of Housing & Community Development (DHCD)
- Department of Labor Standards (DLS)
- Department of Public Health (DPH)
- Department of Public Utilities (DPU)
- Department of Transportation (DOT)
- Division of Capital Asset Management & Maintenance (DCAMM)
- Division of Ecological Restoration (DER)
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- Office of Coastal Zone Management (CZM)
- Office of Preparedness & Emergency Management (OPEM)
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- Healthcare Without Harm
- Mass Audubon
- Massachusetts Association of Community Development Corporations (MACDC)
- Massachusetts Bays National Estuary Partnership (MassBays)
- Massachusetts Food Systems Collaborative
- Massachusetts Lobstermen's Association (MLA)
- Massachusetts Municipal Association (MMA)
- Massachusetts Port Authority (Massport)
- Massachusetts Water Resources Authority (MWRA)
- Mattapan Food & Fitness Coalition (MFFC)
- Metropolitan Area Planning Council (MAPC)
- Mystic River Watershed Association (MyRWA)
- National Grid
- National Oceanic and Atmospheric Administration (NOAA)
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- U.S. Environmental Protection Agency (EPA)
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Community Liaison Organizations

Berkshire Environmental Action Team

Berkshire Regional Planning Agency

Communities Responding to Extreme Weather

Commonwealth Green Low Income Housing Coalition

Franklin Regional Council of Governments

Groundwork Lawrence

Multicultural BRIDGE

Neighbor to Neighbor

Neighborhood of Affordable Housing

Quincy Asian Resources, Inc.

1. Introduction

1.1 Context and Audience

This Massachusetts Climate Change Assessment (Climate Assessment) evaluates a broad range of climate change risks to the Commonwealth, including impacts on public and private assets, natural and cultural resources, and human health. The Climate Assessment serves to directly inform the 2023 update to the State Hazard Mitigation and Climate Adaptation Plan (SHMCAP), specifically concerning the detailed hazard risk assessment. The outputs of the Climate Assessment are designed to meet the requirements for State Hazard Mitigation Planning documents, and to directly inform and provide a risk prioritization focus to the Mitigation Strategy.

This report focuses on assessment of climate change impacts, but a key component of the Commonwealth's strategy for reducing the risks of climate change also includes a leadership role in significantly reducing the greenhouse gas emissions that cause global climate change. The recently published Massachusetts Clean Energy and Climate Plan for 2050 outlines specific carbon emissions reduction actions to be taken in multiple sectors, to achieve net-zero carbon emissions by 2050 and ensure Massachusetts contributes to global efforts to limit climate change and its impacts.[1]

The Climate Assessment is designed for multiple audiences, including the residents of the Commonwealth; stakeholders in the public, private, and non-profit sectors; and state and local agency and elected officials empowered to act on its findings. The Executive Summary in particular is designed to be accessible to all audiences. The main report is targeted toward readers with at least some background in hazard and vulnerability assessment, and the ways in which climate change presents risks to people, assets, and livelihoods across the Commonwealth. Technical appendices are designed for experts in the field, to better understand the details of the methods and data produced by the Climate Assessment.

1.2 Climate Assessment Objectives and Scope

Overall, the Climate Assessment is designed to answer three basic questions:

- How large of an impact do we expect from projected climate hazards on potentially vulnerable human populations, natural environment, and built infrastructure assets?

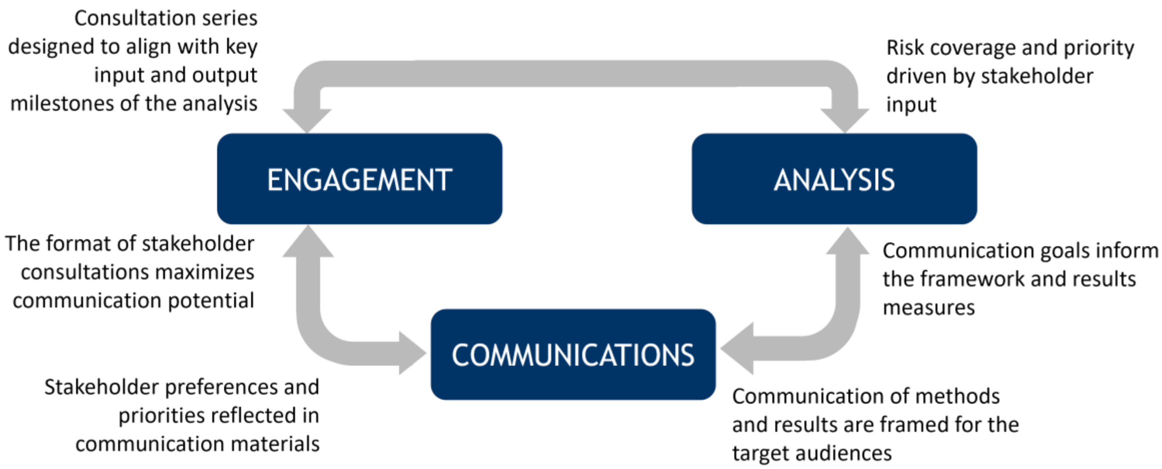
[1] Massachusetts Executive Office of Energy and Environmental Affairs (2020), Massachusetts 2050 Decarbonization Roadmap, published December 2020 and available at: https://www.mass.gov/doc/ma-2050-decarbonization-roadmap/download; Massachusetts EOEEA (2022), Massachusetts Clean Energy and Climate Plan for 2025 and 2030, published June 30, 2022 and available at: https://www.mass.gov/doc/clean-energy-and-climate-plan-for-2025-and-2030/download ; Massachusetts EOEEA (2022), Massachusetts Clean Energy and Climate Plan for 2050, published December 21, 2022 and available at: https://www.mass.gov/info-details/massachusetts-clean-energy-and-climate-plan-for-2050

- Do we expect populations living in environmental justice communities to be affected more than the rest of the population?[2]
- Are we currently doing enough to adapt to these impacts or are there gaps in effective adaptation actions? How soon is action needed?

To answer these questions, a process that embodies three basic principles was pursued, outlined in Figure 1 below:

1. **Public and governmental stakeholder engagement** throughout the development of the study's objectives, scope, preliminary results, and final recommendations.
2. **Rigorous analysis**, including application of best available data to support conclusions, careful research, and a combination of quantitative and qualitative techniques of assessment, using a transparent and consistent risk prioritization method.
3. **Clear and transparent communication**, including publicly accessible products for the engagement process, reporting stages, and publication of results and data.

Figure 1. Principles Applied to Complete the 2022 Massachusetts Climate Assessment



The result is an evidence base which can be used to identify the most urgent impacts to focus action and attention, both statewide and for each of seven diverse geographic regions across the Commonwealth. As outlined in the next section, the sectoral scope of the Climate Assessment is broad, and includes potential impacts of climate change in 37 specific impact categories in the Human, Infrastructure, Natural Environment, Governance, and Economy sectors.

1.3 Organization of this Report

Volume I of this report is the Executive Summary, which addresses both statewide and regional results. Volume II of this report includes four main sections:

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[2] As used in this report, environmental justice (EJ) communities are block groups defined by EEA based on US Census data, for more information see: https://www.mass.gov/info-details/environmental-justice-populations-in-massachusetts

- **Chapter 2** summarizes the approach, including an overview of the scope of the Climate Assessment sectors and regional delineations; details on the assessment of the Magnitude of Consequence, Disproportionality, and Adaptation Gap for each of the 37 impact categories; review of the goals and execution of the stakeholder engagements conducted throughout development of this report; and a brief summary of the key limitations of the Climate Assessment.
- **Chapter 3** provides a broad overview and summary of the climate science applied in the Climate Assessment, and some examples of results of the climate projections developed for the Climate Assessment that connect directly to key climate impacts. Further details on the climate data used in the Climate Assessment can be found in Appendix B.
- **Chapter 4** reports the results of the statewide impact urgency prioritization for each sector, including summaries for each of the top three most urgent impacts per sector. Summaries for the remaining impacts are provided in Appendix A.
- **Chapter 5** summarizes uncertainties and gaps in the findings and results, and next steps.

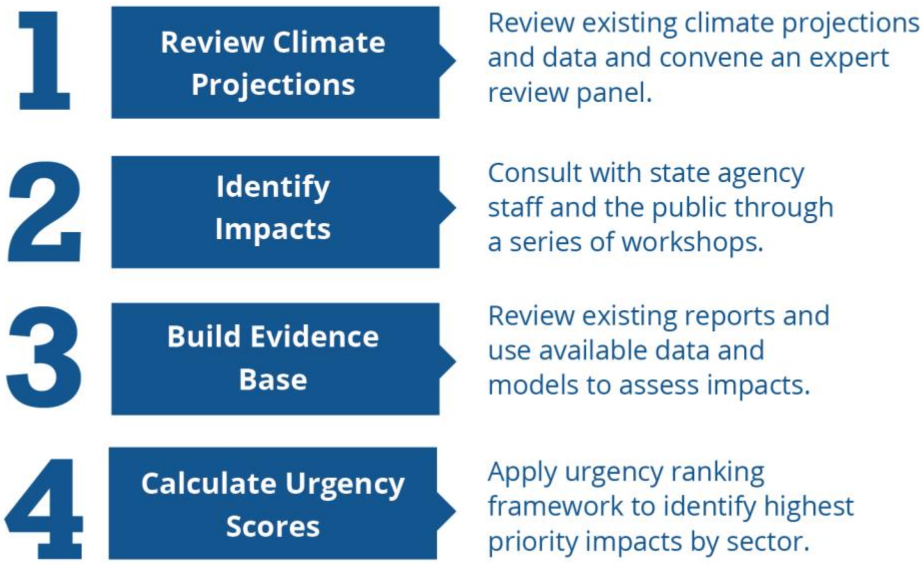
This Volume II also includes a brief glossary and technical appendices on climate inputs, the full set of urgency scores and rankings, detailed assessment methods, and details on the results of each wave of stakeholder engagement. Volume III includes regional impact summaries and more detailed regional reports for the seven regions of the Commonwealth used in this report. The regional products also separately identify the top two most urgent impacts (or three in the case of ties) per sector and per region, for a total of ten regional priority impacts.

Note that the statewide and regional assessments draw from the same methods, data, and evidence base, but the scoring and ranking of priority impacts at the statewide and regional scale are independent of each other. In other words, the statewide rankings are not an aggregation of regional results. The analysis is effectively repeated at the statewide level and for each of the seven regions, reflecting variation across the regions in population and demographics, natural resources, infrastructure, the scope and scale of climate hazards, climate projections, and climate adaptation effort. As a result, different impact priorities can and have been identified at the statewide and regional scales.

2. Approach

This Climate Assessment intends to provide evidence-based priorities to the Commonwealth and community decision makers to guide climate adaptation action. Priority impacts were reached using the process outlined in Figure 2.

Figure 2. Steps used to Reach Ranked Impacts by Urgency



First, the Climate Assessment team reviewed the latest available climate data and selected the data products best fit for Massachusetts and this Climate Assessment. Next, the Climate Assessment team compiled a list of the impacts of climate change by consulting with state agency staff, local and federal government partners, non-profit and community group representatives, and public stakeholders. The list was refined through an iterative process with these stakeholders to reach a set of 37 impacts of climate change most relevant to Massachusetts.

The Climate Assessment team then built an evidence base by evaluating each identified impact to understand the projected outcomes in Massachusetts and understand who is affected most by the changes to answer the questions ***How big of a climate effect will this have?*** and ***Will populations living in environmental justice areas be disproportionally affected***? Populations living in environmental justice areas are identified as the people living in Census block groups characterized as Environment Justice (EJ) population areas by the Massachusetts Executive Office of Energy and Environmental Affairs (EEA) based on demographic characteristics including race and ethnicity, income level, and English language proficiency.[3] The team also inventoried and catalogued over 400 Massachusetts-wide, local, and regional adaptation plans

[3] https://www.mass.gov/info-details/environmental-justice-populations-in-massachusetts

and action descriptions to consider the question ***Are we currently doing enough to adapt to this impact***?

Following the impact urgency framework outlined in Section 2.2.2 and building on this evidence base, impacts were scored and ranked to identify statewide and regional priorities.

2.1 Climate Assessment Methods

2.2.1 Overview of Climate Assessment Sectors

Aligned with the 2018 SHMCAP, this Climate Assessment considers five sectors which represent major categories of projected impacts of climate change with common groupings of exposed assets, individuals, or resources, and that generally fall under the responsibility of similar state agencies. The sectors are:

- **Human:** Impacts to people's health, welfare, and safety
- **Infrastructure:** Impacts to buildings and transportation systems, and how we get our electricity and water
- **Natural Environment:** Impacts to ecosystems and natural resources, and how plants and animals can thrive here
- **Governance:** Impacts to state and local government owned buildings, government finances, and demand on government services
- **Economy:** Impacts to people's ability to work and make a living, due to damages to infrastructure, our natural environment, or people's health, and people's ability to find housing that is affordable.

Sectors are a helpful organizational structure and allow for the prioritization across impacts with similar types of effects, however, it is important to note that the effects of climate change do not fall neatly within the defined sectors, and there are many interactions between impacts both within and across sectors. For example:

- During extreme heat events, relief from air conditioners may become unavailable due to heat-induced power outages. Rail delays associated with high heat events may cause more people to be exposed to high heat conditions for longer while waiting at stations, or if power is lost altogether, the trains may not run. Loss of urban trees further exacerbates extreme heat health effects.
- Habitat shifts in the natural environment impact the productivity of marine fisheries and agriculture. Degradation of forests and wetlands reduce tourism and recreational opportunities and diminish a source of mental health benefits.
- Infrastructure failures during extreme events, such as stormwater and coastal flooding, can lead to contamination releases into the natural environment, including drinking water sources.
- Simultaneous stressors compound the need for government services and response, straining emergency response and recovery systems. Transportation delays and

economic disruptions can reduce people's capacity to repair homes and receive care from adverse health effects.

To the extent possible, these interactions are noted in the Climate Assessment, and the most important ones are listed in a summary at the end of these impact write-ups.

2.2.2 Spatial and Temporal Scale

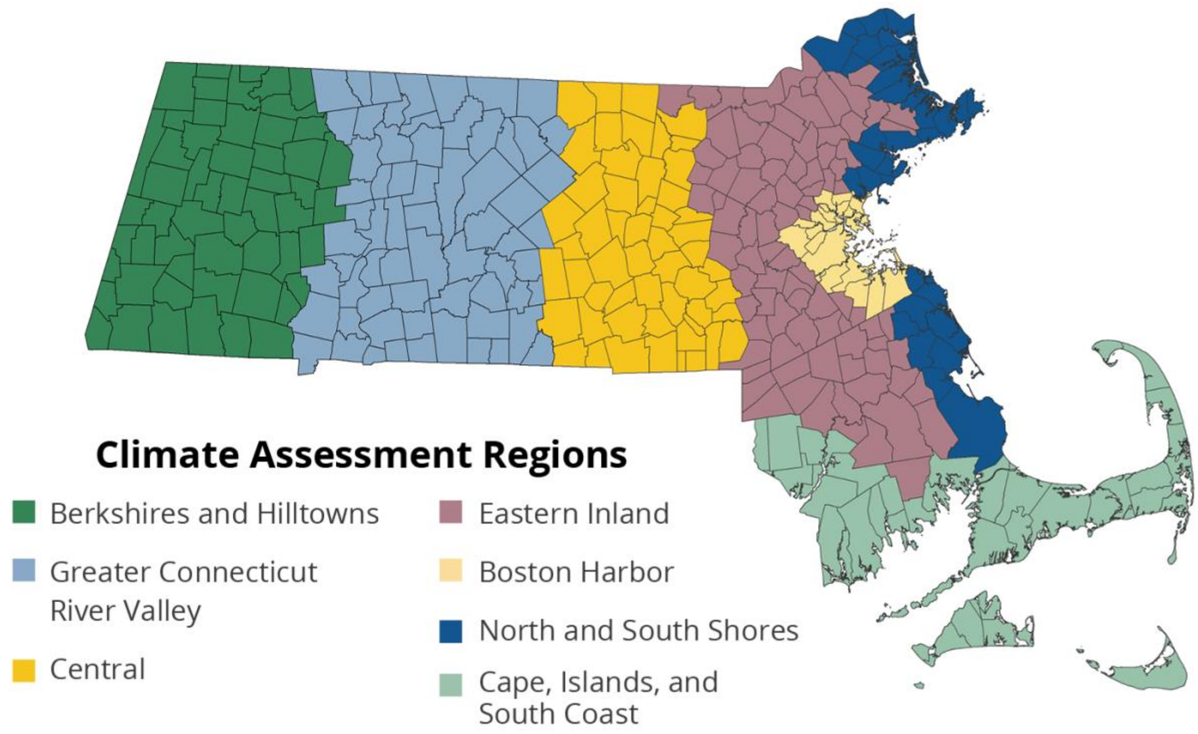
Climate Assessment results are evaluated for four time periods primarily identified in this report by the central year in 20-year periods:

- 2030: near-term (2020-2039);
- 2050: mid-century (2040-2059);
- 2070: mid-late century (2060-2079); and
- 2090: end of century (2080-2099).

The 20-year eras capture general trends in climate over the century and smooth out year-to-year variability in annual trajectories.

The Climate Assessment covers the Commonwealth of Massachusetts. Results are presented and summarized for the Commonwealth as a whole and by seven regions, shown in Figure 3. The seven regions were developed by grouping cities and towns with the goals of aligning with existing planning regions and jurisdictions and grouping areas that face similar climate risks, have similar vulnerabilities, and share affinity with other cities and towns in the region.

Figure 3. Massachusetts Climate Assessment Regions



Generally, the Climate Assessment regions match the Municipal Vulnerability Preparedness (MVP) Program regions central to various planning initiatives in the western and central areas of the Commonwealth. MVP regions that include coastal areas are split to identify areas where sea level rise and other coastal hazards are expected.

Table 1 presents basic demographic information by region using data provided in the 2020 Census for total population and the 2019 American Community Survey (ACS) five-year estimates for demographic characteristics. This combination of data sources represents the best available population data, as the 2020 Census provides the most up-to-date population counts but does not provide the same level of demographic information as the 2019 ACS at the time of publishing this report. The Massachusetts 2020 EJ Viewer also relies on the 2019 ACS data for demographic information.

Table 1. Demographics by Climate Assessment Region

Region	Total Population (2020)	% minority	% low-income	% households with limited English language proficiency	% of block groups with any EJ designation
Berkshires & Hilltowns	156,440	12.7%	24.9%	1.2%	37.7%
Greater Connecticut River Valley	788,189	32.8%	30.9%	4.7%	52.0%
Central	960,236	27.4%	20.4%	4.7%	39.9%
Eastern Inland	2,112,456	31.4%	16.7%	4.9%	37.0%
Boston Harbor	1,623,633	50.7%	27.0%	10.2%	66.5%
North & South Shores	731,000	25.4%	20.1%	4.1%	30.9%
Cape, Islands, & South Coast	657,963	20.4%	25.4%	4.4%	38.6%
Statewide	7,029,917	33.4%	22.5%	5.9%	45.9%

Source: 2020 Census (Population); 2019 ACS 5-year estimates (demographcis); EEA EJ Viewer (EJ designations)

2.2.3 Impact Urgency Framework

Each impact is assigned a statewide urgency score and regional urgency scores to assist in prioritizing adaptation action within each sector. This volume focuses on the statewide scores; regional scores and rankings are presented in Volume III.

The approach is modeled after the 2020 National Climate Change Risk Assessment for New Zealand, with modifications to meet the needs of Massachusetts. Impact Urgency Scores are assigned based on three components:

Magnitude of Consequence. How large of a climate effect do we expect from this impact?
Consequence scores are built from an evidence base of quantified physical impacts (e.g., modeled projections of acres of marsh lost, number of buildings flooded); quantified economic impacts, including changes in expenses or revenues and welfare measures (e.g., delay cost, health risk); and qualitative measures of the impacts of climate change, specified for each sector. In many cases, the available information allows for one quantitative measure per impact with supporting qualitative findings used to modify the consequence score. The level of concern stakeholders hold for each impact also factors into the magnitude of consequence rating (i.e., high stakeholder concern leads to a higher magnitude of consequence rating in some supported

cases), particularly for emerging risks where evidence is lacking in the literature, but lived experiences of residents shared with the Project Assessment team during stakeholder engagement provide evidence for higher levels of consequence. Where possible, dollar losses are estimated, including losses on state assets, as required under the Federal Emergency Management Agency (FEMA) State Hazard Mitigation Planning requirements [44 CFR §201.4(c)(2)(ii) and §201.4(c)(2)(iii)]).

Examples of models utilized in this Climate Assessment include the Massachusetts Coast Flood Risk Model (MC-FRM) – a customized coastal flood risk tool that integrates changes in sea level, tropical storm activity, and "sunny-day flooding"; the Benefits and Mapping Analysis Program (BenMAP) for air pollution and pollen analyses; and a broad range of other health, infrastructure, and natural resource impact models developed by the US Environmental Protection Agency for the Framework for Estimating Damages and Impacts (FrEDI – an effort to project physical and economic measures of climate change in the U.S. using standardized methods and climate science inputs).

Magnitude of consequence scores are classified on a five-point scale, ranging from Extreme – the largest and most impactful outcomes in each sector—to Insignificant. At the Commonwealth-level, no impacts receive an Insignificant score, as the impacts elevated for this Climate Assessment meet a threshold of consequence for inclusion. At the regional level, Insignificant scores occur primarily for impacts driven by coastal hazards in inland regions. Note that this step of the analysis also considers some of the positive effects of climate change (e.g., less need for space heating in the winter) but the net effect of climate change tends to be negative (e.g., increased need for space cooling and air conditioning in summer). Scores for this component focus on the magnitude of the impacts of climate change rather than the general magnitude of the issue. Some impacts, for example those regarding food security, affordably priced housing, and mental health, have many contributing factors; here the focus is the effects of climate change on the issue.

Disproportionality of Exposure. Will populations living in Environmental Justice areas be affected more than the rest of the population?

Disproportionality scores evaluate whether areas identified as Environmental Justice (EJ) population areas are disproportionately exposed to the impact. [4] Scores are evaluated both quantitatively and qualitatively. The quantitative evaluation involves comparing the average magnitude of consequence in EJ population areas to the average consequences in other areas of the Commonwealth. EJ population areas are identified following the EEA's June 2021 Environmental Policy. In that policy, EJ population areas are identified at the Census block group level, where Census block groups typically include between 250 and 550 households. There are approximately 5,000 block groups in the Commonwealth.

[4] As defined by the Commonwealth, "Environmental Justice (EJ) is based on the principle that all people have a right to be protected from environmental hazards and to live in and enjoy a clean and healthful environment. EJ is the equal protection and meaningful involvement of all people with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies and the equitable distribution of environmental benefits." See: https://www.mass.gov/environmental-justice

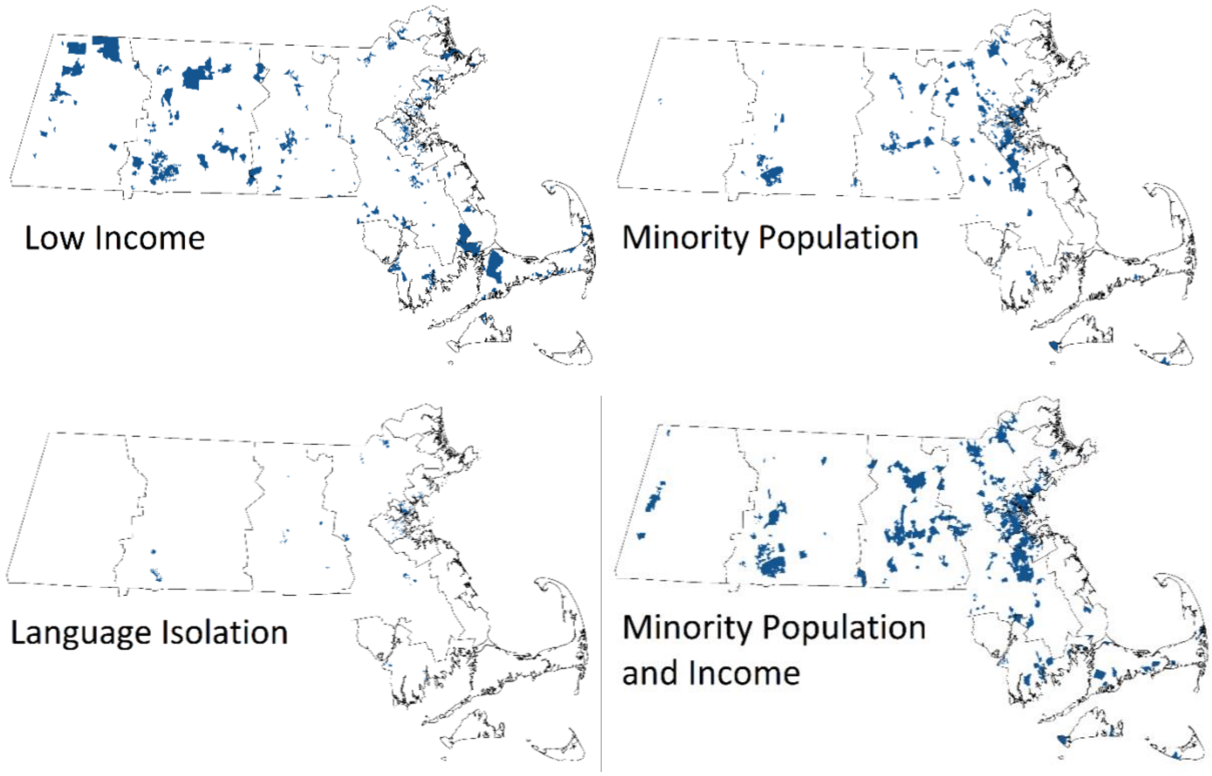
EJ block groups are defined on the basis of each of the following criterion:

- **Low-income:** the annual median household income is 65 percent or less of the statewide annual median household income
- **Minority:** minorities make up 40 percent or more of the population
- **English Isolation:** 25 percent or more of households identify as speaking English less than "very well"
- **Minority and Low-income:** minorities make up 25 percent or more of the population and the annual median household income of the municipality in which the neighborhood is located does not exceed 150 percent of the statewide annual median household income.

Figure 4 shows the location of EJ block groups for all criteria reflected in the June 2021 EEA Environmental Policy.[5] Note that all Climate Assessment regions include EJ block groups.

Figure 4. Environmental Justice Block Groups by Criteria

Maps show the distribution of environmental justice block groups across the Commonwealth. Definitions of each group are provided above. Note that the 'Minority Population and Income' category uses different thresholds than each of the two individual categories.



Source: https://www.mass.gov/info-details/environmental-justice-populations-in-massachusetts

[5] The Commonwealth has also established the Environmental Justice Council which is specifically tasked by law with reviewing the definition of EJ communities on an ongoing basis. More information on the activities of the EJ Council can be found at: https://www.mass.gov/orgs/environmental-justice-council

A Note on the Use of the Term 'Minority'

The term 'minority' is used in this report for consistency with existing statutes and state policy that utilize that term, citing specific threshold percentages of racial demographics as criteria for identifying EJ populations under Massachusetts law. While recognizing that the term may be outdated, it is used here in order to clearly align the goals of the statewide Climate Assessment with the goals of EEA's EJ Policy and the "EJ Principles" defined in Chapter 8 of the Acts of 2020 (An Act Creating a Next-Generation Roadmap for MA Climate Policy).

Some impacts rely on qualitative assessments of disproportionality, either where spatially refined information is not available to compare impacts at the block group level or where certain populations are known to have disproportionate exposure that is not captured by where people live, for example workers in certain industries.

Disproportionality is measured on a three-point scale:

- **Limited Disproportionality:** The analysis does not find a quantitative positive correlation between the locations of exposure to the given impact and EJ population areas, and available qualitative information does not suggest a highly disproportionate exposure. For impacts with this score, it is important to note that not all populations will have the same experience with the effects of climate change and the impact because of pre-existing social vulnerabilities that are difficult to measure or comprehensively quantify across the Commonwealth.
- **Potential for Disproportionality:** Some quantitative or qualitative evidence available to suggest exposure to the impact is disproportionate. In the case of Natural Environment sector impacts, all impacts receive this score as all residents interact and have value for natural resources and it is difficult to disentangle if certain populations are more or less affected by changes to natural resources.
- **Disproportionate Impacts:** Available evidence shows populations defined by the EEA EJ Policy are disproportionately exposed to the given impact.

Need for Effective Adaptation. *Are we currently doing enough to adapt to this impact or are there gaps in effective adaptation actions? How soon is action needed?*

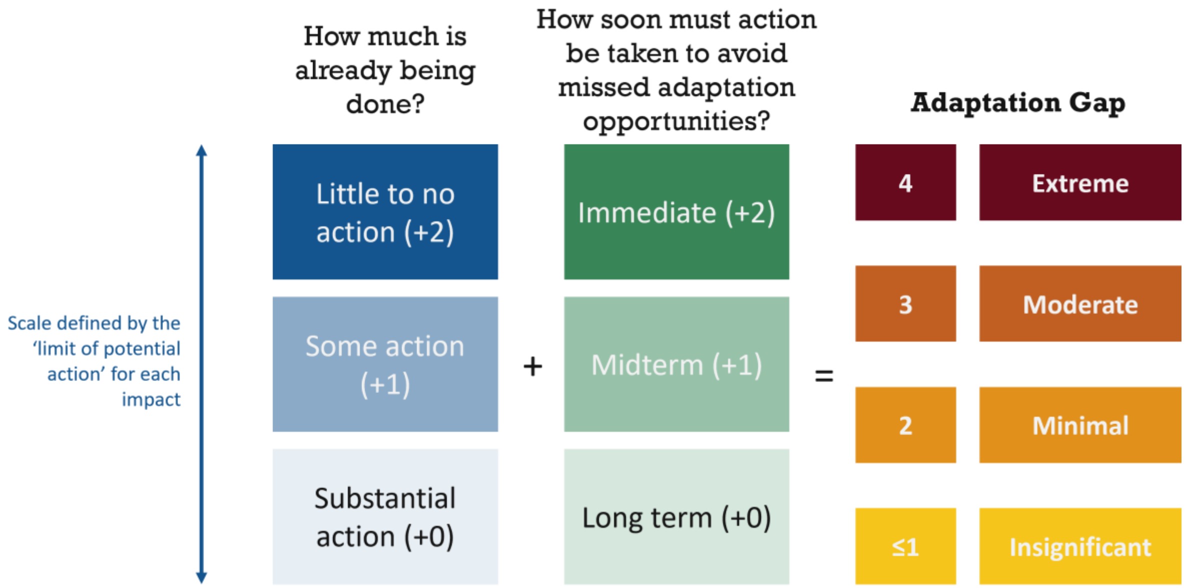
The adaptation gap score is intended to take stock of the actions currently underway to address each impact and identify any time pressures for the need to adapt. Adaptation gap scores are assigned to each impact by applying the following approach:

1. **Develop database of adaptation actions and plans.** The database of adaptation actions and plans was constructed primarily from four sources: Appendix F of the 2018 Massachusetts SHMCAP, the SHMCAP Action Tracker, the MVP Action Grant database, and Georgetown Climate Center's Adaptation Clearinghouse (an online database of state and local adaptation plans). A web-based search for hazard mitigation and climate action and adaptation plans, with emphasis on the state's largest municipalities by population, supplemented these lists. More than 400 climate adaptation and hazard mitigation documents were collected, which describe plans or actions ranging from state, region, city/town, and even site-specific scales.

2. **Analyze actions and plans for relevance to Climate Assessment impacts.** Each document was assigned a unique identifier, the document was read, and its contents were coded to identify all climate-related adaptation actions described in the document. Each action code was recorded in the database and further annotated with plan specific details (e.g., street name, dam location), scale of action (i.e., state, region, city/town, site), and degree of progress (e.g., planning/assessment = 1, action implementation = 2). Actions were then assessed to identify which of the 37 impacts it would most effectively address (actions could be assigned to more than one impact). Action codes were mapped to the climate impacts in the database. Finally, the database created automated summations of action codes, which were further organized by impact, scale, and region.
3. **Evaluate actions by impact and assign an adaptation gap score.** After reviewing, coding, and annotating each climate adaptation document, each identified action was examined by impact and to assess the ability of each action to mitigate risk of the impact. Using these data and the framework in Figure 5, each impact is assigned an adaptation gap score. The score is a summation scoring metric that assesses how much is already being done to address each impact and how quickly does action need to be taken to avoid missed adaptation opportunities. The adaptation gap score can range from “insignificant” to “extreme”.
    - The evaluation of “how much is already being done?” considers the possible adaptation actions for the impact and rate adaptation action in Massachusetts compared to the possibility of effective action (where effective action considers both the magnitude of the problem and the availability of known solutions). Two impacts with the same number of actions may receive different scores based on the possible actions available and the scale and scope of current actions.
    - The evaluation of “How soon must action be taken to avoid missed adaptation opportunities” considers the timing of impacts as identified in the magnitude of consequence analysis. It also considers the planning and implementation time horizon required for available adaptation actions. An impact could receive a higher rating if a) large impacts are expected in the near term, and/or b) available adaptation actions will take significant time to plan and implement.

Figure 5. Adaptation Gap Scoring Framework

Each impact is scored according to the following framework, which evaluates action to date and time pressures on adaptation.



Note that modeling and other information gathering activities, as well as planning documents are considered in this assessment as they represent key first steps in adaptation for many impacts. However, when assessing the adaptation gap, this type of activity is considered to close the gap less than on-the-ground actions.[6]

Urgency Score Calculation

Impacts are given a score ranging from 0 to 100 for each of the three components described above. Scores for the three components are averaged to calculate an urgency score, shown in Figure 6.[7] Urgency scores are intended to be compared within sectors, and not across sectors, because rankings are assigned within each sector relative to other impacts in that sector. Using this framework, the impacts receiving the highest urgency score (or the highest priority impacts for adaptation actions) are those that have large projected effects, disproportionately affect

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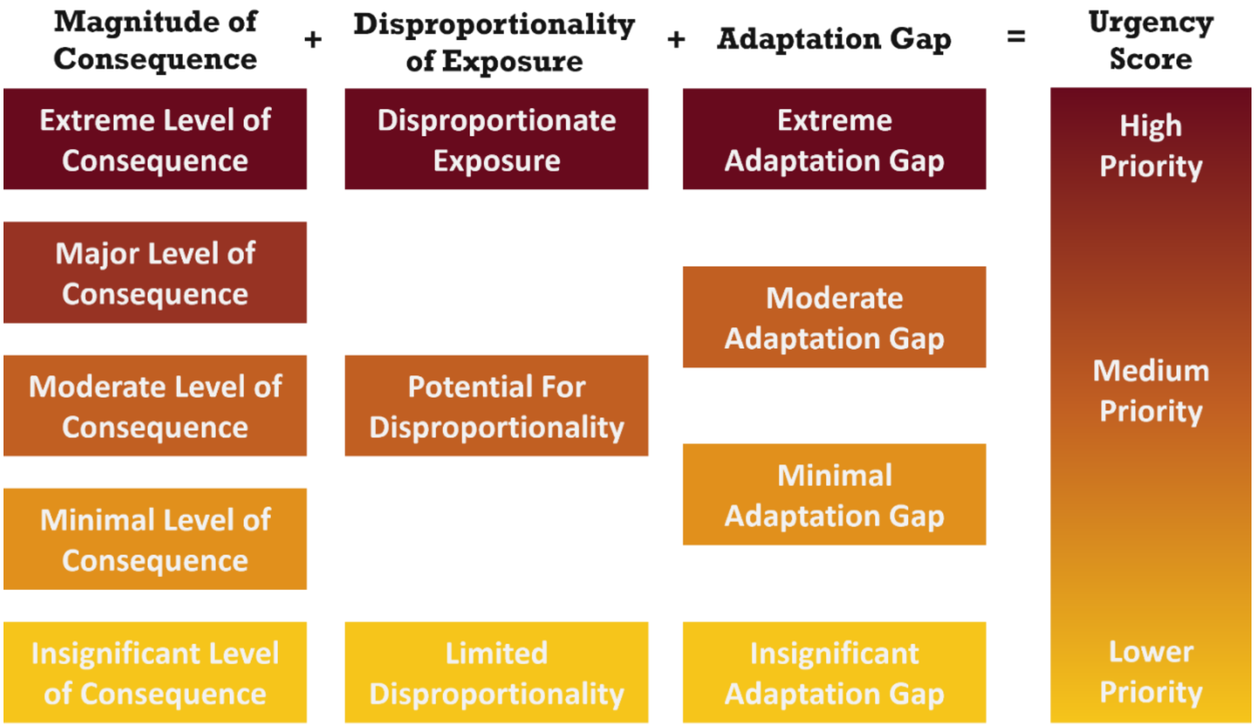
[6] Planning alone is likely to result in a Moderate to Extreme adaptation gap score as this type of work often represents 'Little to no action' in terms of 'How much is already being done?', however it can reduce the need for immediate action (e.g., to Midterm) in some cases by increasing certainty around needed actions. Depending on the limit of potential action, planning paired with modest on the ground action could result in a minimal adaptation gap.

[7] Note there are a different number of categories in each component (i.e., five magnitude categories, three disproportionality categories, and four adaptation gap categories) due to limitations in precision. Therefore, the difference in scoring between the any two adjacent categories differs by component. For example, 'Disproportionate Exposure' equals 100 points and 'Potential for Disproportionality' equals 50 points, a 50-point swing, while 'Extreme Level of Consequence' equals 100 points and the second highest magnitude category, 'Major Level of Consequence' equals 75 points, only a 25-point swing. Furthermore, the magnitude scores tend to be skewed towards higher scores at the statewide level because the set of 37 impacts was selected as the highest potential impacts. Therefore, the disproportionality score tends to have a high weight in the final average urgency score and rankings by sector. See urgency scores by impact in Appendix A.

socially vulnerable groups, and for which adaptation actions are needed soon and current actions do not do enough to mitigate the risks.

Figure 6. Urgency Score Components

Each impact is evaluated for the three components on the left of the graphic. Scores are averaged to calculate an urgency score, which is a measure of the priority of the need for adaptation for each impact within each sector.



Limitations

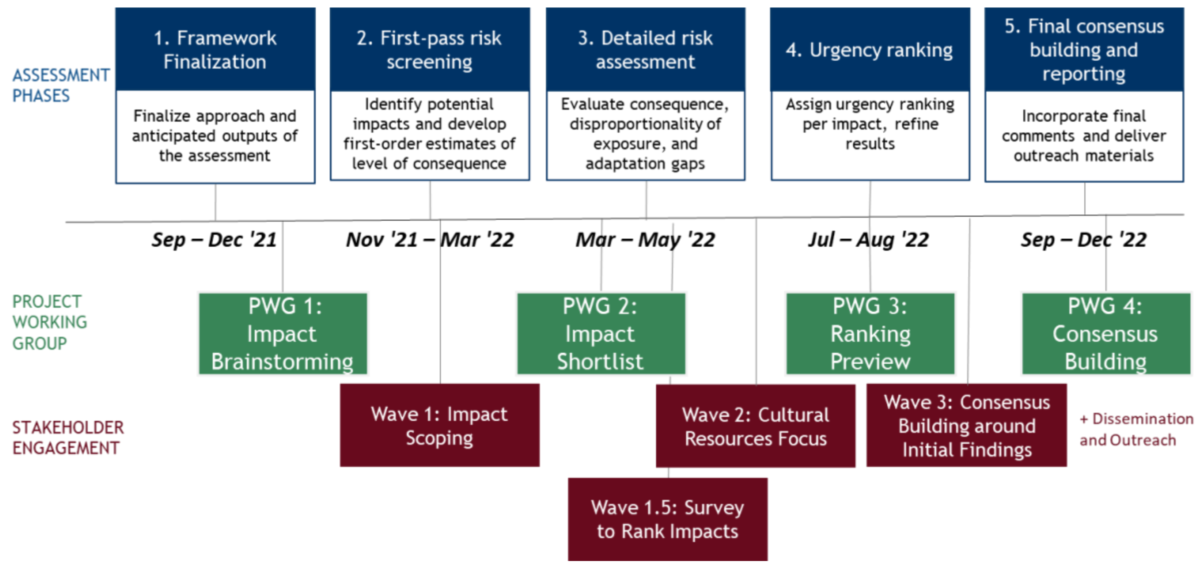
Estimating climate parameters, vulnerabilities, and impacts for all areas of the Commonwealth, through the end of the 21st century, necessarily involves multiple uncertainties and limitations. Some of the climate forecast uncertainties are reflected in the summary of climate inputs provided in the next chapter, with reference to the range of projected outcomes for temperature and precipitation across available climate models. In addition, each of the statewide climate impact summaries in Chapter 4 includes a section on key limitations and uncertainties that are specific to that sector and impact category.

2.2 Stakeholder Engagement Plan

Throughout the process, stakeholders from within state, federal, and non-governmental organizations, which formed the Project Working Group (PWG) and the public have played an important role in defining the set of impacts evaluated in the Climate Assessment and providing data and insights to augment the analysis. Figure 7 shows the key interactions with each group as they fit into the assessment phases. Both groups participated in the process of drafting a “long list” of climate impacts and narrowing that list into the “shortlist” of 37 impacts (7-10 per sector) included in the detailed assessment. A detailed description of the stakeholder engagement activities supporting this Climate Assessment is provided in Appendix C of this report.

Figure 7. Project Working Group and Public Stakeholder Engagement Activities

The Project Working Group (PWG) and public stakeholders provided critical inputs and review throughout the Climate Assessment, as shown in this figure.



Public stakeholder engagement occurred in three waves over the course of the Climate Assessment. A team of community liaisons from across the state encouraged participation in the public conversations. In each wave, stakeholders were asked to answer a key question to inform the Climate Assessment. Input from these conversations resulted in additional impacts added to the Climate Assessment and refinement of urgency scores based on evidence relayed from stakeholders. Select stakeholder quotes submitted in an online survey are presented in callout boxes in Chapter 4. Example comments presented are chosen to represent the common themes heard, not only in the survey, but across all public stakeholder engagement activities. See Appendix C for more information on the community liaisons involved in the Climate Assessment and an accounting of how stakeholder feedback informed the impacts assessed and component scoring.

Table 2. Stakeholder Engagement Waves

Waves	Key Question	Primary Outreach Modes
Wave 1	What impacts of climate change are you concerned about?	• Public Meetings (virtual)
Wave 2	Which of the identified impacts of climate change concern you most? What cultural resources are at risk in a changing climate?	• Public Meetings (virtual) • Online Survey • Focus Groups
Wave 3	What feedback do you have on the draft Climate Assessment report?	• Focus Groups

3. Climate Change in Massachusetts

Massachusetts' current climate, and the threat of future climate change, is the result of two key dimensions of weather: temperature and precipitation. Changes in global temperatures over time also contribute to a third key dimension of climate change, sea level rise. As outlined in the 2018 State Hazard Mitigation and Climate Adaptation Plan (SHMCAP), the present day climate gives rise to a suite of natural hazards, which are expected to be exacerbated by future climate change and are addressed in this document, and include inland flooding and drought (associated with precipitation); coastal flooding and coastal erosion (associated with sea level rise and extreme weather, both of which are linked to global temperature); heat waves and conditions that foster vector-borne disease and changes in species distribution (associated with local temperature); and extreme weather, including hurricanes, severe winter storms, and strong windstorms (associated with temperature and the moisture holding capacity of the atmosphere).

Because weather is constantly changing, it is challenging to determine a single "current climate." For the purposes of this assessment, the incremental risks of climate change are established by reference to a baseline scenario from which the projected future risks of climate change are measured. The climate baselines used, by necessity, vary by the source of the climate data. In addition to temperature and precipitation, this climate baseline also reflects the frequency of extreme events, such as rainstorms, windstorms, and tropical cyclones.

3.1 Climate Data Review

A key input to the Climate Assessment is high-quality and up-to-date climate projections, which are critical to evaluating the areal extent, severity, and frequency of relevant climate hazards, and how they may change relative to the "current climate" baseline. The Climate Assessment team worked with an external peer review panel of climate scientists, with expertise in projections of temperature, precipitation, sea level rise, and coastal and inland storm incidence specific to Massachusetts, and affiliated with Massachusetts Institute of Technology; University of Massachusetts at Amherst; Cornell University; Salem State University; and the National Oceanic and Atmospheric Administration (NOAA). Based on consultation with the panel, the Climate Assessment relies on five sources of climate projections or impact-based climate datasets:

1. ***Cornell University's Stochastic Weather Generator Dataset.*** This source provides projections of temperature and precipitation variables, for four future eras (2030, 2050, 2070, and 2090) for the 10^{th}, 90^{th}, and median percentiles. It relies on projections from among 20 Global Climate Models (GCMs) for the Representative Concentration Pathway

(RCP) 8.5 greenhouse gas emissions scenario. The baseline climate for this source is 1950-2013. [8]

2. ***Cornell University's Scaled Intensity-Duration-Frequency (IDF) Curve Dataset.*** This dataset scales "current climate" IDF curves provided in NOAA Atlas 14 by the theoretical rate of increase in atmospheric moisture holding capacity that is correlated with projected temperature increases.[9] The data are provided for a range of future potential temperature increases. The baseline climate for this source is consistent with that in the NOAA 14 documentation, which is 1981-2020.
3. ***Downscaled Global Climate Models (GCMs) from the Multivariate Adaptive Constructed Analogs (MACA) repository.*** The Climate Assessment preferentially uses information from the Stochastic Weather Generator or Scaled IDF curves, which synthesize and interpret information from global climate models in readily accessible formats, such as estimates of the number of days exceeding certain temperature thresholds. As the external peer review panel acknowledged, however, for some impact categories data from downscaled global climate models were directly accessed, to more closely align with specific temporal or spatial aspects of impact models applied in the Climate Assessment.[10] GCMs produce large amounts of data that should be carefully interpreted, but the detailed daily projections of both temperature and precipitation are useful for some impact estimates that rely on the daily sequence of hot/cold and wet/dry days. MACA is a statistically downscaled interpretation of GCMs that is well-suited for use in the Climate Assessment.[11] MACA uses a 1971-2000 baseline period.

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[8] The Stochastic Weather Generator and the Scaled IDF Curve Dataset reviewed in this Climate Assessment are outputs of EEA's Massachusetts Climate and Hydrologic Risk Project (Phase 1). For the Stochastic Weather Generator, see Steinschneider, S., and Najibi, N. 2022. A weather-regime based stochastic weather generator for climate scenario development across Massachusetts, Technical Documentation, Biological and Environmental Engineering, Cornell University, Ithaca, NY, April 2022. For the IDF curve approach, see Steinschneider, S., and Najibi, N. 2022. Observed and Projected Scaling of Daily Extreme Precipitation with Dew Point Temperature at Annual and Seasonal Scales across the Northeastern United States, Journal of Hydrometeorology, 23 (3): 403-419, DOI: https://doi.org/10.1175/JHM-D-21-0183.1.

[9] NOAA Atlas 14 contains precipitation frequency estimates for the United States and U.S. affiliated territories with associated 90 percent confidence intervals and supplementary information on temporal distribution of heavy precipitation, analysis of seasonality and trends in annual maximum series data, and other information useful for design of infrastructure and hazard mitigation projects. Documentation is available here: https://www.weather.gov/media/owp/oh/hdsc/docs/Atlas14_Volume11.pdf

[10] For example, where impact results are based on mean seasonal to annual precipitation projections, such as drinking water supply and agriculture, the peer review panel recommended use of downscaled GCMs. In addition, in cases where existing published research is accessed, the impact models could not re-run using a different climate projection (e.g., air quality in Human sector, Inland Flooding in Infrastructure sector), and the Climate Assessment therefore relies on the source of climate projections used in the existing study (often but not always LOCA or MACA).

[11] MACA is based on the Intergovernmental Panel on Climate Change's (IPCC) Coupled Model Intercomparison Project (CMIP5) ensemble and employs a quantile mapping and constructed analogs approach, a methodology that is similar to other options for downscaled GCM data but which also provides a daily synoptic weather field and additional climate inputs such as wind speed and solar radiation that are not available from other products. More details on the MACA approach are included in Appendix A.

Some impact categories instead use another downscaled GCM source, the Localized Constructed Analogs (LOCA) repository, which uses a baseline of 1986-2005.[12]

4. ***The Metropolitan Area Planning Council (MAPC) Land Surface Temperature Index.*** This source provides a spatially downscaled representation of temperature peaks for historical periods, taking explicit account of local heat island and other anomalies. Originally developed for the Greater Boston metropolitan area, this product was recently extended to all of Massachusetts. The most recent version of these data is based on interpretation of satellite data from 2018 through 2020.
5. ***The Massachusetts Coast Flood Risk Model (MC-FRM).*** This source incorporates climate projections, including sea level rise and coastal storm frequency and intensity projections, and processes those projections to develop risk-based climate datasets for water surface elevation (corresponding to "stillwater levels" excluding wave heights), and annual exceedance probability scenario layers. When considering coastal flooding, which combines consideration of sea level rise, coastal storm frequency and intensity, and tides, the baseline period corresponds to a 19-year tidal epoch of 1999 to 2017, centered on 2008.

Many of the models and approaches used in the Climate Assessment are flexible in their inputs and can be readily applied using data from a wide range of sources. Some use a combination of the above listed sources to estimate impacts. For the coastal climate impact assessment, the MC-FRM tool was applied using a specific set of climate data projections relevant to estimating coastal flood risk, specifically, a projection of sea level rise and coastal storm activity (both extratropical and tropical storms). The MC-FRM does not directly estimate these climate projections but processes them as inputs to assess risks of coastal flooding. Clarifying details of the sea level rise, storm, and other inputs used in statewide applications of the MC-FRM are provided in Appendix B.

3.2 Summary of Climate Stressors and Key Hazards Projected to Result from Climate Change

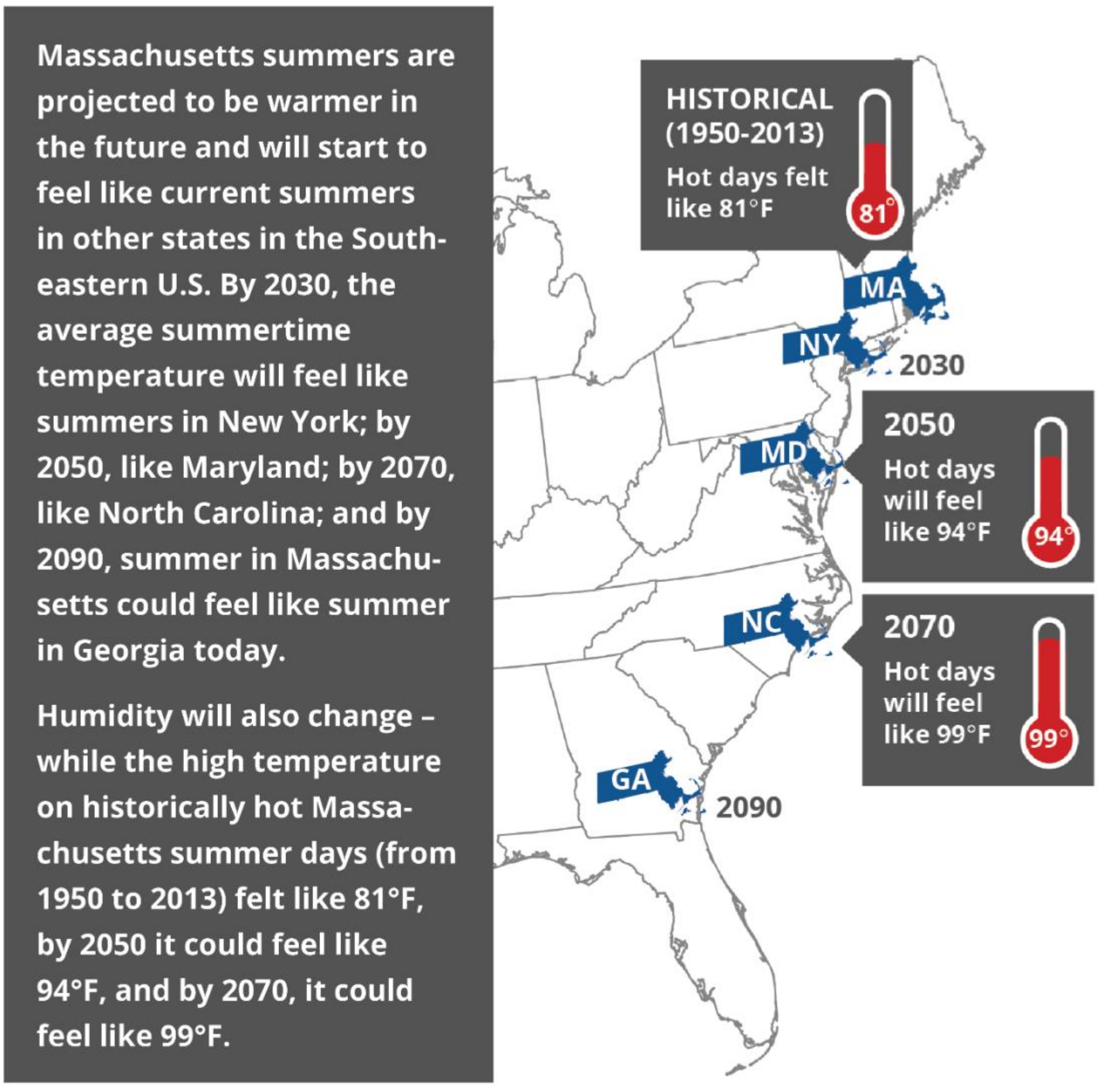
The remainder of this chapter provides a summary of the climate inputs used in the Climate Assessment, including relevant details about trends in the climate projections for each of the four projection eras (2030, 2050, 2070, and 2090) and variation across Massachusetts regions used for the Climate Assessment.

[12] The impact analysis exceptions that employ the LOCA data make use of impact data and methods from the U.S. EPA's Climate Impacts and Risk Analysis project. While those studies are national in scope, they generate climate impact estimates using Massachusetts local data at the watershed, county, Census tract, or Census block group level, but rely on application of the LOCA data employed in the U.S. Global Climate Research Program's National Climate Assessment. Examples include the air quality, extreme temperature, and vector-borne disease impacts in the Human sector; Electric Transmission and Distribution, Inland Flooding, and Damage to Roads and Rails impacts in the Infrastructure sector; water quality estimates for the Freshwater Ecosystem Degradation impact in the Natural Environment sector; and Agriculture, Marine Fisheries, and Reduced Ability to Work impacts in the Economy sector, Details are included in the individual impact write-ups, also see www.epa.gov/CIRA for more information.

Temperature

Warmer temperatures and more frequent heat waves are connected to impaired human health, increased droughts, reduced agriculture yields, species range shifts, and damaged infrastructure. Figure 8 below summarizes how summer temperature could be expected to change in Massachusetts over the next century. These warmer temperatures and more heat waves prompt adaptation actions to improve human health, mitigate droughts, change agricultural practices, and conduct infrastructure repairs and ecosystem restoration.

Figure 8. Change in Average Summertime Temperatures for Massachusetts

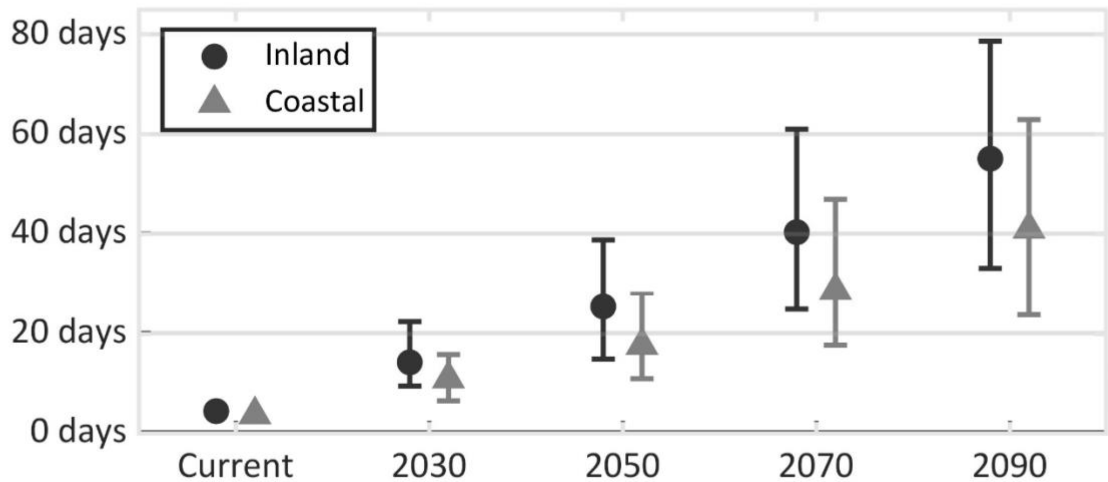


Source: Stochastic Weather Generator and analysis of LOCA GCM data outside of Massachusetts

Figure 9 provides a different perspective, focused on the number of days per year where temperatures could exceed 90°F, compared to current climate. The available climate model projections all show a warming trend throughout the 21st century, with inland areas warming faster than coastal areas. By mid-century, the median projection has about 25 more days above 90°F for inland areas, and about 19 more days above 90°F for coastal areas. Overall, compared to inland areas, coastal areas would see between 25 and 30 percent fewer days per year with maximum temperatures above 90°F – but these coastal areas nonetheless see a substantial increase in extremely hot weather.

Figure 9. Change in the Number of Days Per Year Over 90°F Compared to Current Climate

Current climate is the 1950-2013 era, projections are for 20-year eras centered on the year shown from the Stochastic Weather Generator. Black circles represent the median (50th percentile) projections for inland regions (Berkshires and Hilltowns, Greater Connecticut River Valley, Central, and Eastern Inland), gray triangles represent mean for coastal regions (North and South Shore, Boston Harbor, and Cape, Islands, and South Coast). The brackets show the range from the 10th to 90th percentile, providing a measure of uncertainty in the projections.



Source: Stochastic Weather Generator

The estimates in Figure 9 do not include the effect of changes in humidity. As temperatures rise, the air can hold more moisture – and available estimates suggest that absolute humidity will increase over time, making these temperatures feel even warmer. In other words, every 90°F day in the future could feel warmer, and have a greater impact on human health for example, than current 90°F days.

In addition, the spatially averaged estimates in Figure 9 do not reflect substantial variation in hotter weather across the Commonwealth, associated with urban heat island effects. Figure 15 in the next chapter provides the geographic distribution of current extreme temperature hot spots, representing areas among the top 5 percent of the Land Surface Temperature index. The figure shows hot spots concentrated mainly in the most populous portions of the Commonwealth, in Boston, Worcester, and Springfield, as well as other urban areas of the state. The correlation between extreme heat and larger population centers an important impact on population health, as described further in Chapter 4.

Season Length

Changes in temperature regimes can also alter the length of seasons from baseline climate periods, for example, extended but more intensely hot summers and shorter and more mild winters. These changes have effects on both human and natural systems, such as changed recreation patterns and opportunities, and changes in the timing of key phenological events in plant species, such as flowering and pollen release.

Estimating changes in season length is complicated by the lack of well-established measures for changes in seasons (other than calendar time). A complex indicator used in one of the impact analyses, exposure to certain types of pollen (aeroallergens) is an indirect measure of changes in seasons, which reveals increase in pollen season of 10 to 15 percent over the century for selected pollen types (oak, birch, and grasses). Other physical indicators used in the Natural Environment sector, such as for forest health, may also be informative. One commonly used measure that is temperature-based and readily available from the Stochastic Weather Generator is Growing Degree Days (GDD), which are generally used in plant phenology to estimate the growth and development of plants and insects during the growing season. The basic concept behind GDD is that plant growth will only occur if the temperature exceeds some minimum development threshold, or base temperature. Table 3 provides these projections for all regions of Massachusetts, and statewide. The projections show large increases in GDD relative to baseline estimates, increasing by about one-third by mid-century and by almost two-thirds by the end of the century.

Table 3. Changes in Growing Degree Days

Future projections presented for four time periods identified in the table by their central year: Baseline is 1950-2013; 2030 (near-term, 2020-2039); 2050 (mid-century, 2040-2059); 2070 (mid-late century, 2060-2079); and 2090 (end of century, 2080-2099).

Region	Baseline Growing Degree Days	Percent Change from Baseline			
		2030	**2050**	**2070**	**2090**
Berkshires & Hilltowns	2,586	22%	40%	54%	67%
Greater Connecticut River Valley	2,670	21%	37%	51%	64%
Central	2,882	21%	34%	49%	60%
Eastern Inland	3,018	21%	33%	49%	61%
Boston Harbor	3,083	21%	32%	49%	60%
North & South Shores	2,941	22%	35%	50%	63%
Cape, Islands, & South Coast	2,938	24%	36%	51%	64%
Statewide	**2,818**	**22%**	**36%**	**51%**	**63%**

Source: Stochastic Weather Generator

Precipitation

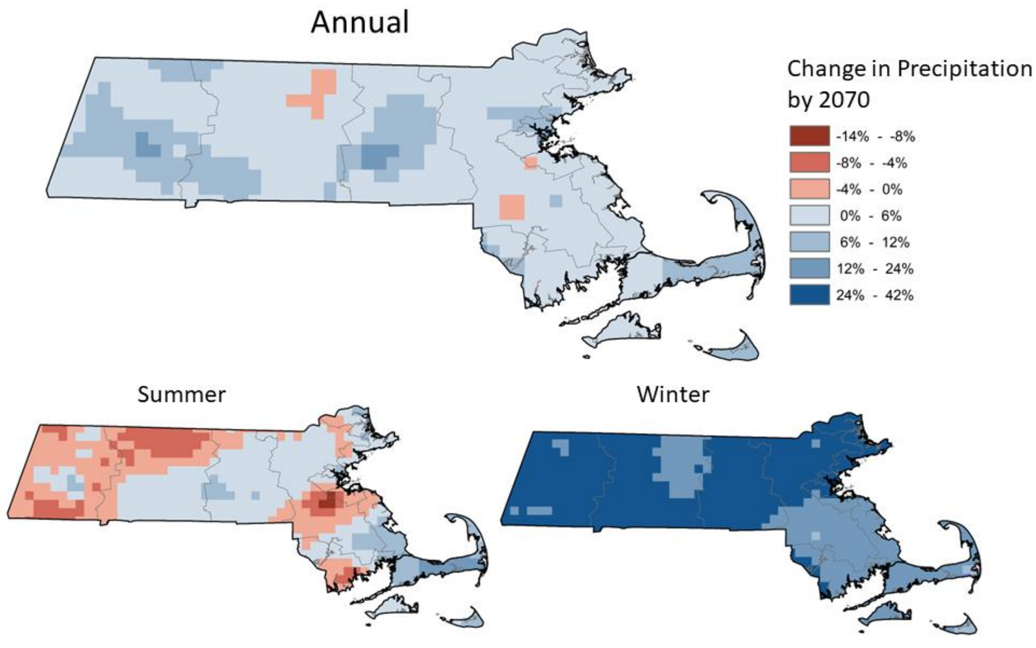
Forecasting precipitation under climate change is more complex. In general, scientists expect that there will be more rain overall in Massachusetts, on an annual basis and in most years, as higher temperatures will mean the moisture holding capacity of the atmosphere increases. The days of rainfall, however, could be more variable, and reduced overall, implying that on those days when it does rain or snow, there will be more moisture. The reduction in days when it rains has implications for air quality, generally reducing the "washout" effects that a rainy day has in reducing concentrations of soot, particulate matter, and even pollen in the atmosphere, as well as water quality and quantity.

Figure 10 is a map, derived from LOCA GCM data, which shows that most areas of Massachusetts can expect to see an increase in the annual total precipitation (increases are shown in blue).[13] In most locations the increase in annual precipitation is less than 8 percent per year, and in a few locations (shown in red) small decreases in annual precipitation of less than 4 percent are expected. The data shown in Figure 10 is an ensemble mean result from 20 GCMs, so individual GCM projections could vary from the mean, and it is expected that the variance and uncertainty in these projections would grow over time, with larger variance and uncertainty in late-century than early or mid-century.

Most of the differences in precipitation, however, are confined to differences in seasonal projections. As shown in the "summer" and "winter" panels in the lower part of Figure 10, most of these increases are expected in winter, are much larger than the annual increases, and more consistent over space. In summer, the overall state average (not shown) has little or no change from the 1986-2004 baseline period from the LOCA data, but a wide range of variation over space, with increases in the 18 to 24 percent range over Cape Cod, and decreases in the 89 to 14 percent range in the area just southwest of Boston, coupled with decreases in the Berkshire and Hilltowns, and Greater Connecticut River Valley in the western part of the state.

Figure 10. Change in Annual, Summer, and Winter Season Precipitation in 2070 Compared to Current Climate

Current climate is the 1986-2005 era, the projection for 2070 is for a 20-year era centered on 2070. Maps show LOCA downscaled GCM projections at the 50th percentile across 20 LOCA GCMs that overlap with the GCMs used in the Stochastic Weather Generator.



[13] LOCA is used rather than MACA in this figure for technical reasons related to consistent mapping of grid cells, but the projections are largely consistent and are based on the same CMIP5 GCMs.

In addition, the days of rainfall could be more variable, and reduced overall. The reduction in days when it rains has implications for air quality, for example, generally reducing the "washout" effects that a rainy day has in reducing concentrations of soot, particulate matter, and even pollen in the atmosphere. These daily patterns could also be important for drought measures. Table 4 shows two measures of these daily patterns – Panel A shows the number of events of consecutive dry days (of any length of number of days) derived from the Stochastic Weather Generator. Panel B shows the annual total number of days without rain per year. Together they show consistent results, with both sources indicating a reduction of about 3 percent in both the number of consecutive dry day events and the total number of days without rain statewide by 2090. The increase in dry days is somewhat larger in the Berkshires and Hilltowns region, and somewhat smaller in the Boston Harbor region, than statewide.

Table 4. Indicators of Drought – Consecutive Dry Day Events and Total Annual Days without Rain in Massachusetts

Future projections presented for four time periods identified in the table by their central year: 2030 (near-term, 2020-2039); 2050 (mid-century, 2040-2059); 2070 (mid-late century, 2060-2079); and 2090 (end of century, 2080-2099). Values may not sum due to rounding.

Panel A: Consecutive dry day events (number of multiple-dry-day events per year)

Region	Baseline	2030	2050	2070	2090
Berkshires & Hilltowns	29	29	30	30	31
Greater Connecticut River Valley	31	31	32	32	33
Central	32	32	32	33	33
Eastern Inland	32	32	32	33	33
Boston Harbor	31	31	32	32	33
North & South Shores	31	31	32	32	33
Cape, Islands, & South Coast	31	31	32	32	33
Statewide	**31**	**31**	**31**	**32**	**33**
Statewide Percent Change	**0%**	**1%**	**2%**	**4%**	**6%**

Source: Stochastic Weather Generator

Panel B: Annual number of days without rain (days per year)

Region	Baseline	2030	2050	2070	2090
Berkshires & Hilltowns	159	161	165	167	170
Greater Connecticut River Valley	171	172	175	178	181
Central	180	182	185	188	192
Eastern Inland	186	181	185	188	193
Boston Harbor	192	185	192	194	198
North & South Shores	184	182	187	190	195
Cape, Islands, & South Coast	186	182	187	191	194
Statewide	**176**	**175**	**179**	**182**	**187**
Statewide Percent Change	**0%**	**-1%**	**2%**	**3%**	**6%**

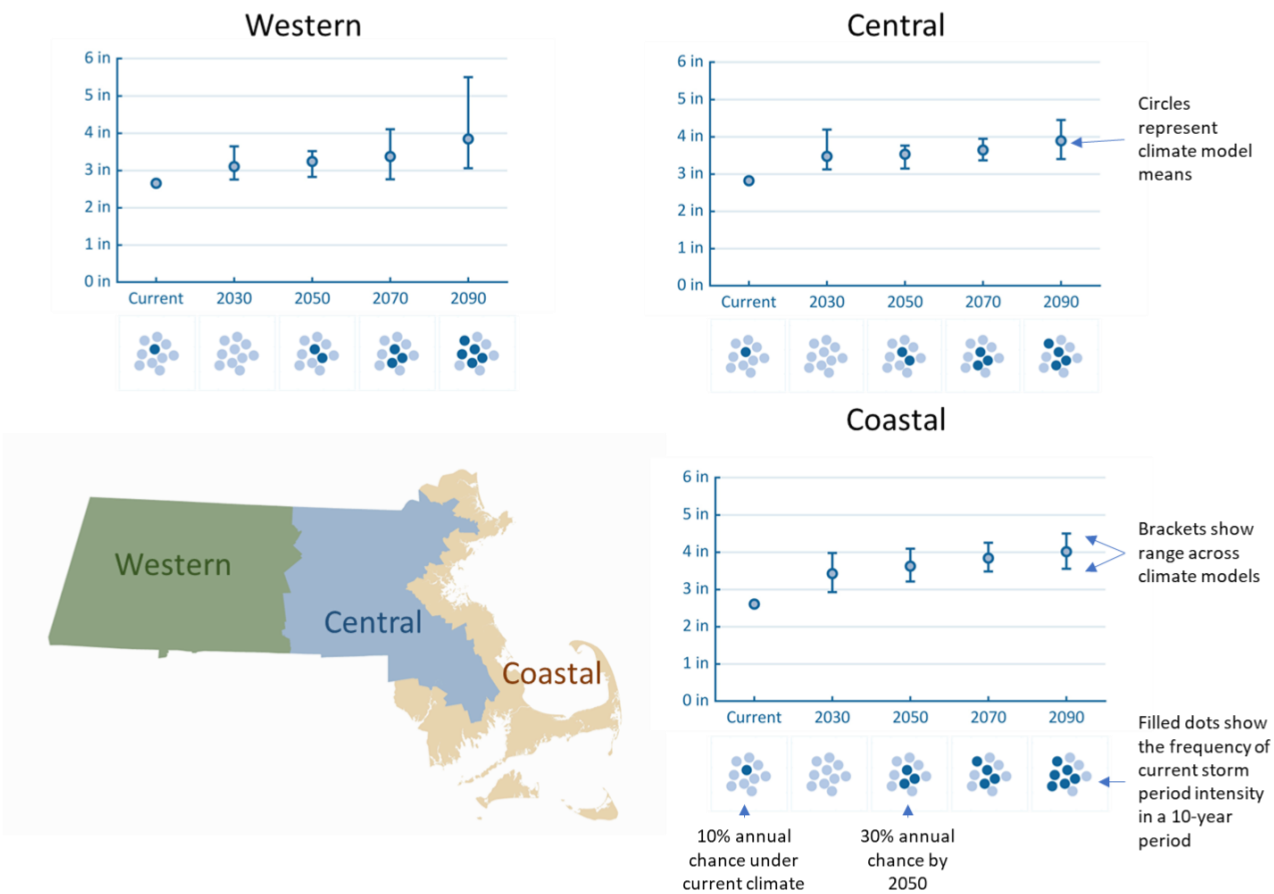
Source: Analysis of LOCA downscaled GCM projections

While climate projections find that there may be fewer days that are rainy or snowy, on those days when it does rain or snow, there can be more moisture. The greater intensity and duration of rainfall on rainy days can lead to flooding, stress on built infrastructure, natural ecosystems and consequent impacts on human health. Figure 11 provides a sense of how precipitation intensity and frequency could change over time (i.e., future design storms), and across Massachusetts regions. The graphs show changes in rain that can be expected in the 24-hour, 10 percent chance of occurring or being exceeded annually rain event (or 10-year return period event). Under current climate that event is roughly 3 inches for all regions. In the future, the intensity of that event could increase by one third, to 4 inches in a day. At the same time, the frequency of the 3-inch historical event changes – the dots along the bottom of graphic show this change. A reduction in the frequency of the 3-inch event is seen in all regions in 2030, but by 2050, the frequency doubles compared to current climate, and by 2090, the frequency increases by a factor of five for the Western and Coastal regions of the Commonwealth, and by a factor of four in the Central region. These changes in both the frequency and intensity of extreme precipitation events are connected to higher temperatures, and the increased capacity of the atmosphere to hold water. Changes in precipitation patterns can affect the frequency, intensity, and duration of inland flooding, the possibility of stormwater volumes exceeding drainage capacities which have been “sized” for current climate, and the possibility of inland dams being overtopped or breached.

Appendix B provides comparable data for additional types of precipitation events, including the 4 percent annual chance (25-year return period); 2 percent annual chance (50-year); and 1 percent annual chance (100-year) events.

Figure 11. Change in Intensity and Frequency of Extreme Precipitation Events: Impact of Climate Change on the 10 Percent Annual Probability (10-year return period) Historical Rainstorm

Current climate is the 1985-2005 era, projections are for 20-year eras centered on the year shown, data from analysis of Global Climate Models, downscaled using the Localized Constructed Analogs (LOCA) approach. Graph shows change in frequency of the historical 10 percent annual chance decade storm (1 in 10-year return period). Circles on the graph represent the mean of available climate models, brackets show the range across available climate models, providing a measure of uncertainty in the projections. Dots below the graphs show the change in frequency of the historical 10-year 24-hour rain event. Western includes the Berkshires and Hilltowns and Greater Connecticut River Valley regions; Central includes the Central and Eastern Inland regions, and Coastal includes North and South Shore, Boston Harbor, and Cape, Islands, and South Coast regions.



Sea Level Rise and Coastal Flooding

This Climate Assessment follows the approach in the 2017 National Climate Assessment and the Global and Regional Sea Level Rise Scenarios (USGCRP 2017, 2018) by adopting a scenario for sea level rise that supports planning and decision-making, while taking into account uncertainty and future risks. For the purposes of this assessment, the Commonwealth of Massachusetts has selected from among several options the USGCRP's High scenario as the preferred scenario for assessment of vulnerability and flood risk. This scenario is consistent with the probabilities that it is unlikely to be exceeded (with 83 percent probability) under the RCP 8.5 GHG emissions scenario used in this Climate Assessment, when accounting for possible Antarctic ice sheet instabilities.[14] The relative sea level rise which Massachusetts residents may see in the future reflects both sea-level and land-level changes, as well as other regional factors which can affect the rate of sea level rise. In the northern part of Massachusetts, this scenario corresponds to approximately 21 inches (54 cm) between 2020 and 2050, and 43 inches (109 cm) between 2020 and 2070; estimates for the southern part of Massachusetts are slightly higher - 23 inches (59 cm) by 2050 and 45 inches (113 cm) by 2070.[15]

This specific sea level rise projection provides the background sea level estimates used for detailed, site-specific hydrodynamic modeling using the MC-FRM, which also integrates mapping of storm surge impacts and influences of localized processes along the coast (such as tides). The MC-FRM also includes simulations of both extra-tropical (i.e., nor-easters) and tropical (i.e., hurricanes) cyclones. The role of extra-tropical storms tends to be more important for the regions north of Cape Cod, and especially Boston Harbor, while the shorelines of southern Cape Cod and Buzzards Bay can be much more strongly influenced by tropical storms. The modeling incorporates an increase in the frequency of tropical hurricanes in the Atlantic as a result of climate change - this increase is correlated with increases in ocean temperature. Some research also indicates that extra-tropical storm activity could increase with climate change, but in consultation with the external panel of climate scientists, this Climate Assessment holds the frequency and intensity of extra-tropical storms constant at historical levels. The impact of both types of storms is combined with changes in sea level over time.

The detailed MC-FRM modeling provides outputs on both the frequency and water surface elevation of current and future coastal flood events. Figure 12 shows the spatial extent of one type of flood event, the 100-year return period flood, which has a 1 percent probability of occurring or being exceeded in any year, and the expansion of the areal extent as sea level rises to levels expected in 2030, 2050, and 2070. The map shows how rising sea levels and more intense and frequent coastal storms will increase the area affected by the 100-year storm - darker blue colors show the current area within the 100-year return period coastal floodplain, and lighter blue colors show how the area could expand through 2070. The insets provide additional detail for a few select populated coastal areas.

[14] These sea level rise projections were developed specifically for the Commonwealth of Massachusetts and the conditions expected to occur in the Northeast United States and follow guidance on emissions scenarios generated by the IPCC. More details are provided in Appendix B.

[15] The MC-FRM Frequently Asked Questions document (see https://eea-nescaum-dataservices-assets-prd.s3.amazonaws.com/cms/GUIDELINES/MC-FRM_FAQ_04-06-22.pdf) presents the SLR projections for 2030, 2050, and 2070 for the northern region, in feet, relative to a standard vertical datum knows as NAVD88. The estimates presented here are adjusted to an estimated 2020 vertical datum, can converted to inches and centimeters. The details of these adjustments are provided in Appendix B.

Figure 12. Area Extent of 1 Percent Annual Chance (100-year) Flood, with Detail for Selected Areas

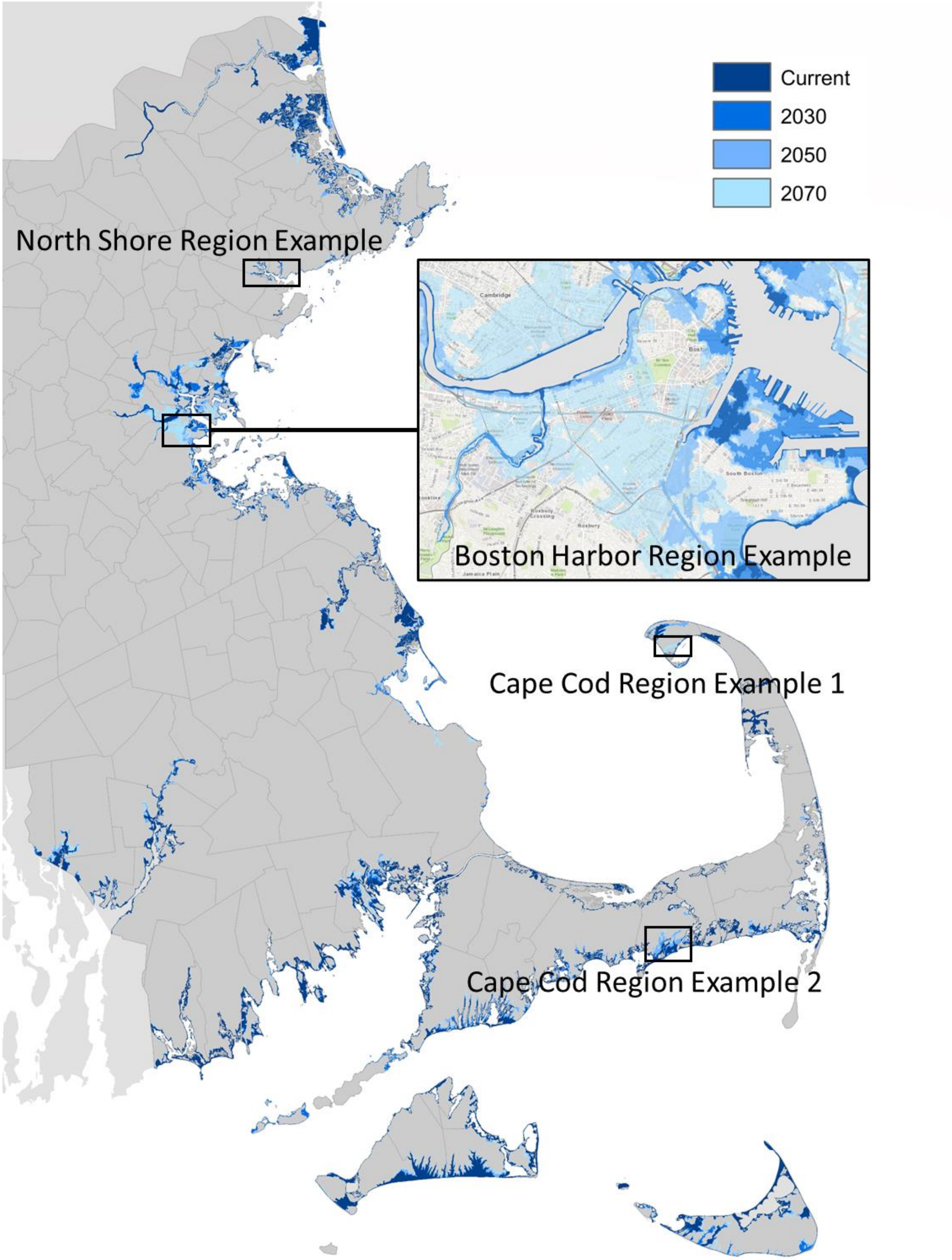
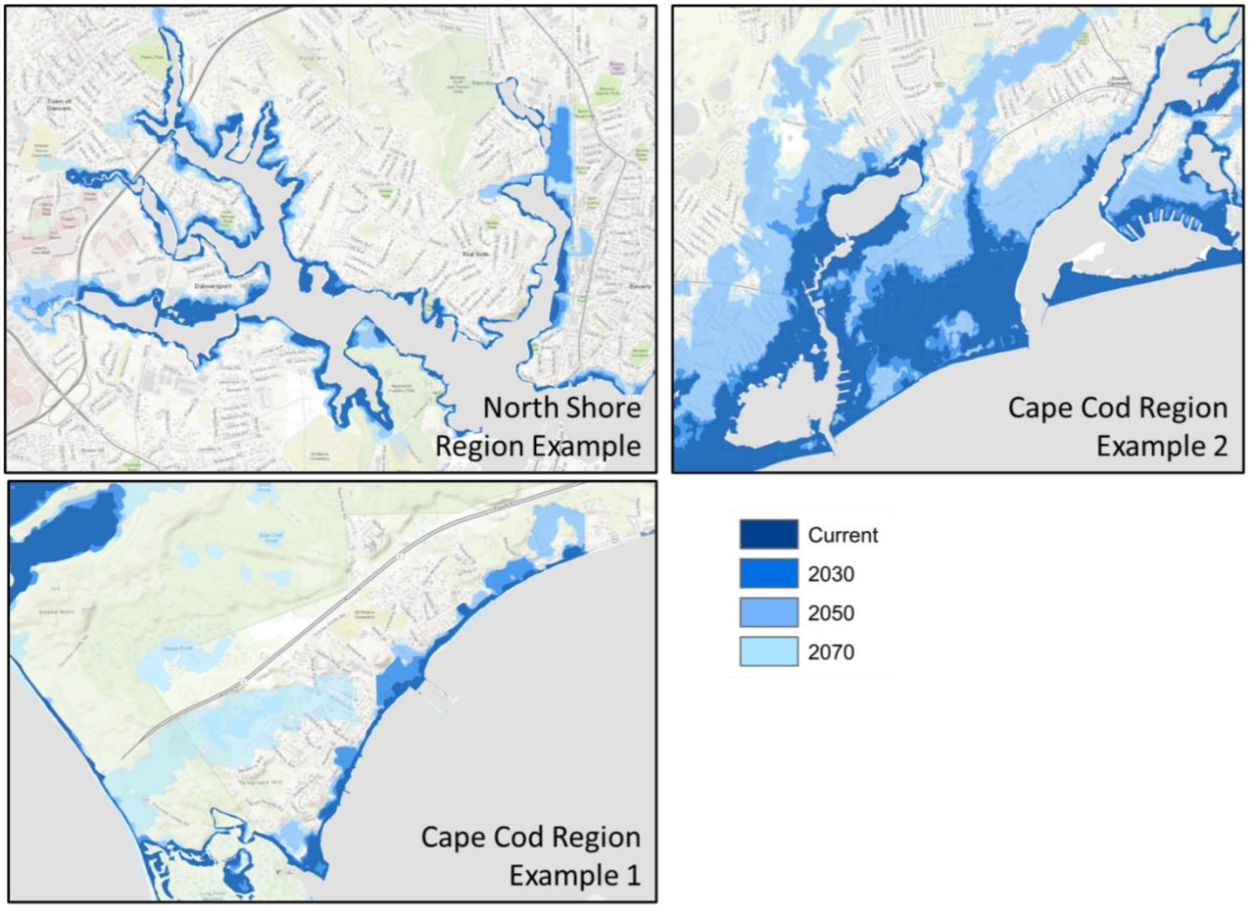
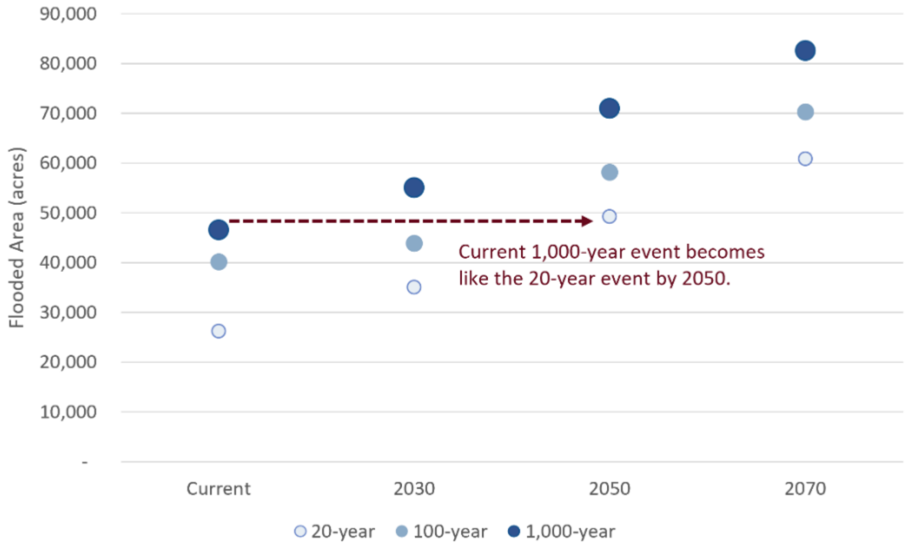


Figure 12 (continued). Area Extent of 1 Percent Annual Chance (100-year) Flood, with Detail for Selected Areas



Another way to think about the frequency of coastal flooding is to quantify the area flooded for events with different return periods and probabilities of occurring in a single year. Figure 13 provides estimates of these areas for the 20-year (5 percent annual probability), 100-year (1 percent probability), and 1000-year (0.1 percent probability) events, focusing only on developed land areas (classified as residential, commercial, industrial, or institutional). A result of examining the MC-FRM results in this way is that the area flooded by the current 1000-year return period event is comparable to the area of a 50 times more frequent 20-year event anticipated in 2050. As the graphic shows, even more area could be affected by equivalent annual probability events in 2070.

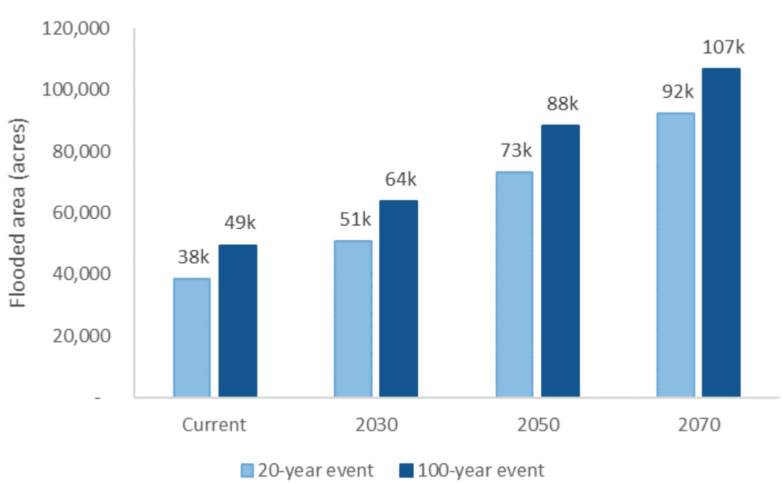
Figure 13. Total Flooded Area of the Commonwealth for Selected Flood Return Periods



The map and the graphic above both characterize the full areal extent that might experience any depth of coastal flood water – but the surface elevation of flood water is also an important determinant of impacts to both built infrastructure and natural areas. Figure 14 shows how the developed land area in coastal Massachusetts that could be flooded with 12 inches or more of water for both the 20-year return period storm (with a 5 percent annual probability) and the 100-year return period storm (with a 1 percent annual probability) changes over time. The area with at least 12 inches of water expands substantially over time, from 38,000 acres in the current (historical 1999-2017 period) to 73,000 acres in 2050 and 92,000 acres in 2070 as a result of climate change for the 20-year event. For context, the land area of the City of Boston is about 30,000 acres; for the City of Worcester, about 25,000 acres; and for the City of Springfield, about 20,000 acres.

Figure 14. Areas Flooded Coastwide with One Foot or Higher Water Depth

Comparison of areas flooded with one foot or greater water depth. Current period is 2008.



Source: Spatial analysis of Massachusetts Coastal Flood Risk Model (MC-FRM) results

4. Impacts of Climate Change in Massachusetts

This chapter presents the impact summaries for the urgent impacts in each of five sectors. The summaries provide information on the data sources relied upon and details on the Climate Assessment findings. Table 5 presents the three most urgent impacts in each sector for the Commonwealth and the sections that follow present impacts by sector, in order of urgency within each sector. Additional detail on the impacts outside of the top three most urgent per sector can be found in Appendix A. Volume III reports the most urgent impacts by sector for each of the seven Climate Assessment regions.[16]

Table 5. Three Most Urgent Impacts by Sector for the Commonwealth

Most urgent impacts based on urgency scores evaluated as described in Chapter 2. Four impacts are listed for the Natural Environment sector due to tied scores.

Human Sector

- **Health and Cognitive Effects from Extreme Heat**, including premature death and learning loss.
- **Health Effects from Degraded Air Quality**, including new childhood asthma diagnoses and premature death due to the direct impact of climate on particulate matter and ozone air quality.
- **Emergency Service Response Delays and Evacuation Disruptions** from extreme storms, leading to injuries, loss of life, and requiring health, safety, and traffic first responders.

Infrastructure Sector

- **Damage to Inland Buildings** from heavy rainfall and overwhelmed drainage systems.
- **Damage to Electric Transmission and Utility Distribution Infrastructure** associated with heat stress and extreme events.
- **Damage to Rails and Loss of Rail/Transit Service**, including flooding and track buckling during high heat events.

Natural Environment Sector

- **Freshwater Ecosystem Degradation** due to warming waters, drought, and increased runoff.
- **Marine Ecosystem Degradation** because of warming, particularly in the Gulf of Maine, water quality issues, and ocean acidification.
- **Coastal Wetland Degradation** from sea level rise and storm surge.
- **Forest Health Degradation** from warming temperatures, changing precipitation, extreme storms, and increasing pest occurrence.

Governance Sector

- **Reduction in State and Municipal Revenues,** including a reduced property tax base due to coastal and inland flood risk.
- **Increase in Costs of Responding to Climate Migration**, including planning for abrupt changes in local populations.
- **Increase in Demand for State and Municipal Government Services**, including emergency response, food assistance, and state-sponsored health care.

[16] Note that the statewide results evaluate the components of urgency scoring while considering the state overall, they are not aggregations of the regional results.

Economy Sector

- **Reduced Ability to Work**, particularly for outdoor workers during extreme heat, as well as commute delays due to damaged infrastructure.
- **Decrease in Marine Fisheries and Aquaculture Productivity** from changing ocean temperatures and acidification, which leads to decreased catch and revenues and impacts on related industries.
- **Reduction in the Availability of Affordably Priced Housing** from direct damage (e.g., flooding) and the scarcity caused by increased demand.

4.1 Human Sector

Many of the most urgent impacts in the Human Sector have disproportionate exposure, meaning the incremental health effects of climate change will layer on existing disproportionate burdens. Details on the sources and data used to identify impacts in the "Description" field below are provided in the detailed impact text in this chapter and in Technical Appendices B and C.

Table 6. Urgent Impacts in the Human Sector

IMPACT	DESCRIPTION	MAGNITUDE	DISPROPORTIONATE EXPOSURE	ADAPTATION GAP
Health and Cognitive Effects from Extreme Heat (MOST URGENT)	Impacts of extreme heat episodes on health, learning, and workplace injuries – covers all health aspects of changes in frequency and severity of days with extreme temperatures.	Extreme	Disproportionate	Moderate
Health Effects from Degraded Air Quality (MOST URGENT)	Impacts of climate-induced changes in ambient and indoor air quality on health (e.g., premature loss of life, health care costs, missed school). Focused on changes from the direct impact of climate on particulate matter and ozone air quality, and the resulting health effects associated with these pollutants.	Major	Disproportionate	Moderate
Emergency Service Response Delays and Evacuation Disruptions (MOST URGENT)	Extreme storms cause delays in response time, potentially leading to loss of life. Extreme coastal storm surge events and inland flooding could flood evacuation routes, trapping residents, leading to increased loss of life and injuries.	Major	Disproportionate	Moderate
Reduction in Food Safety and Security	Temperature increases, spoilage, and power outages can lead to increased food contamination. Changes in food production and supply chain disruption linked to climate change will worsen existing food insecurity.	Moderate	Disproportionate	Moderate
Increase in Mental Health Stressors	Negative effects of weather and climate change on mental health, including a broad range of impacts on overall well-being associated mostly with temperature stress.	Major	Potential	Moderate
Health Effects from Aeroallergens and Mold	Impacts from extended pollen seasons, particularly on people with asthma or hay fever, and increases in exposure to mold spores associated with more frequent flood events and higher humidity conditions.	Moderate	Potential	Moderate
Health Effects of Extreme Storms and Power Outages	Power outages and flooding, which could increase with more frequent extreme events, lead to a range of morbidity and sometimes fatal health outcomes and an increase in requests for emergency services.	Moderate	Potential	Moderate
Damage to Cultural Resources	Climate stressors can damage important cultural resources that hold special value to residents of the Commonwealth.	Moderate	Potential	Moderate
Increase in Vector Borne Diseases Incidence and Bacterial Infections	Increase in incidence of West Nile Virus, Lyme disease, and other diseases, and associated fatal and nonfatal outcomes, as a result of changes in temperature and an extended seasons for vectors and/or impact on bacterial loads.	Major	Limited	Moderate

Human Sector: Urgent Impact #1

Health and Cognitive Effects from Extreme Heat

Impacts of extreme heat episodes on health, learning, and workplace injuries – covers all health aspects of changes in frequency and severity of days with extreme temperatures.

Extreme Level of Consequence	Disproportionate Exposure	Moderate Adaptation Gap
• Over 400 additional deaths anticipated by end of century.	• Linguistically isolated individuals are 28 percent more likely to experience premature mortality as a result of extreme heat.	• Increasing tree canopy cover is a favored solution to combat impacts of extreme heat, especially in urban areas.

Impact Summary

Climate change is expected to increase frequency of extreme heat days, resulting in an increase in heat-related illnesses and deaths, as well as adverse cognitive effects. Extreme heat days are defined as days that are substantially hotter than the average summer temperature.[17] Extreme heat days are most closely linked to health outcomes, but the cumulative effects of higher average summer temperatures can also affect human health.

Extreme heat results in morbidity outcomes, such as emergency department (ED) visits, and premature deaths by compromising the body's ability to regulate temperature and aggravating pre-existing conditions. Conversely, climate change is expected to decrease the frequency of extreme cold days, minimizing health effects associated with very low temperatures. Both the increases in extreme heat effects and the decrease in extreme cold effects are considered in the magnitude of consequence results presented in Table 7.

Learning and cognition are also negatively impacted by extreme heat associated with climate change. Hot classrooms may reduce the quality of instructional time and, in extreme cases, cause schools to close early, reducing the amount of instructional time. These sometimes difficult to measure cognitive effects nonetheless have been shown to impact test scores, like the PSATs, among students.

Urgency Ranking Results

This impact is ranked as a **high priority** because of its large and disproportionate impacts.

Excess mortality associated with extreme temperature is evaluated using LOCA daily temperature projections and extreme temperature thresholds and effect coefficients for the

[17] Average summer temperatures are also projected to increase over time, however the threshold used to define "extreme heat" days stays constant over time.

city of Boston from Mills et al. (2014).[18,19] Emergency department visits and changes in student PSAT scores as a proxy for change in cognitive effects associated with extreme heat are also considered qualitatively in the urgency scoring.

> *"Extreme heat means children cannot play safely outdoors, which undermines the sense of community where I live."*
>
> *"There are minimum requirements for heat to renters but no cooling requirements. There is fuel assistance for heating but little to none for cooling."*
>
> - Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The consequences of increased extreme heat are projected to be **extreme** due to the severity of those effects, including widespread and substantial increases in extreme heat-induced premature deaths. Currently, 19 annual premature deaths could be attributed to extreme temperature statewide, based on application of the Mills et al. (2014) study to the baseline frequency of extreme temperature days (over the period 1986-2005). Over and above this baseline, more than 400 additional premature deaths per year are estimated in the Commonwealth as a result of climate change by the end of the century. If no adaptation action is taken, the statewide net mortality rates from temperature extremes will increase from 0.2 deaths per 100,000 population in 2030 to 5 deaths per 100,000 by 2090 (note that the current and projected death rates vary by county throughout the state, and may be higher or lower than the statewide rate). Using survey and other economic estimates of individual values for reduction of changes in the risk of fatality, the economic impact of these additional premature deaths could be as large as $200 million in 2030, and well over $6 billion by the end of the century. These estimates assume that there would be no or limited further adaptation to extreme temperatures beyond those in place during the base period of the analysis (up to about 2010). As noted below in the limitations section, however, the recent observed record shows a declining trend in heat-related mortality, primarily due to air conditioning being increasingly common in residential and work settings. Massachusetts has relatively low rates of central air conditioning in residential settings (around 30 percent), but most homes at least have access to a room air conditioning unit.[20]

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[18] "LOCA" stands for Localized Constructed Analogs and refers to the statistical process used to project local climate outcomes from less spatially refined global climate models.

[19] Mills, D., Schwartz, J., Lee, M., Sarofim, M., Jones, R., Lawson, M., Duckworth, M., and Deck, L. (2014). Climate change impacts on extreme temperature mortality in select metropolitan areas in the United States. *Climatic Change*, 131, 83-95.

[20] A 2019 study showed about 30 percent of residences had central air conditioning, 57 percent had a room air conditioner, and 8 percent had a central or mini-split heat pump. Navigant 9. Massachusetts Residential Baseline Study, Prepared for: The Electric and Gas Program Administrators of Massachusetts, available at: https://ma-eeac.org/wp-content/uploads/RES-1-Residential-Baseline-Study-Comprehensive-Report-2019-04-30.pdf

Table 7. Additional Premature Deaths Associated with Extreme Temperature

Premature deaths for individuals of all ages attributable to climate change (heat and cold combined). Statewide economic costs are based on willingness to pay to avoid premature deaths. Future impacts presented for four time periods identified in the table by their central year: 2030 (near-term, 2020-2039); 2050 (mid-century, 2040-2059); 2070 (mid-late century, 2060-2079); and 2090 (end of century, 2080-2099). Values may not sum due to rounding.

	Additional annual premature deaths			
Region	**2030**	**2050**	**2070**	**2090**
Berkshires & Hilltowns	0	0	1	3
Greater Connecticut River Valley	0	3	11	22
Central	0	6	18	35
Eastern Inland	6	30	72	132
Boston Harbor	6	30	77	131
North & South Shores	3	12	26	48
Cape, Islands, & South Coast	2	9	21	37
Statewide	**17**	**89**	**230**	**410**
Economic Costs ($millions)	**$200**	**$1,200**	**$3,400**	**$6,700**

Source: Derived from Mills et al. (2014) and Project Team analysis

The majority of extreme heat impacts fall in the more populous Eastern Inland and Boston Harbor regions. Similarly, the highest rates of additional premature deaths are observed in the Boston Harbor Region, where rates are 30 to 50 percent higher than the state average. Rates in the Cape, Islands, and South Coast region and the North & South Shores region are also 3 to 20 percent higher than the state average. The higher rates of premature deaths in these regions are associated with a higher projected occurrence of extreme hot temperature events that lead to premature heat-related deaths.[21]

Bernstein et al. (2022) has also identified a relationship between historical daily maximum temperature and children's hospital emergency department visits.[22] Authors found that all-cause emergency department visits increased in response to increased temperatures. The results of this study indicate emergency department visits could increase with climate change. ED visits are currently 17 percent above baseline for days at or above the current 95th percentile maximum temperature day – with more frequent occurrence of these high temperatures, impacts could be higher in the future, but these impacts have not yet been projected using the climate science projections applied in the Climate Assessment. A recent study of New England communities also found that there are cumulative effects over time of extreme heat on both morbidity and mortality (Wellenius et al. 2016).[23]

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[21] Sources for these statements are Mills et al. (2014) and Project Team analysis.

[22] Bernstein, A.S., Sun, S., Weinberger, K.R., Spangler, K.R., Sheffield, P.E., and Wellenius, G.E. 2022. Warm Season and Emergency Department Visits to U.S. Children's Hospitals. Environmental Health Perspectives, 130(1).

[23] Wellenius, G.A., Eliot, M.N., Bush, K.F., Holt, D., Lincoln, R.A., Smith, A.E. and Gold, J., 2017. Heat-related morbidity and mortality in New England: evidence for local policy. Environmental research, 156, pp.845-853.

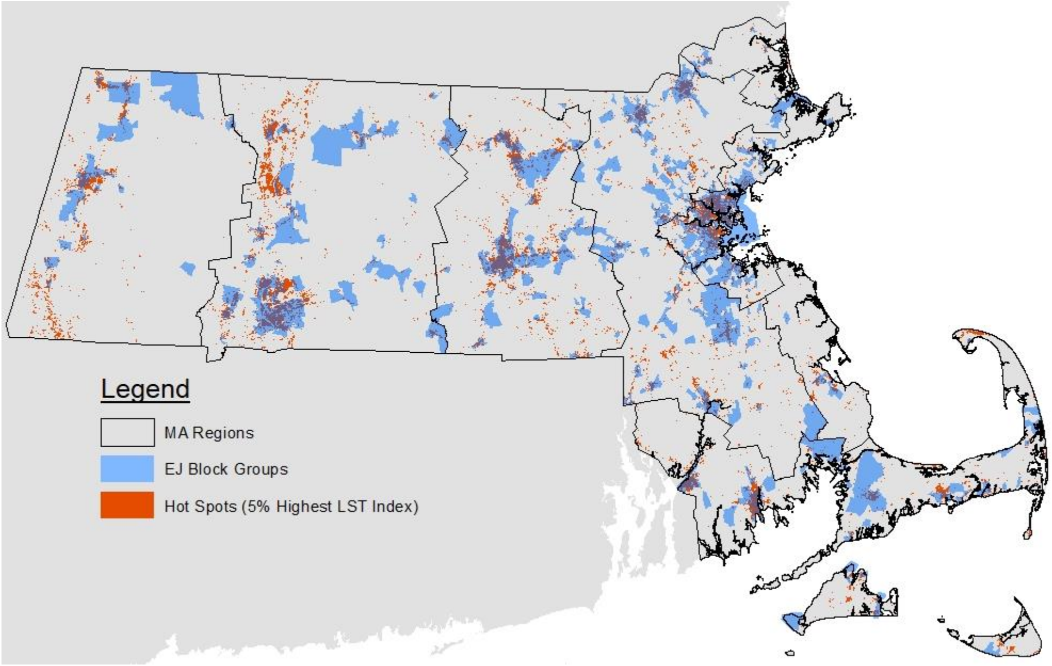
Park et al. (2020) has also quantitatively assessed impacts of extreme heat on learning on a national scale.[24] Researchers estimated that, without air conditioning, each 1°F increase in school year temperature reduced the amount learned that year by one percent, measured by test performance. Park et al. estimated that at least 40 percent and as much as 100 percent of classrooms in Massachusetts counties lack air conditioning, compared to 0 to 20 percent of classrooms in southeastern U.S. states that are better adapted to extreme heat. Region- and state-specific effects of extreme heat and cognition have not yet been quantified but may be significant.

In addition, a recent national study finds evidence that extreme heat can increase occupational injuries.[25] While the larger impacts in this study were found in southern states, and those southern states also account for the largest share of current heat related occupational injuries, the overall finding is that occupational injuries could increase by a factor of four by 2050.

Disproportionality

Figure 15 shows the geographic distribution of current extreme temperature hot spots, representing areas among the top 5 percent of the Land Surface Temperature index, and EJ populations. EJ populations reside in hot spots throughout the state, with the highest concentration in urban areas such as Boston, Worcester, and Springfield.

Figure 15. Hot Spots of Land Surface Temperature (LST) and EJ Block Groups in Massachusetts



Source: Derived from MAPC Land Surface Temperature Index and EEA EJ Block Group data

[24] Park, R.J., Goodman, J., Hurwitz, M., and Smith, J. 2020. Heat and Learning. American Economic Journal: Economic Policy, 12(2), 306-339.

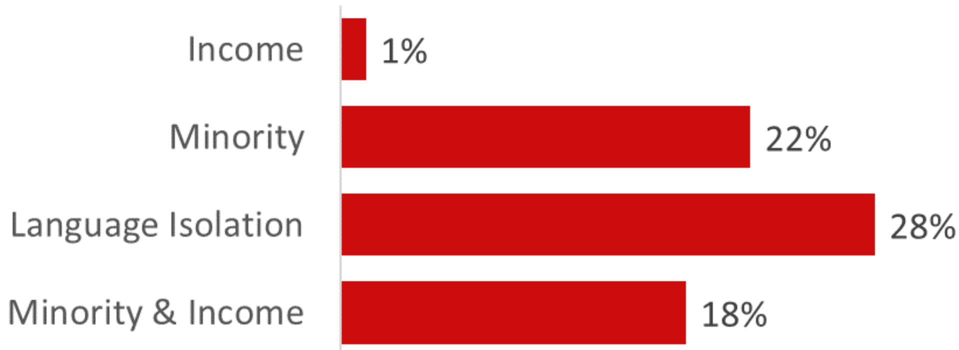
[25] Park, R. J., Pankratz, N., and Behrer, A.P. 2021. Temperature, Workplace Safety, and Labor Market Inequality. IZA Institute of Labor Economics. IZA DP No. 14560. July. https://www.iza.org/publications/dp/14560/temperature-workplace-safety-and-labor-market-inequality.

Exposure to this impact is highly **disproportionate**. Populations living in EJ block groups defined on the basis of:

- minority population could have 22 percent higher rates of estimated premature death from extreme heat, based on the analysis described above, than the rest of the Commonwealth
- language isolated populations could have 28 percent higher rates of estimated premature death from extreme heat, based on the analysis described above, than the rest of the Commonwealth

Figure 16. Disproportionality of Extreme Temperature Mortality

Comparison of extreme temperature mortality for individuals of all ages in EJ block groups defined by income, minority status, language isolation and minority status and income combined, compared to all other block groups in the state. Positive numbers and red bars represent disproportionate exposure for the listed population segment. See Section 2.1 for further description of the EJ block group definitions.



Minority populations are concentrated in regions of the Commonwealth that experience more significant extreme heat. Further, studies have found higher temperature mortality rates among minority subgroups, such as Black and Hispanic populations.[26] Access to air conditioning, which can mitigate adverse heat-related health effects, may be limited among vulnerable populations and the energy costs of running air conditioners may be cost prohibitive for some.

Adaptation

There is a **moderate** adaptation gap to addressing the health and cognitive effects of extreme heat. Many plans are actively implementing a variety of solutions to combat the effects of extreme heat. The most common approaches are increasing urban tree cover and expanding the network of cooling centers in urban areas. Some cities are incentivizing building-level action, including adoption of green, blue, and white roofs and energy efficiency retrofits. Further building-level adaptation like increased air conditioning penetration is happening organically as extreme heat events become more common, but government support can speed this process. Roughly half of all plans addressing extreme heat are in a stage of planning, assessment, or exploration, while the other half have begun implementation. There is very little

[26] EPA. 2021. Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. U.S. Environmental Protection Agency, EPA 430-R-21-003. www.epa.gov/cira/social-vulnerability-report

planning around other potential solutions that more directly address the health and cognitive effects of extreme heat, such as public engagement and education on risks of extreme heat and emergency health worker training on responding to extreme heat emergencies as they become more common. Similarly, there is limited discussion of actions to specifically address impacts in schools or in the full breadth of potentially affected occupational settings.

Example Adaptation Plans with Actions Addressing this Impact

- City of Boston's Heat Resilience Solutions for Boston (2022)
- Holyoke Urban Forest Equity Plan

Sensitivities and Uncertainty

This analysis was run using a city-level epidemiological study focused on extreme temperature mortality in U.S. cities, including Boston. The function for estimating excess risk in Boston was applied to all areas of the state, based on recent literature which suggests that extreme heat-related health impacts in the Northeast U.S. region are not limited to urban areas, and may be of comparable magnitude in non-urban areas (see Madrigano et al. 2015).[27]

This analysis does not yet quantify morbidity effects or cognitive effects associated with extreme heat, which are likely to increase as temperature increases. Beyond emergency department visits discussed by Bernstein et al. (2022), hospital admissions for cardiovascular and respiratory disorders are also provoked by extreme heat.

A key limitation in the study applied here and much of the existing research on extreme temperature mortality is that historic trends and future projections in air conditioning prevalence as adaptation are not considered. Recent work demonstrates that there is a historic downward trend in extreme temperature mortality, which is attributed to increased adoption of air conditioning over time, but other work suggests that increases in mortality from extreme heat remain likely, particularly among populations unable to afford air conditioning.[28] It is also important to note that air conditioning, while effective at reducing health effects of extreme temperature, may not eliminate all extreme heat health effects, especially among individuals

[27] Madrigano, J., Jack, D., Anderson, G.B., Bell, M.L. and Kinney, P.L., 2015. Temperature, ozone, and mortality in urban and non-urban counties in the northeastern United States. Environmental Health, 14(1), pp.1-11.

[28] Kinney, P. 2018. Temporal Trends in Heat-Related Mortality: Implications for Future Projections. Atmosphere, 9:409. doi:10.3390/atmos9100409; Lay, C.R., M.C. Sarofim, A.Vodonos Zilberg, D.M.Mills, R.W. Jones, J.Schwartz, P.L. Kinney 2021. City-level vulnerability to temperature-related mortality in the USA and future projections: a geographically clustered meta-regression. Lancet Planetary Health, 5:e338-46. https://doi.org/10.1016/ S2542-5196(21)00058-9; and Cromar, K. S.C. Anenberg, J.R. Balmes, A.A. Fawcett, M. Ghazipura, J.M Gohlke, M. Hashizume, P.Howard, E. Lavigne, K. Levy, J. Madrigano, J.A. Martinich, E.A. Mordecai, M.B. Rice, S. Saha, N.C. Scovronick, F. Sekercioglu, E.R. Svendsen, B.F. Zaitchik, and G.Ewart. (2022). Global Health Impacts for Economic Models of Climate Change: A Systematic Review and Meta-Analysis. Annals of the American Thoracic Society. DOI: 10.1513/AnnalsATS.202110-1193OC

with outdoor occupations, and presents affordability challenges (both upfront and operating costs) for some.[29]

Related Impacts

Table 8 lists the impacts in other sectors that have a connection to this impact.

Table 8. Additional Impacts related to Health and Cognitive Effects of Extreme Heat

Sector	Impact	Connection
Economy	Reduced Ability to Work	Extreme heat may limit possible work hours and reduce productivity in climate-vulnerable industries. Individuals may miss work while sick or caring for others who are sick.
Economy	Reduction in the Availability of Affordably Priced Housing	There may be some pressure to retrofit existing housing and including air conditioning in new development, or provide monetary assistance for energy costs.
Governance	Increase in State and Municipal Expenditures on Government Services	Increase in demand for health care costs to treat adverse health effects.
Infrastructure	Loss of Urban Tree Cover	Loss of tree cover could exacerbate heat island effects and associated adverse health effects.

[29] Cong, S., Nock, D., Qiu, Y.L. and Xing, B., 2022. Unveiling hidden energy poverty using the energy equity gap. Nature communications, 13(1), pp.1-12.

Human Sector: Urgent Impact #2 (tie)

Health Effects from Degraded Air Quality

Impacts of climate-induced changes in ambient and indoor air quality on health (e.g., premature loss of life, health care costs, missed school). Focused on changes from the direct impact of climate on particulate matter and ozone air quality, and the resulting health effects associated with these pollutants.

Major Level of Consequence	Disproportionate Exposure	Moderate Adaptation Gap
• Over 100 additional statewide asthma diagnoses annually from air pollution by 2030; over 900 additional asthma diagnoses and 200 deaths by 2090.	• Minority and language isolated populations are more than 20 percent more likely to live in areas with the highest projected increases in childhood asthma diagnoses.	• Some warning systems and pollution reduction plans in place but technological limitations bound further action.

Impact Summary

Climate change is expected to degrade air quality which results in a variety of adverse health effects. Examples of the ways climate change worsens air quality include:

- Ground-level ozone formation occurs faster when temperatures are warmer
- Particulate matter (dust, soot, and smoke) is flushed out of the air less often in periods when rain events may become less frequent
- Increasing frequency of wildfires, in Massachusetts and across North America, produce more particulate matter. Some of this fine particulate matter can travel long distances and have a large impact on air quality in Massachusetts, as recent events in the Western US and Eastern Canada have demonstrated.

Exposure to poor air quality has been linked to a wide range of lung and respiratory diseases, such as new diagnoses of childhood asthma, which can require frequent medical visits (as well as missed school and work for caretakers), costly prescriptions, changes in daily activities, and in severe cases, death. Currently 1 in 8 children in Massachusetts suffer from asthma.[30]

Urgency Ranking Results

This impact is ranked as a **high priority** because of its large and disproportionate impacts.

This impact is evaluated using U.S. Environmental Protection Agency (USEPA)-sponsored literature at county- or finer scale to evaluate the impacts of climate change on outdoor air quality (particulate matter and ozone) to measure new childhood asthma diagnoses, premature

[30] Based on a statewide childhood asthma prevalence rate of 12.9 percent from https://www.mass.gov/service-details/statistics-about-asthma

deaths for ages 65+, and economic valuation of each outcome.[31] The health impact estimates attributed to climate change that are presented here reflect a forecast through 2040 of gradually reduced air pollutant emissions over time, independent of climate change but based instead on recent trends in air pollutant emissions in compliance with and gradual tightening of the federal Clean Air Act and local Commonwealth air pollution regulations. A wide range of other illnesses are also associated with poor air quality, including cases of low birth weight, heart disease and stroke, lung cancer, and reduced performance on standardized intelligence testing, as recently supported in a study at Boston College.[32] Additionally, health impacts of poor air quality caused by wildfires (primarily due to fires occurring outside the Commonwealth) and indoor air quality are also considered qualitatively in the urgency scoring.

"*I'm scared the air outside will not be good for me in a few years.*"

"I am a member of the aging population and will need to reduce my outdoor activities due to climate changes and poor-quality air."

"Air quality is a huge concern for me, I already have asthma and I'm afraid it will get worse."

- Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The consequences of degraded air quality are projected to be **major** due to widespread and substantial increases in air quality-related health effects, and the severity of those effects. Currently, 30,000 annual new diagnoses of childhood asthma and 1,900 annual premature deaths among older adults are attributable to impaired air quality in the Commonwealth. Just fewer than 1,000 new diagnoses of childhood asthma are estimated in the Commonwealth solely as a result of the impact of climate change by the end of the century (but the estimate could be three times higher if air pollutant emissions stationary, mobile, and other sources that lead to impaired air quality do not continue recent trends, which reflect substantial ongoing effort to improve air quality in the Commonwealth). The change in asthma incidence rates will increase from 7 in 100,000 in 2030 to 53 in 100,000 by 2090. The cost for a new diagnosis of

[31] Fann, N., C. Nolte, M. Sarofim, J. Martinich, and N. Nisokolas (2021). Associations between simulated future changes in climate, air quality, and human health. *JAMA Network Open*, doi:10.1001/jamanetworkopen.2020.32064. Note that while this study is national in scope, it makes use of local data to generate the estimates, including the state's contribution to the EPA National Emissions Inventory air pollutant emissions; air quality modeling that provides projections at a 36 km grid scale (implying that there are more than 20 grid cells in the Commonwealth), modeling which also considers detailed local meteorology data; and county-specific Census reported baseline and projected mortality rates, as well as U.S. Centers for Disease Control baseline asthma incidence data.

[32] Landrigan, P.J., S. Fisher, M.E. Kenney, B. Gedeon, L. Bryan, J. Mu, and D. Bellinger (2022). A replicable strategy for mapping air pollution's community-level health impacts and catalyzing prevention. Environmental Health 21:70, https://doi.org/10.1186/s12940-022-00879-3. See also an interactive map for Massachusetts towns at https://www.bc.edu/bc-web/centers/schiller-institute/sites/masscleanair.html

asthma is estimated to be $48,500 and includes lifetime medical costs and productivity losses.[33] Over 200 additional premature deaths among the population age 65-plus are estimated as a result of climate change statewide by the end of the century. The change in air quality related mortality rates attributable to climate change is estimated to grow from 2 in 100,000 in 2030 to 11 in 100,000 by 2090.[34] Mortality attributed to air pollution is valued based on individual values for avoiding the risk of premature death.

Table 9. Health Effects of Ozone and Particulate Matter

New diagnoses of childhood asthma and premature deaths for individuals over 65 attributable to climate change. Statewide economic costs are based on lifetime incidence costs (asthma) and willingness to pay to avoid premature deaths. Future impacts presented for four time periods identified in the table by their central year: 2030 (near-term, 2020-2039); 2050 (mid-century, 2040-2059); 2070 (mid-late century, 2060-2079); and 2090 (end of century, 2080-2099). Values may not sum due to rounding.

	New diagnoses of childhood asthma				Additional premature deaths (65+)			
Region	**2030**	**2050**	**2070**	**2090**	**2030**	**2050**	**2070**	**2090**
Berkshires & Hilltowns	-4	-10	-7	-11	0	-1	1	0
Greater Connecticut River Valley	-12	-36	-14	-21	0	-2	7	7
Central	-5	-20	22	27	1	0	12	14
Eastern Inland	41	46	240	330	9	14	53	67
Boston Harbor	71	100	300	430	11	18	55	74
North & South Shores	16	22	87	120	5	8	27	35
Cape, Islands, & South Coast	8	9	49	66	3	3	13	14
Statewide	**120**	**110**	**680**	**940**	**29**	**40**	**170**	**210**
Economic Costs ($millions)	**$6**	**$6**	**$33**	**$45**	**$340**	**$540**	**$2,600**	**$3,500**

Source: Derived from Fann et al. (2021)

The spatial distribution of both outcomes varies substantially across regions. The majority of negative impacts of climate change fall in the eastern regions, where climate change is expected to increase both ozone and particulate matter concentrations, in the more populous Eastern Inland and Boston Harbor regions. Changes in incidence rates are highest in the Boston Harbor region, followed by the North & South Shores and the Eastern Inland region. In the western part of the state, the combination of beneficial changes in rainfall patterns and reductions in upwind air pollutant emissions in neighboring states results in a mostly beneficial effect of climate change on air quality. This is true in the Berkshires and Greater Connecticut River Valley regions throughout the century, and for the first half of the century in the Central region.

Indoor air quality may also be affected by climate change. Indoor air is heavily influenced by air exchange with outdoor air pollutants, which are projected to cause the detrimental health

[33] USEPA. 2022. BenMAP-CE User Manual. Available at: https://www.epa.gov/benmap/benmap-ce-manual-and-appendices

[34] See data for Massachusetts from Fann et al. (2021), cited above.

impacts described above. Further, exposure to indoor air pollutants such as carbon monoxide, radon, and lead, changes in infiltration, and improper generator use are expected to result in adverse health effects that become more frequent with climate change.[35] Morbidity and mortality impacts associated specifically with changes in indoor air quality have not yet been quantified in the literature.

Morbidity effects associated with $PM_{2.5}$ pollution from wildfires has been quantified, along with projected climate change-related impacts.[36] Impacts are minor relative to those associated with air quality changes directly attributable to climate change (quantified in this section), especially in the eastern U.S. where large wildfires are rare and most impacts are associated with wildfire smoke transport from other regions.

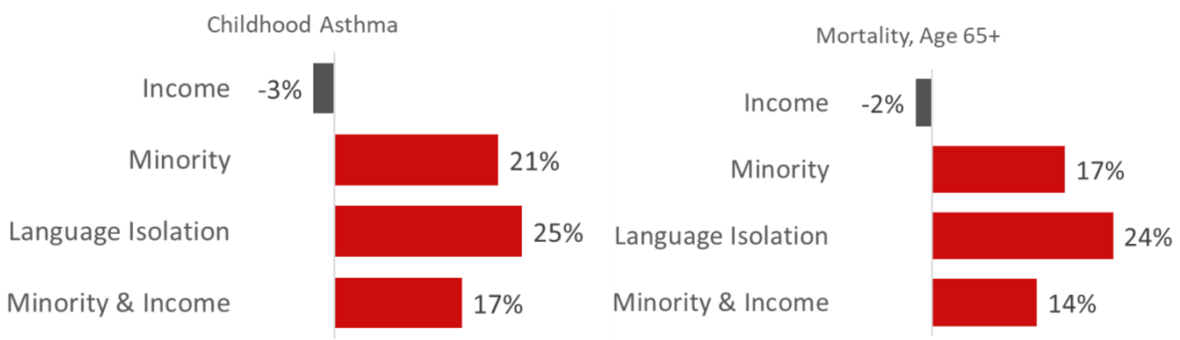
Disproportionality

Exposure to this impact is highly **disproportionate**. Populations living in EJ block groups defined on the basis of:

- minority population have 21 percent higher rates of new asthma diagnoses among children than the rest of the Commonwealth
- language isolated populations have 25 percent higher rates of new asthma diagnoses among children and 24 percent higher rates of premature death among the 65+ population than the rest of the Commonwealth

Figure 17. Disproportionality of Health Effects of Degraded Air Quality

Comparison of the incidences of childhood asthma (left) and mortality for individuals 65 and older (right) in EJ block groups defined by income, minority status, language isolation and minority status and income combined, compared to all other block groups in the state. Positive numbers and red bars represent disproportionate exposure for the listed population segment. See Section 2.1 for further description of the EJ block group definitions.



These results are consistent with a broad literature which identifies a higher risk of air pollution for minority and other socially vulnerable populations. The important quantifiable factors

[35] Fann, N., Brennan, T., Dolwick, P., Gamble, J.L., Ilacqua, V., Kolb, L., Nolte, C.G., Spero, T.L., and Ziska, L. 2016. Ch. 3: Air Quality Impacts. The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment. U.S. Global Change Research Program, Washington DC, 69-98.

[36] Neumann, J.E., Amend, M., Anenberg, S, Kinney, P.L., Sarofim, M., Martinich, J., Lukens, J., Xu, J., and Roman, H. 2021. Estimating PM2.5-related premature mortality and morbidity associated with future wildfire emissions in the western U.S. Environmental Research Letters, 16(3).

identified in the literature which contribute to the result of disproportionate risks to EJ populations include the following: disproportionately poor current air quality in EJ block groups, as well as worse forecast air quality attributable to changes in climate in these areas, particularly in urban areas; higher baseline prevalence of asthma and other respiratory conditions in minority populations, usually attributed to disproportionately high historical rates of exposure to air pollution over years to decades which research has linked to a history of structural racism, redlining of housing opportunity, and subsequent concentration of multiple EJ populations within close proximity to major roadways, which are a key source of air pollutant emissions; and disproportionately poor access to preventive health care and treatment. Air pollution from transportation sources, however, should be reduced by implementation of a range of transportation system electrification measures identified in the Commonwealth's Climate and Clean Energy Plan.[37] See USEPA (2021) for a more detailed summary of the literature connecting climate change, air quality, and factors of social vulnerability.[38]

Adaptation

There is a **moderate** adaptation gap for this impact. Actions to reduce the health effects of degraded air quality are currently focused on air quality warning systems that allow people to change their behaviors on days with poor air quality and on emission reduction programs that also reduce air pollution (e.g., overall relatively high levels of compliance with Federal National Ambient Air Quality standards for $PM_{2.5}$ and ozone; Massachusetts policies to reduce reliance on gas powered vehicles or limit use of fossil fuels and associated combustion-related air pollution overall; recent Federal incentives to adopt renewable energy and electric vehicle technologies; and efforts to increase urban tree cover and reduce heat island effects which can contribute to higher ozone concentrations in some urban areas). Although more can be done in this arena, the available options for adaptation to poor air quality are limited by available technology.

Example Adaptation Plans with Actions Addressing this Impact

- EEA MassAir Statewide Air Quality Warnings
- City of Boston Climate Action Plan: Develop a zero-emission vehicle road map
- Pioneer Valley Climate Action and Clean Energy Plan: anti-idling education campaign

[37] Massachusetts Executive Office of Energy and Environmental Affairs. 2020. Massachusetts 2050 Decarbonization Roadmap. Published December 2020 and available at: https://www.mass.gov/doc/ma-2050-decarbonization-roadmap/download; Massachusetts EOEEA. 2022. Massachusetts Clean Energy and Climate Plan for 2025 and 2030. Published June 30, 2022 and available at: https://www.mass.gov/doc/clean-energy-and-climate-plan-for-2025-and-2030/download

[38] EPA. 2021. Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. U.S. Environmental Protection Agency, EPA 430-R-21-003. See in particular Chapter 3, Air Quality and Health. www.epa.gov/cira/social-vulnerability-report

Sensitivities and Uncertainty

There is a broad literature establishing disproportionate sensitivity of certain demographic groups to health effects of air pollution, associated in part with incomplete or poor access to preventive and clinical health care which could reduce those sensitivities. A recent peer- and public-reviewed summary of the relevant literature particularly cites low-income groups, racial minorities, those with chronic health conditions such as heart and lung disease, and those 65 and older as particularly sensitive to health effects of air pollution[39] – not all of these sensitivities yet can be quantitatively assessed, which is a key limitation of the current risk assessment for this impact.

New diagnoses of asthma are analyzed for those age 17 and under, while premature mortality is analyzed only for those age 65 and older. The results do not capture impacts outside of these age groups, though these impacts exist. Additionally, this analysis is conducted using 36-km square grid average air quality concentrations, which may not capture small scale spatial variation, such as health impacts experienced by near-roadway communities.

Related Impacts

Table 10 lists the impacts in other sectors that have a connection to this impact.

Table 10. Additional Impacts related to Health Effects of Degraded Air Quality

Sector	Impact	Connection
Economy	Reduced Ability to Work	Individuals miss work while sick or caring for others who are sick. Missed school days are also strongly associated with impaired air quality.
Governance	Increased Demand for State and Municipal Government Services	Increased demand for state support of health care costs to treat adverse health effects.

[39] USEPA. 2021. Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. U.S. Environmental Protection Agency, EPA 430-R-21-003. www.epa.gov/cira/social-vulnerability-report

Human Sector: Urgent Impact #2 (tie)

Emergency Service Response Delays and Evacuation Disruptions

Extreme storms cause delays in response time, potentially leading to loss of life. Extreme coastal storm surge events and inland flooding could flood evacuation routes, trapping residents, leading to increased loss of life and injuries.

Major Level of Consequence	Disproportionate Exposure	Moderate Adaptation Gap
• Effects from flooding roads could increase emergency and law enforcement service response time, particularly in Suffolk and Middlesex counties, leading to indirect effects on mortality and morbidity.	• All classifications of EJ block groups will experience greater impacts than the rest of the Commonwealth.	• Mitigation measures for road flooding will support evacuation and emergency response teams, but proactive emergency planning and personnel training can be more widely implemented.

Impact Summary

Over the next century, climate change is expected to increase coastal traffic delays during storm events when roads become impassable due to the combined effects of sea level rise and storm surge events. These events will affect access to transportation networks, thereby delaying access to critical emergency response services, especially hospitals, emergency medical services (EMS), law enforcement, and fire response—with adverse consequences for human health and property.

Urgency Ranking Results

This impact is ranked as a **high priority** because of its expected major magnitude of impact, moderate adaptation gap, and high level of disproportionate impact.

This impact is evaluated quantitatively using the results of road delays associated with high-tide flooding, estimated in the Infrastructure sector analysis of Damage to Road and Loss of Road Services category, and a method for estimating the human health impact of road delays on the provision of fire and emergency medical technician responses.

> *"The lack of emergency services may impact me and my family as we age, plus this could be critical if there are more health issues due to extreme storms & power outages."*
>
> - Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The magnitude of consequence for this impact is **major** based on quantitative analysis of the potential for delays in select categories of emergency response. This impact includes the economic impacts of traffic delays due to flooded or damaged roadways from sea level rise and storm surge on access to three critical emergency response services – specifically access to hospitals, EMS, and fire response. Additional non-quantified but important impacts affect law enforcement response time as well as the need for law enforcement traffic control during these emergencies. Data and procedures developed for this type of analysis by FEMA are used to estimate impacts to response times and the human health consequences of these delays.[40] First, annual national emergency estimates are used to calculate emergency incidence rate for the affected population for the duration in which roads were affected. Next, Pew Research Center's 2018 estimate of an average of 13 minutes travel time to an emergency department in New England is used as a baseline, upon which the incremental changes in traffic delays is calculated using road and flood mapping from the coastal flood risk to roads modeling used in the Infrastructure sector analyses (see Infrastructure sector, Damage to Roads and Loss of Road Service impact category). The calculation of incremental delays attributable to a storm considers whether the specific areas affected have alternative routes available, in a general sense, based on the density of the local road network – a much more detailed model would be needed to specifically identify critical road routes, although it remains difficult to determine the exact locations where emergency and law enforcement response would be directed (e.g., to a downed power line, impassible road, or multiple injury location).

Traffic delay data were used to calculate delays in emergency response time. Using the referenced FEMA methodology, emergency response delays are translated into average mortality rates per incident and multiplied the incremental loss of life using an estimate of individual values for fatality risk reduction. The metric that results is the economic value of losses from sea level rise- and storm surge-induced traffic delays per incident, as a function of response time delays for three categories of emergency response: structure fire, EMS call for cardiac arrests, and unintentional injury.

[40] This analysis follows a benefit-cost methodology outlined by the Federal Emergency Management Agency (FEMA) to estimate the benefits of these critical services during an emergency: U.S. Federal Emergency Management Agency (FEMA). 2016. Benefit-Cost Sustainment and Enhancements: Baseline Standard Economic Value Methodology Report. Retrieved from: https://www.caloes.ca.gov/RecoverySite/Documents/Benefit%20Cost%20Sustainment.pdf

Table 11. Emergency Response Service Impacts from Traffic Delays Due to Sea Level Rise and Storm Surge

Economic impact of impacts to human health and property losses associated with road delays for emergency service calls. The road delays are from flooding events from accelerated sea level rise and storm surge from climate change. Future impacts presented for three time periods identified in the table by their central year: 2030 (near-term, 2020-2039); 2050 (mid-century, 2040-2059); and 2070 (mid-late century, 2060-2079). Modeling results not available for 2090 (end of century, 2080-2099). Values may not sum due to rounding.

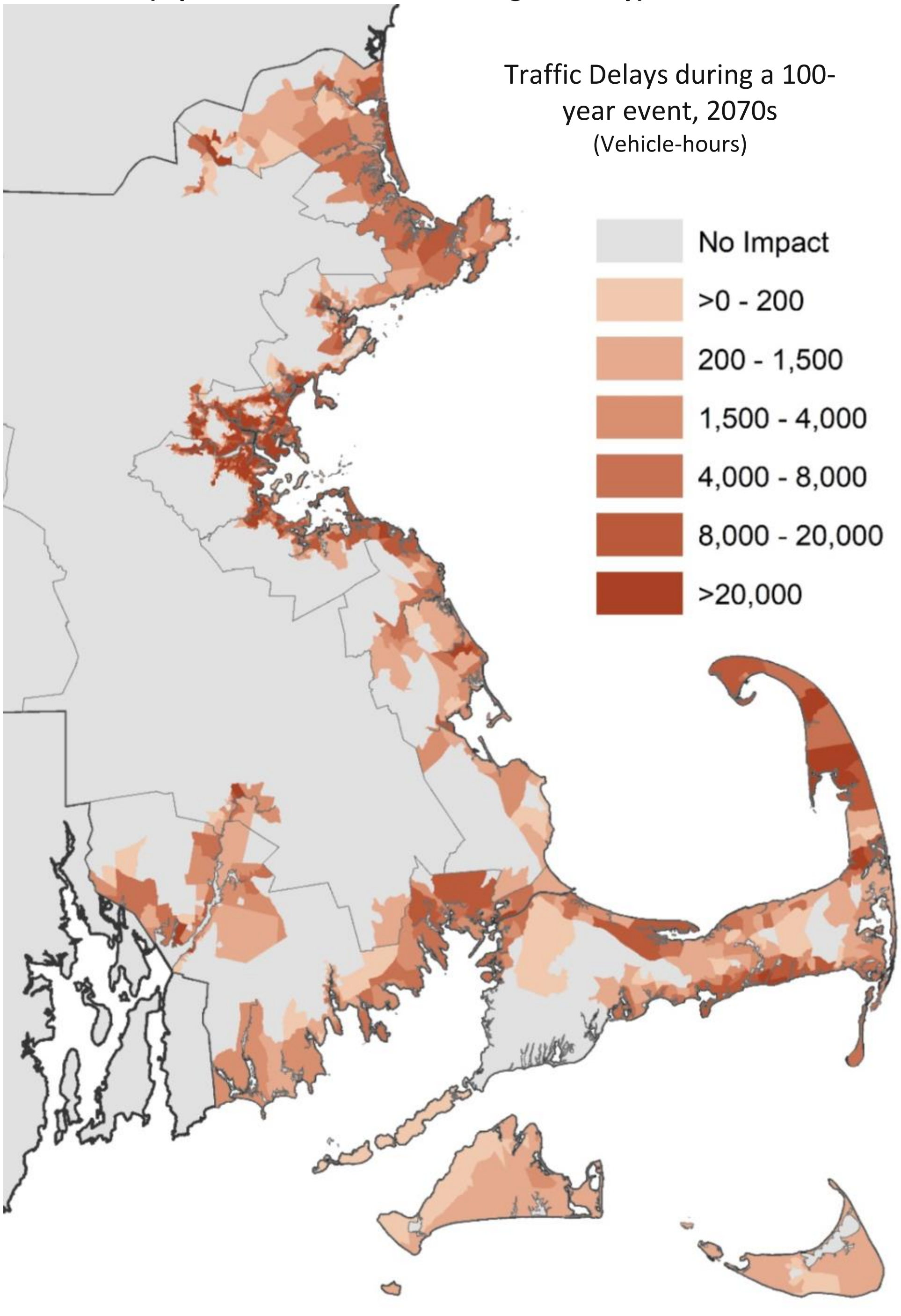
	Annual total expected impacts from climate change ($)			
Region	**Current**	**2030**	**2050**	**2070**
Eastern Inland	$600	$200	$500	$1,000
Boston Harbor	$220,000	$110,000	$475,000	$1,300,000
North & South Shores	$14,000	$10,000	$24,000	$43,000
Cape, Islands, & South Coast	$11,000	$4,700	$16,000	$27,000
Statewide	**$250,000**	**$130,000**	**$520,000**	**$1,400,000**

Note: There are no impacts from sea level rise and storm surge induced traffic delays in the Berkshire & Hilltowns, Greater Connecticut River Valley, Central, or Eastern Inland regions.

Source: Project Team analysis using a FEMA developed methodology

The spatial distribution of these impacts is concentrated in the Boston Harbor region, reflecting the spatial pattern of both sea level rise and storm surge induced traffic delays and the intensity of traffic demand in that region, particularly in Suffolk and Middlesex counties (see Figure 18, for example). In other counties and regions, delays are likely to be less intense in part because of the availability of less vulnerable alternative routes for emergency response during flooding and extreme events.

Figure 18. Traffic delays impacting emergency response by block group for a 100-year return period coastal flood (1 percent chance of occurring annually) in the 2070s



Source: Project Team analysis using a FEMA developed methodology

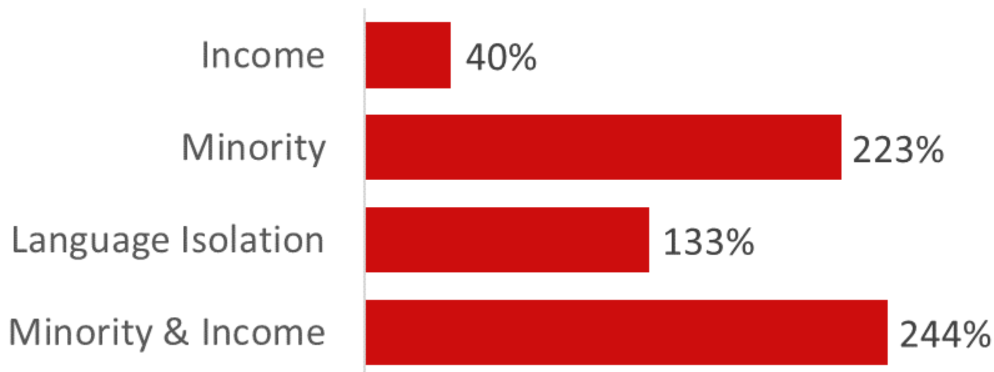
Disproportionality

Exposure to this impact is expected to have a **disproportionate** exposure**,** based on quantitative analyses. Populations living in EJ block groups defined on the basis of:

- Low-income population have a 40 percent greater impact than in the rest of the coastal areas potentially affected by high-tide flooding road impacts
- minority population have 223 percent greater impacts than in the rest of the coastal areas potentially affected by high-tide flooding road impacts
- language isolated populations have 133 percent greater impacts than in the rest of the coastal areas potentially affected by high-tide flooding road impacts
- minority population and income combined have 244 percent greater impacts than in the rest of the coastal areas potentially affected by high-tide flooding road impacts

Figure 19. Disproportionality of Impacts of Emergency Service Impacts Due to Traffic Delays During High-Tide Flooding

Comparison of the incidence of health impacts incurred as a result of road delays for emergency service calls in EJ block groups defined by income, minority status, language isolation and minority status and income combined, compared to all other block groups in the area of the state potentially affected by high-tide flooding traffic delays. Positive numbers and red bars represent disproportionate exposure for the listed population segment. See Section 2.1 of the main report for further description of the EJ block group definitions.



These results reflect the high level of traffic delays expected in the large urban areas of Suffolk and Middlesex Counties in the Boston Harbor region.

Adaptation

There is a **moderate** adaptation gap for addressing emergency service response delays and evacuation disruptions. Flood mitigation actions that target road infrastructure will serve as indirect adaptation measures to this impact, but more direct adaptation action may be needed. Some municipalities are taking more focused approaches by increasing backup power generators for critical infrastructure, developing city-wide emergency coordination plans, working with the most climate-vulnerable populations on developing clear evacuation guidelines, and practicing emergency response and evacuation scenarios. Climate change is projected to increase extreme precipitation events and storm surge, which will contribute to increases in inland and coastal flooding. The scale and planning needed to effectively address evacuation and emergency response efficacy requires that these hazards be addressed soon.

Example Adaptation Plans with Actions Addressing this Impact

- Resilient Ring's Island - Preventing a Neighborhood from Being Stranded by Flooding Phase 2 (Salisbury)
- MA DOT Flood Risk Assessment
- Regional Low-Lying Road Assessment and Feasibility Study – Wellfleet, Truro, Eastham, Brewster, Barnstable, & Bourne

Sensitivities and Uncertainty

Massachusetts-specific values for incidence rates of emergencies or average response times underlying the estimation of impacts on emergency services were not available for this study. As a result, the analysis relies upon standard values for these incidence rates, as suggested by FEMA in their benefit-cost methodology for estimating the value of emergency services. Some of these values were calculated from data from the early 21st century. These values may not account for changing trends in incident rates or local patterns. The uncertainties introduced by national values instead of Massachusetts-specific values are unknown.

In addition, the estimation of these economic impacts did not account for the potential increase in incidence rates during extreme weather or climate change. Results for the impact category summarizing Health Effects of Extreme Storms and Power Outages suggests that some categories of health impacts that might require an emergency response, such as injuries, could increase as a result of climate change. The impact of not accounting for this increase suggests the estimates of emergency response time impacts may be underestimated, because of increased demand for emergency services during extreme weather events.

Related Impacts

Table 12 lists the impacts in other sectors that have a connection to this impact.

Table 12. Additional Impacts Related to Emergency Response Delays

Sector	Impact	Connection
Infrastructure	Damage to Roads and Loss of Road Service	Traffic delays from high-tide flooding in the infrastructure/roads category are direct inputs to the emergency response delays category
Governance	Increase in Demand for State and Municipal Government Services	Addressing delays in emergency service may lead to increased investments in emergency response readiness and/or additional locations to better service affected populations
Human	All	Increases in the need for emergency response from nearly any climate-related health effect may affect the estimates presented here by increasing demand for emergency response beyond baseline levels

Human Sector: Remaining Urgent Impacts

The following impacts are also evaluated for urgency in the Human sector. The summaries below provide a snapshot of each impact, in order of urgency. More details on each impact, and the sources and methods used to derive results, can be found in Appendix A.

Reduction in Food Safety and Security

Temperature increases, spoilage, and power outages can lead to increased food contamination. Changes in food production and supply chain disruption linked to climate change will worsen existing food insecurity.

Moderate Level of Consequence	Disproportionate Exposure	Moderate Adaptation Gap
• Impacts could result from reduced crop yields, price effects, and supply chain interruptions, as well as food quality reductions.	• Food price increases in particular have a potentially strongly disproportional effect on low-income populations.	• Regional plans in place in some areas to build resilient local food systems; food safety has not been addressed on a large scale.

Increase in Mental Health Stressors

Negative effects of weather and climate change on mental health, including a broad range of impacts on overall well-being associated mostly with temperature stress.

Major Level of Consequence	Potential for Disproportionality	Moderate Adaptation Gap
• Suicide statewide could increase from 580 to 610 per year by 2090; but other qualitatively assessed impacts may be more important and widespread.	• Suicide impacts are not disproportionate among EJ block groups, but qualitative information shows mental stress from flood risk could be focused on EJ areas.	• Climate-induced mental health stressors are often not addressed in state and municipal resiliency planning.

Health Effects from Aeroallergens and Mold

Impacts from extended pollen seasons, particularly on people with asthma or hay fever, and increases in exposure to mold spores associated with more frequent flood events and higher humidity conditions.

Moderate Level of Consequence	Potential for Disproportionality	Moderate Adaptation Gap
• Several hundred additional emergency department visits for asthma expected by end of century, with annual medical costs of about $200,000.	• Available evidence suggests disproportional exposure does not exceed 2 percent, but baseline rates of conditions that sensitize populations to allergic reactions to pollen or mold are higher in EJ populations.	• Little action is being taken to address this impact directly despite the increasing rates of asthma associated with climate change-induced exposures to aeroallergens and mold.

Health Effects of Extreme Storms and Power Outages

Power outages and flooding, which could increase with more frequent extreme events, lead to a range of morbidity and sometimes fatal health outcomes and an increase in requests for emergency services.

Moderate Level of Consequence	Potential for Disproportionality	Moderate Adaptation Gap
• Quantifiable health effects from existing literature are relatively small compared to other categories.	• Impacts tend to fall among populations with less access to backup power or in areas vulnerable to inland flooding, with potential for disproportionate exposure.	• Increased focus on critical infrastructure redundancy and residential backup generation is needed, as well as support for individuals who may rely on electric power for critical medical devices.

Damage to Cultural Resources

Climate stressors can damage important cultural resources that hold special value to residents of the Commonwealth.

Moderate Level of Consequence	Potential for Disproportionality	Moderate Adaptation Gap
• Culturally important places and resources (e.g., museums, historical sites and districts, archaeological sites) and general attributes of life in Massachusetts (e.g., seasonality, seafood-based cuisine, local agriculture) may be at risk.	• Different populations hold value for different cultural resources and existing structures for protection and funding may not protect all resources equally, disproportionally affecting historically marginalized groups, including Massachusetts's federal- and state-recognized Tribes and other Indigenous communities.	• Actions targeted at a number of other impacts (e.g., flooding, power outages) will mitigate some general risk, however more attention is needed to target protection of cultural resources, including increasing the baseline inventory of at-risk resources.

Increase in Vector Borne Diseases Incidence and Bacterial Infections

Increase in incidence of West Nile Virus, Lyme disease, and other diseases, and associated fatal and nonfatal outcomes, as a result of changes in temperature and an extended seasons for vectors and/or impact on bacterial loads.

Major Level of Consequence	Limited Disproportionality	Moderate Adaptation Gap
• Over 31 new cases of West Nile Virus disease by end of century (valued at $35 million).	• The diseases of largest concern show no disproportionate exposure, however EJ block groups defined on the basis of minority and language isolated populations are disproportionately exposed to West Nile Virus.	• Public education and health monitoring currently underway are useful, but further research and development is needed to improve control methods.

4.2 Infrastructure Sector

Flooding (coastal and inland) is a major threat to infrastructure, however, drought, freeze-thaw cycles, high heat, heavy rainfall, and wind are also of concern. Because of infrastructure lifespans and planning horizons, adaptation action is often needed near term.

Table 13. Urgent Impacts in the Infrastructure Sector

IMPACT	DESCRIPTION	MAGNITUDE	DISPROPORTIONATE EXPOSURE	ADAPTATION GAP
Damage to Inland Buildings (MOST URGENT)	Addresses the risk of flooding to inland structures from rainfall (pluvial flooding) when drainage systems are overwhelmed by large rainstorms and rivers (fluvial flooding).	Major	Disproportionate	Moderate
Damage to Electric Transmission and Utility Distribution Infrastructure (MOST URGENT)	Costs to repair transmission infrastructure failure associated with heat stress and extreme events that directly affect the transmission and distribution system. Includes wired communication and information technology systems.	Major	Potential	Extreme
Damage to Rails and Loss of Rail/Transit Service (MOST URGENT)	Extreme temperature events reduce useful life of track and cause buckling events, which also lead to indirect impacts from delays that occur due to track buckling and repair. Also addressed are effects of storms and sea level rise on subway and commuter rail operation.	Moderate	Disproportionate	Moderate
Loss of Urban Tree Cover	Urban trees are susceptible to invasive pests and high heat/drought conditions and provide many services including mitigating heat island effects, pollution removal, etc.	Moderate	Disproportionate	Minimal
Damage to Coastal Buildings and Ports	Sea level rise, coastal erosion, and storm surge, as well as high wind events from tropical and extra-tropical storms, will cause increased damage to coastal structures, land, and related infrastructure such as ports and marinas.	Extreme	Limited	Moderate
Reduction in Clean Water Supply	Addresses changes in water quantity and quality for water supplied for all human uses. Changes in precipitation patterns and saltwater intrusion can lead to impaired surface and groundwater supply available for municipal, industrial, commercial, and agricultural uses	Major	Potential	Minimal

IMPACT	DESCRIPTION	MAGNITUDE	DISPROPORTIONATE EXPOSURE	ADAPTATION GAP
Damage to Roads and Loss of Road Service	Damage to roads from extreme precipitation, flooding, and temperature increases the need for repair and maintenance, and indirect effects of increased vehicle operating costs from driving on roads in poor condition. Includes effects on bridges and culverts at road crossings.	Major	Limited	Moderate
Loss of Energy Production and Resources	Changes in temperature increase electricity demand and reduce production efficiency, requiring changes in the overall network cost of meeting electric demand. Effects on solar energy production potentially subject to flooding are also considered.	Moderate	Limited	Minimal
Increased Risk of Dam Overtopping or Failure	Climate change could lead to more frequent overtopping of some, or all of the state dam safety program designated High or Significant Hazard dams, causing flooding of downstream areas.	Minimal	Potential	Moderate

Infrastructure Sector: Urgent Impact #1

Damage to Inland Buildings

Addresses the risk of flooding to inland structures from rainfall (pluvial flooding) when drainage systems are overwhelmed by large rainstorms, or by rivers affecting buildings in the floodplain (fluvial flooding).

Major Level of Consequence	Disproportionate Exposure	Moderate Adaptation Gap
• Inland residential property damage may increase by 44 percent over baseline by 2050.	• Disproportional exposure for low income (24 percent) and language isolation (39 percent) is high.	• Nature-based stormwater management options are being implemented across the state, but regulatory support for building adaptation is lagging.

Impact Summary

Extreme precipitation events have intensified in recent decades across most of the U.S., and this trend is projected to continue. Flood risk from high excessive riverine flow has been documented to be widespread in the contiguous U.S. and is growing either as a result of changes in housing and population density over time, as a result of climatic changes in the frequency and intensity of precipitation patterns, or both. Riverine flooding, also known as fluvial flooding or flooding along rivers, occurs when excessive rainfall over an extended period of time collects across a watershed and causes a river to exceed its capacity. Another type of inland flooding, pluvial flooding, results from excessive rainfall that collects in an area without adequate drainage and causes flooding independent of the overflow of a water body, usually in low-lying areas and can be a common occurrence in urban areas.

Heavier downpours can result in more extreme flooding, affecting human health and safety, property, infrastructure, and natural resources, as well as business interruption, loss of wages, and loss of emergency or other critical services.

Urgency Ranking Results

This impact is ranked as a **high priority** because of its large and disproportionate impacts. Damages from fluvial flooding to residential properties are evaluated at the Census block group level. Damages to commercial properties from fluvial flooding and damages to all properties from pluvial flooding are examined at a statewide level.

The analysis uses change in expected annual damage (EAD) from flooding at only residential properties in the Commonwealth for different temperature scenarios, which are mapped to the four time periods in the Climate Assessment, to value the damage to structures from riverine flood impacts.[41] The underlying data considers flooding for return intervals of two years (an

[41] The results are based primarily on data from: Wobus, C.W., Porter, J., Lorie, M., Martinich, J., & Bash, R. (2021). Climate change, riverine flood risk and adaptation for the conterminous United States. Environmental Research Letters. doi: 10.1088/1748-9326/ac1bd7. Data on damage ratios by block group and integer degree were downloaded from: www.epa.gov/CIRA/social-vulnerability-report, see data supporting Appendix I.

event with a 50 percent chance of occurring each year) through 500 years (an event with a 0.2 percent chance of occurring each year). Study authors calculate a damage function known as a "frequency-loss curve" – which expresses structural damage for each type of flood event – for each property. From this curve the EAD can be calculated. Data are not reported at the property level, but are available from a secondary source at the block group level. The data do not address flooding events associated with poor or inadequate drainage, quantifying only riverine floods. As a result, the quantified results in this impact category are limited to riverine floods, and other types of flooding events, such as pluvial flooding in urban areas in particular, are considered qualitatively.

The method applied estimates the baseline annual EAD using current structure characteristics (e.g., ground level floor elevation[42], replacement cost, market value), the flood depths associated with baseline conditions for varying return periods[43], and depth-damage functions available from FEMA's HAZUS documentation[44]. The underlying study model provides estimates of projected property damage at multiple spatial scales – for this work, results were provided at the Census block group level; properties were grouped by Census block group and EAD values summed under future climate scenarios. Property values are held constant over the course of the century, and impacts are projected under a "no additional adaptation" scenario.

"The places I live and work on in a flood zone/plain. I could lose my home and my livelihood in the event of severe flooding."

"The heavier rains that we now experience exacerbate the problem, which leads to flooding that used to happen once in a blue moon to being a yearly threat."

- Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The consequences of inland flooding are projected to be **major** due to widespread and substantial increases in economic damage to structures, particularly from 2050 onward. Using the methods described above, baseline annual economic damages of riverine flooding to residential structures, before climate change, are estimated to be $116 million statewide. Annual economic damages are estimated to increase by $8.6 million statewide as a result of climate change, with some regions experiencing a decline in impacts and others an increase, because of differences in both the pattern of precipitation changes and the configuration of local river systems to which runoff flows. By 2050, all regions are projected to experience an

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[42] These characteristics were made available to the EPA study team involved in the Wobus et al. (2021) paper by the First Street Foundation. Details of the dataset are provided in: First Street Foundation. 2020a. The First National Flood Risk Assessment: Defining America's Growing Risk. Available at https://assets.firststreet.org/uploads/2020/06/first_street_foundation__first_national_flood_risk_assessment.pdf

[43] Details of the "current climate" baseline flood risk modeling can be found in First Street Foundation, 2020b. First Street Foundation Flood Model: Technical Methodology Document. Available: https://assets.firststreet.org/uploads/2020/06/FSF_Flood_Model_Technical_Documentation.pdf

[44] FEMA., undated. Multi-hazard Loss Estimate Methodology: Flood Model Technical Manual. https://www.fema.gov/sites/default/files/2020-09/fema_hazus_flood-model_technical-manual_2.1.pdf

increase in damages, totaling over $50 million statewide, a 44 percent increase over baseline, with over half of the impacts in the Eastern Inland region. By 2090, total damages are roughly two times the baseline damages, increasing from $116 million to $226 million. These estimates are consistent with the climate scenarios chosen for this Assessment and the estimates presented in Wobus et al. al. (2021) for economic impacts of inland flooding.

Table 14. Annual Economic Impact Increase of Inland Riverine Flooding to Residential Structures Due to Climate Change

Economic impacts are defined as annual economic impact as compared to the baseline climate scenario (1986-2005). Future impacts presented for four time periods identified in the table by their central year: 2030 (near-term, 2020-2039); 2050 (mid-century, 2040-2059); 2070 (mid-late century, 2060-2079); and 2090 (end of century, 2080-2099). Values may not sum due to rounding.

	Annual economic impact of riverine flooding to residential structures due to climate change ($millions)			
Region	**2030**	**2050**	**2070**	**2090**
Berkshires & Hilltowns	$4.7	$3.3	$6.0	$9.4
Greater Connecticut River Valley	$12	$9.2	$15	$24
Central	-$1.9	$2.4	$3.6	$3.8
Eastern Inland	-$4.0	$27	$43	$54
Boston Harbor	$0.9	$4.7	$8.1	$11
North & South Shores	-$3.2	$2.9	$7.3	$11
Cape, Islands, & South Coast	$0.3	$1.4	$1.9	$2.0
Statewide	$8.6	$51	$85	$110

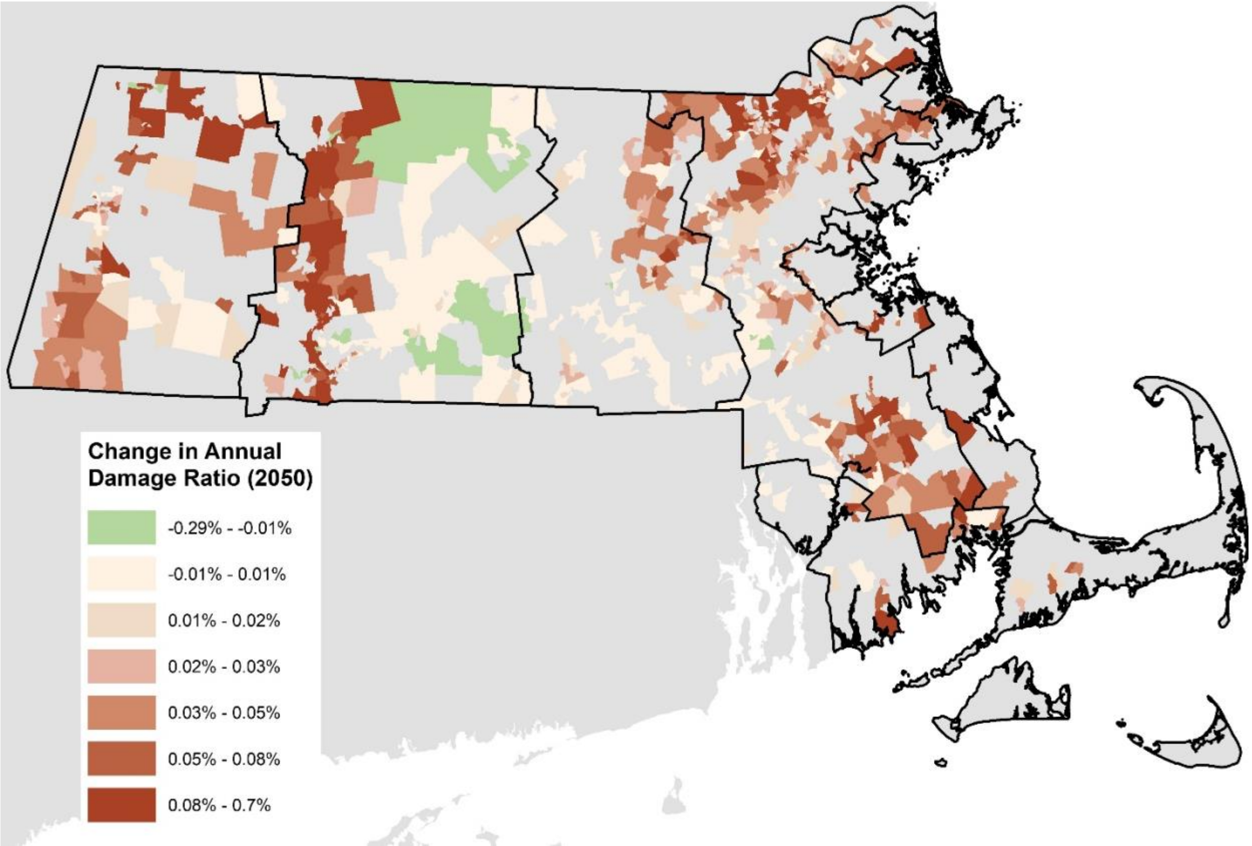
Source: Derived from Wobus et al. (2021), U.S. EPA data at www.epa.gov/CIRA and Project Team analysis

Results in Table 14 for the 2030 period may seem unusual to some readers. It is important to note that negative values represent temporary reductions in flood risk for the 2030 period, in some regions, relative to current flood risks, associated with drying conditions in that period relative to current climate. These regional scale reductions in flood risk, however, are seen only in the 2030 period – by the 2050 period and afterward, damages at regional scale increase relative to current levels of flood and continue to increase steadily over time.

Figure 20 below provides a summary of the annual residential structure damage ratio, in 2050, by block group. As shown in the map, many of the areas expected to see the most severe inland flooding impacts trace the Connecticut River valley itself; the northern portion of Berkshire County; and more isolated areas of the eastern part of the state, in multiple regions. Reductions in damage could occur in the eastern part of the Greater Connecticut River Valley region, associated with changes in circulation patterns and drying conditions leading to reduction in river flow in that area of the region for the 2050 period. Most of this area is less populated than the areas that see increases in flood risk in other parts of the region and statewide, as shown in the map.

Figure 20. Changes in Annual Residential Structure Damage Ratio in 2050, by Massachusetts Block Group

The structure damage ratio at the block group level is the annual expected damage in the 2050 time period divided by the total block group residential structure value. Red areas in the map show an increase in damages relative to baseline climate, and green areas show reduction in damages.



Source: U.S. EPA data at www.epa.gov/CIRA and Project Team analysis

Other impacts not estimated above include impacts to commercial structures and from pluvial flooding – the latter is related to high precipitation events and poor or inadequate drainage. Impacts to commercial structures were estimated by First Street Foundation, but estimates were provided only for multi-hazard flooding combined (that is, tidal, storm surge, pluvial, and fluvial), and only statewide and for the Boston area.[45] That analysis shows that structural damage to commercial properties from all flood hazards might increase by 25 percent (by $115 million statewide) over the next 30 years, but 75 percent of that damage would be in Boston, leading to the conclusion that damage to commercial structures in the First Street Foundation analysis is mostly from coastal rather than inland flooding. As a result, the total structural damage to commercial properties statewide by 2050 might be in the tens of millions of dollars, which would increase the estimates presented for residential structure damage but would not change the magnitude of consequence score for this impact.

[45] First Street Foundation & ARUP. 2021. The 4th National Risk Assessment: Climbing Commercial Closures. Available at https://assets.firststreet.org/uploads/2021/11/The-4th-National-Risk-Assessment-Climbing-Commercial-Closures.pdf

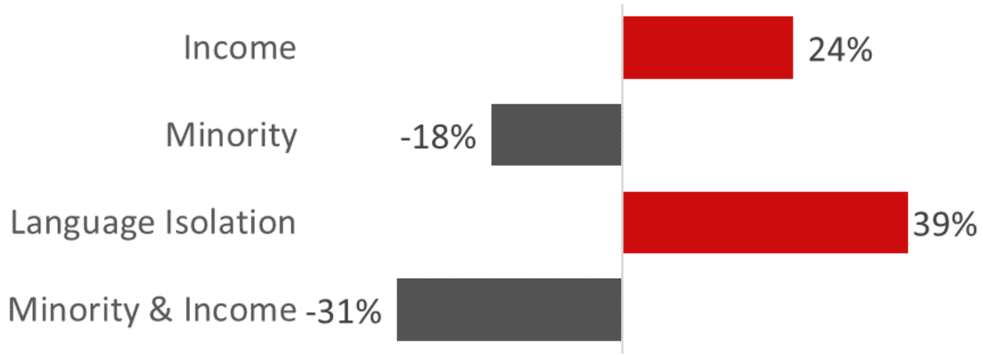
Disproportionality

Exposure to this impact is highly **disproportionate**. Populations living in EJ block groups defined on the basis of:

- Low-income populations have 24 percent higher rates of structural damage to residential structures from riverine flooding than the rest of the Commonwealth. This disparity is apparent in two regions – the Greater Connecticut River Valley and Eastern Inland, where the rates of structural damage are over 50 percent higher in block groups defined on the basis of low income. In all other regions of the state, no disproportionate impact results in aggregate – but it is also true that many communities have specific EJ block groups that are affected by inland flooding.
- Language isolated populations have 39 percent higher rates of structural damage to residential structure from riverine flooding than the rest of the Commonwealth. The disparity is apparent in two regions – Greater Connecticut River Valley (where the rates of structural damage are over 350 percent higher in block groups defined on the basis of language isolation); and Eastern Inland (91 percent higher). In all other regions of the state, no disproportionate impact results.

Figure 21. Disproportionality of Inland Flooding Damage to Residences

Comparison of the rates of structural damage to residential structures from inland riverine flooding in EJ block groups defined by income, minority status, language isolation and minority status and income combined, compared to all other block groups in the state. Positive numbers and red bars represent disproportionate exposure for the listed population segment. See Section 2.1 for further description of the EJ block group definitions.



The disproportionality assessment excludes two aspects of inland flooding that may affect these results: incidence of pluvial flooding, which results from high precipitation events coupled with inadequate drainage; and impacts to commercial structures. Available qualitative information suggests that pluvial flooding in particular may be associated with impacts in EJ block groups. Concerns for socially vulnerable populations in inland floodplains (both pluvial and fluvial) include that these groups are disproportionately located in areas that are most vulnerable to damaging flooding. Recent events such as Hurricane Harvey (characterized by extreme rainfall) have reinforced the social inequities associated with pluvial flood risk and impacts, particularly identifying racial and income inequities. Chakraborty et al. (2019) analyzed whether the spatial distribution of flooding effects were distributed inequitably with respect to race, ethnicity, and socioeconomic status, after controlling for relevant explanatory factors.[46] A similar study found that Hispanic, Black and other racial/ethnic minority households were subject to more extensive flooding than households occupied by White individuals, and that households who experience lower income faced more extensive flooding than higher income households (Collins et al. 2019).[47] Lu (2017) finds that for Houston, TX and other areas, socioeconomic status and racial characteristics correlate with low elevation above coastal and inland water bodies.[48] The 2016 Climate and Health Assessment also found, at a national scale, that people living in floodplains are more vulnerable not only to extreme weather, but also to social and economic stressors that can occur simultaneously or consecutively and accumulate over time.[49] This information generally supports the conclusion of disproportionate exposure to the inland flooding impact.

Adaptation

There is a **moderate** adaptation gap for this impact. There are many adaptation resources available for inland buildings, including building design and retrofitting toolkits and guidelines for homeowners and renters. Nature-based stormwater management tools, including permeable pavements, rain gardens, bioswales, tree filters, and other bioretention systems, are being implemented at sites across the state at a project level but have yet to see widescale adoption, in part because of funding gaps. Zoning and building code updates are commonly mentioned in adaptation plans and represent a key pathway for facilitating adaptation in state- and privately-owned buildings at larger scales. Near-term implementation of these regulatory changes, coupled with creative funding and incentive structures, would increase the pace of adaptation and lessen the already increasing impacts of climate stressors on buildings.

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[46] Chakraborty J, Collins TW, and Grineski SE. 2019. Exploring the environmental justice implications of Hurricane Harvey flooding in greater Houston, Texas. *American Journal of Public Health* 109**,** 244–50.

[47] Collins TW, Grineski SE, Chakraborty J, and Flores AB. 2019. Environmental injustice and Hurricane Harvey: a household-level study of socially disparate flood exposures in Greater Houston, Texas, USA. *Environmental Research* 179 108772

[48] Lu Y. 2017. Hurricane flooding and environmental inequality: do disadvantaged neighborhoods have lower elevations? *Socius* **3** 1–3. Table 2 reports the average marginal effects of the disadvantage dummies in the 80 regressions. In 11 out of the 20 MSAs, tracts in the bottom income quartile have lower ($p < .05$) elevations compared to other tracts. In 15 out of 20 MSAs, tracts in the top poverty quartile have lower elevations ($p < .05$). Tracts with highest racial/ethnic minority concentration and non-citizen concentration have lower elevations ($p < .05$) in 13 of the MSAs. In 9 of the MSAs, elevation is negatively associated with all four measures of neighborhood disadvantage.

[49] Gamble JL, Balbus J., Berger M, Bouye K, Campbell V, Chief K, Conlon K, Crimmins A, Flanagan B, Gonzalez-Maddux C, Hallisey E, Hutchins S, Jantarasami L, Khoury S, Kiefer M, Kolling J, Lynn K, Manangan A, McDonald M, Morello-Frosch R, Redsteer MH, Sheffield P, Thigpen Tart K, Watson J, Whyte KP, and Wolkin AF. 2016. Ch. 9: Populations of Concern. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment.* U.S. Global Change Research Program, Washington, DC, 247–286. http://dx.doi.org/10.7930/J0Q81B0T

Example Adaptation Plans with Actions Addressing this Impact

- Climate Preparedness & Resilience Catalyst Project – Cambridge
- Climate Change Vulnerability and Resiliency Assessment Study – Canton
- Watershed-Wide Analysis to Optimize and Coordinate Regional Stormwater Management in the Upper Mystic River

Sensitivities and Uncertainty

This analysis does not account for changes in population and development within flood risk zones. Without a reasonable method to predict future floodplain development or policies governing development, these factors are held constant. The impact of this assumption may be to underestimate the economic impact of flood risk. While there is evidence that structure market value grows over time with GDP, income, and population growth, there is also an emerging literature that flood risk is starting to be incorporated in market valuations of the highest risk properties.[50]

The underlying data used in the main quantitative analysis for inland flooding excludes flooding events associated with urban drainage, quantifying only riverine floods and their impact on residential structures. The focus on riverine flooding, as a result, may not account for flooding events in cities and other areas where large populations of socially vulnerable individuals reside. In addition, the underlying flood risk dataset incorporates the mitigating impact of current flood control structures – but no additional structures beyond those currently in place. Flood control structures are likely to be more common in many densely populated urban areas, which may also correlate with the locations of some socially vulnerable populations.

The First Street Foundation data upon which the results depend are the only comprehensive, consistent statewide flood risk data currently available. While the data are appropriate for the planning and priority setting objective of this Climate Assessment, an analysis at this broad scale may omit certain site-specific risks that could affect local flood risk results.

Related Impacts

Table 15 lists the impacts in other sectors that have a connection to this impact.

Table 15. Additional Impacts related to Damages to Inland Buildings

Sector	Impact	Connection
Economy	Economic Losses from Commercial Structure Damage and Business Interruptions	Flooding often leads to business interruptions, of varying lengths tied to flood severity.

[50] See in particular a literature review in Lorie, M., Neumann, J. E., Sarofim, M. C., Jones, R., Horton, R. M., Kopp, R. E., Fant, C., Wobus, C., Martinich, J., O'Grady, M., Gentile, L. E. (2020). Modeling coastal flood risk and adaptation response under future climate conditions. Climate Risk Management, 29. Doi:10.1016/j.crm.2020.100233, although focused on coastal flood risk and erosion of property values in high risk flood zones.

Sector	Impact	Connection
Governance	Damages to Inland State and Municipal Building and Land	State-owned structures may be affected in some way by inland flooding.
Human	Reduction in Food Safety and Security	Some food distribution channels could be affected by inland flooding.
Human	Health Effects of Aeroallergens and Mold	Mold levels may be affected by the frequency and intensity of inland flood risk.
Human	Reduction in the Availability of Affordably Priced Housing	Income- restricted affordable housing, publicly or privately owned, may be affected by inland flooding.
Human	Damage to Cultural Resources	Older culturally important buildings and structures located on previously stable lands adjacent to water bodies now prone to flooding may be at greater risk of damage.
Infrastructure	Damage to Roads and Loss of Road Service; Damage to Rails and Loss of Rail/Transit Service	Low-lying roads and rail may be damaged by inland flooding.

Infrastructure Sector: Urgent Impact #2

Damage to Electric Transmission and Utility Distribution Infrastructure

Costs to repair transmission infrastructure failure associated with heat stress and extreme events that directly affect the transmission and distribution system. Includes wired communication and information technology systems.

Major Level of Consequence	Potential for Disproportionality	Extreme Adaptation Gap
• Repair costs for electric transmission and distribution infrastructure are projected to increase by $87 million per year by 2050.	• Repair costs for electricity infrastructure are not concentrated in EJ areas.	• Some focus on increasing grid reliability with back up energy sources, little on grid infrastructure resilience.

Impact Summary

This analysis estimates damages to electric transmission and distribution infrastructure due to climate change. This multi-dimensional analysis considers a wide range of climate stressors, including extreme temperature, extreme storms, lightning, vegetation growth, wildfire activity, and coastal flooding. Impact receptors include transmission and distribution lines, poles/towers, and transformers. The costs are based on changes to repair activities to these receptors at the time that a particular climate stressor causes failure.

It is also known that certain climate stressors do cause power outages associated with a failure of grid infrastructure, in addition to incremental repair costs. Power outages have potentially large associated direct and indirect economic costs, but these damages are not included here. They are instead addressed as part of other impact categories under the Human (Health Effects of Extreme Storms and Power Outages) and Economy (Economic Losses from Commercial Structure Damage and Business Interruptions) sectors.

Urgency Ranking Results

This impact is ranked as a **high priority** because of its large impact and adaptation gap, and potential for disproportionate impacts.

Monetized damages for this sector are the costs of repair or replacement of damaged infrastructure, reported in Fant et al. (2020).[51] The impact model for this sector was run under two infrastructure system scenarios: one with expansion of infrastructure associated with demand growth, and one with static infrastructure. Increases in demand growth may be due to population growth, or increased demand due climatic change — in particular, warmer temperatures increase usage of air-conditioning. The model identifies changes in performance

[51] Fant, C., B. Boehlert, K. Strzepek, P. Larsen, A. White, S. Gulati, Y. Li, and J. Martinich (2020). Climate change impacts and costs to U.S. electricity transmission and distribution infrastructure. *Energy*, 195, 116899, doi:10.1016/j.energy.2020.116899. Available online at https://www.sciencedirect.com/science/article/pii/S0360544220300062

and longevity of physical infrastructure, such as power poles and transformers, and quantifies these impacts in economic terms. While certain climate stressors do cause power outages which have associated direct and indirect economic costs, these damages are not included in damage estimates. Repair costs are also allocated based on the activity being performed. These activities include transmission line capacity, wildfire repair, tree trimming, substation affected by sea level rise, substation affected by storm surge, wood pole decay, transmission transformer lifespan, and distribution transformer lifespan. Although these are the categories of impact quantified in the relevant literature, impacts to the grid could also be associated with river flooding or other climate hazards, but these have not been quantitatively assessed at this time.

> *"We have had severe damage to our electrical grid in the past year, and I am certain it will only get worse as storms become more severe."*
>
> \- Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The consequences of climate on grid infrastructure are projected to be **major** due to widespread and substantial increases in economic damage to these assets, including large impacts in 2030. The method applied focuses on additional repair costs, capital costs, and operating costs to be incurred mostly by electric utilities in the Commonwealth. Baseline annual repair costs are not currently available, but national estimates for maintaining the distribution grid are in the tens of billions of dollars. Most utilities have experienced rapidly growing costs in the area as a result of weather-related damage to distribution networks and costs for preventative maintenance such as vegetation management.[52]

Table 16. Annual Economic Impact of Climate Change on Electric Grid Infrastructure

Change in electric transmission and distribution infrastructure impacts ($millions/year, real 2015$) compared to a 1986-2005 baseline. Future impacts presented for four time periods identified in the table by their central year: 2030 (near-term, 2020-2039); 2050 (mid-century, 2040-2059); 2070 (mid-late century, 2060-2079); and 2090 (end of century, 2080-2099). Values may not sum due to rounding.

	Annual economic impact of climate change to electric grid infrastructure ($millions)			
Region	**2030**	**2050**	**2070**	**2090**
Berkshires & Hilltowns	$1.5	$2.7	$4.2	$5.8
Greater Connecticut River Valley	$5.9	$10.7	$17.0	$22.9
Central	$6.3	$12.3	$19.4	$27.5
Eastern Inland	$15.2	$29.6	$49.7	$74.5
Boston Harbor	$6.0	$12.2	$20.0	$30.0
North & South Shores	$7.7	$13.4	$24.8	$36.9

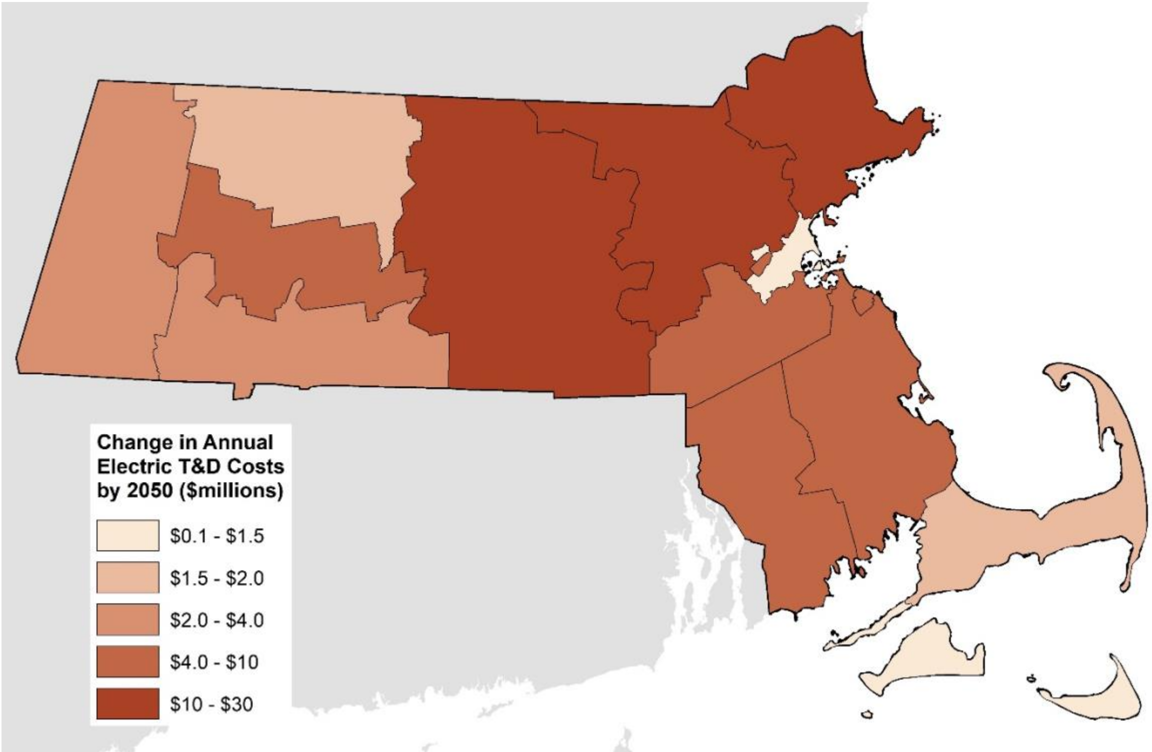
[52] National-scale baseline estimates from 2021 ASCE Report Card for America's Infrastructure site, available at: https://infrastructurereportcard.org/cat-item/energy-infrastructure/

	Annual economic impact of climate change to electric grid infrastructure ($millions)			
Region	**2030**	**2050**	**2070**	**2090**
Cape, Islands, & South Coast	$2.9	$5.6	$9.2	$12.9
Statewide	**$45.5**	**$86.6**	**$144.2**	**$210.4**

Source: Fant et al. (2020) and project team analysis

Impacts are concentrated in areas where the distribution and transmission networks are most dense, where lightning and vegetation-related damage are expected to be highest, and where temperature extremes are expected to be most severe. All regions can expect an increase in climate change related costs, growing over the 21st century. The Eastern Inland region has the highest estimate of incremental repair costs, primarily linked to more severe forecast extreme weather-related events, such as lightning storms.

Figure 22. Estimated Increase in Electric Transmission and Distribution Repair Costs by 2050



Source: Fant et al. 2020

Disproportionality

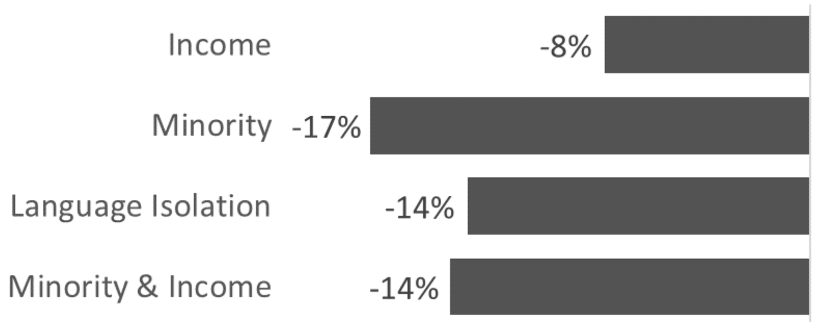
This impact has a **potential** for disproportionate exposure. All categories of populations living in EJ block groups have lower rates of exposure to grid infrastructure repair costs than populations in the rest of the Commonwealth, as shown in Figure 23.[53] While typically these

[53] Note that this impact, in the Infrastructure sector, focuses on the repair costs of failed grid infrastructure. The effects of electricity outages on health and business, which are more likely to have disproportionate impacts, are discussed in the Human and Economy sectors, respectively.

costs are spread over the entire customer base and not focused on particular geographies, for this analysis the location of grid infrastructure points of stress are used as a proxy for the geography where impacts may be most acutely experienced. Nonetheless, impacts to the grid in the underlying literature have been assessed only at the county level, and could be more localized. Further, qualitative considerations suggest that EJ communities may have less access to backup power during periods when damage to transmission and distribution infrastructure leads to power outages. Based on these qualitative considerations and consultation with utility sector experts, this impact has a potential for disproportionate exposure to this impact.

Figure 23. Disproportionality of Grid Infrastructure Impacts

Comparison of repair costs for grid infrastructure in EJ block groups defined by income, minority status, language isolation and minority status and income combined, compared to all other block groups in the state. Negative numbers and gray bars represent a negative correlation between the block groups meeting the EJ criteria on the basis listed and the magnitude of consequence. See Section 2.1 of the main report for further description of the EJ block group definitions.



Adaptation

There is an **extreme** adaptation gap for this impact. Statewide, there is significant focus on adapting the grid to mitigate the effects of disruptions by implementing microgrids, increasing small-scale local renewable energy production, and installing backup energy storage and generation for key infrastructure. These approaches decrease overall vulnerability by distributing production and increasing grid flexibility. Several local plans aim to prevent disruptions by making transmission and distribution infrastructure more resilient to climate threats like severe storms and extreme heat but these actions are not yet underway across the Commonwealth. Adaptation options include burying transmission wires[54]and protecting existing and new substations from flooding risks with appropriate mitigation measures. The Department of Public Utilities has begun including requirements for flood risk evaluation every five years in new substation approvals.

[54] Burying transmission lines is a common resiliency strategy, particularly against extreme weather, however it may not increase resiliency to extreme heat. In a recent heat wave, Eversource reported failures due to overheating equipment in underground systems, where airflow is limited (Boston Globe, August 3, 2022. https://www.bostonglobe.com/2022/08/03/science/tens-thousands-lost-power-july-heat-wave-is-electrical-system-prepared-climate-change/)

Example Adaptation Plans with Actions Addressing this Impact

- Hazard Mitigation Plan – Springfield: See underground placement of new utility lines
- Ready for Tomorrow - Climate Change Vulnerability Assessment and Adaptation Plan – Salem: See burying the electrical distribution system

Sensitivities and Uncertainty

While certain climate stressors do cause power outages which have potentially large associated direct and indirect economic costs, those additional costs are not included in damage estimates, but considered in other impact categories (see list below).

The model for quantifying damages also assumes that grid demand (load) is most influenced by population change and climatic factors; grid demand is assumed to not be influenced by economic growth and currently the Climate Assessment is unable to comprehensively address the effect of decarbonization and renewable generation policies on grid demand. Future changes in the design and structure of electric grids, such as those that might be required to support decarbonization and/or distributed renewable infrastructure, are not considered in this study.[55] Finally, two of the nine infrastructure types considered in this study (transmission lines and electrical substations) are not scaled for changes in population or economic growth, because there is not a clear relationship between those variables in the underlying literature; those costs are included in the overall results but not adjusted for population or other growth factors over time.

Related Impacts

Table 17 lists the impacts in other sectors that have a connection to this impact.

Table 17. Additional Impacts related to Electric Grid Infrastructure

Sector	Impact	Connection
Economy	Economic Losses from Commercial Structure Damage and Business Interruptions	Power outages related to distribution and transmission grid failures have substantial impacts on businesses.
Human	Health Effects from Extreme Storms and Power Outages	Power outages have been linked to specific human health impacts such as food contamination, carbon monoxide poisonings (from improper portable generator use) and impacts on populations dependent on electric supply for medical equipment.

[55] The 2025/2030 Clean Energy and Climate Plan (released June 30th, 2022) may provide key insights into future infrastructure changes but has not yet been reviewed for the Climate Assessment.

Infrastructure Sector: Urgent Impact #3

Damage to Rails and Loss of Rail/Transit Service

Extreme temperature events reduce useful life of track and cause buckling events, which also lead to indirect impacts from delays that occur due to track buckling and repair. Also addressed are effects of storms and sea level rise on subway and commuter rail operation.

Moderate Level of Consequence	Disproportionate Exposure	Moderate Adaptation Gap
• Rail repair costs could reach up to $6 million per year by 2050 and $35 million per year by end of century.	• EJ block groups defined on the basis of minority population have 24 percent higher exposure to rail maintenance costs than the rest of the Commonwealth.	• Adaptation strategies are available but costly, and little action has been taken.

Impact Summary

Rail in Massachusetts consists of three main components: commuter rail; long-distance passenger and freight rail; and transit. The first and third components are concentrated in the eastern portion of the state, but all regions rely on rail for movement of passengers and freight to at least some extent. Impacts may also occur to the rail maintenance facilities (e.g., flooding) which if not fully operable will prevent rail service operation. Quantified climate impacts to rail are costs of replacing track to repair lateral alignment defects in the buckling zone and costs of re-aligning rail in adjoining zones, incurred as a result of extreme heat deforming rails. This category excludes associated costs of train delays, which are addressed elsewhere.

Due to constraints of governing bodies that maintain the rail system, primarily the MBTA, including maintenance budgets and repair crew availability, there may be a decline in the level of service for rail that would have additional impacts on users and system reliability.

Urgency Ranking Results

This impact is ranked as a **high priority** because, even though the increase in quantified maintenance costs is moderate, impacts have a high potential for disproportionate impacts and the adaptation gap is also moderate.

This impact is evaluated using the approach described in Neumann et al. (2021)[56] with more detail in Chinowsky et al. (2017)[57]. Impacts are associated with high heat, which can deform rails and requires rail repair or replacement while also leading to user delays and reductions in system reliability. The approach estimates climate-related changes in rail maintenance costs such that the current level of service provided is maintained over time, but it is highly

[56] Neumann, J.E., Chinowsky, P., Helman, J., Black, M., Fant, C., Strzepek, K., and Martinich, J. (2021) Climate effects on US infrastructure: the economics of adaptation for rail, roads, and coastal development. Climatic Change 167, 44 (2021). https://doi.org/10.1007/s10584-021-03179-w

[57] Chinowsky P, Helman J, Gulati S, Neumann J, Martinich J (2017) Impacts of climate change on operation of the US rail network. Transport Policy. https://doi.org/10.1016/j.tranpol.2017.05.007

aggregated in nature and so may over- or under-estimate costs in particular locations. Changes in costs are estimated using an engineering-type life-cycle analysis and damage assessment. These climate-driven effects were evaluated per rail mile on a half-degree (latitude/longitude) grid and distributed by rail mile using the latest rail network data from MassGIS.

"The commuter rail has always issues and delays, especially during extreme storms. This affects me personally, due to I cannot trust on this service when I really need to be at certain time in a place."

"I depend on public transportation, so rail service is very important to me."

- Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The consequences of increased rail maintenance costs are projected to be **moderate** due to the increased costs, summarized in Table 18 below. Costs are only about $2 million above baseline in the 2030s but increase to $6 million in 2050 and $35 million in 2090. Current climate-induced rail maintenance costs are not available. As shown in Table 18, rail maintenance costs are highest and increase more significantly in the eastern parts of the state, particularly the Boston Harbor and Eastern Inland regions.

Table 18. Impacts to rail maintenance costs associated with extreme heat

Change in rail maintenance and repair costs compared to a 1986-2005 baseline. Future impacts presented for four time periods identified in the table by their central year: 2030 (near-term, 2020-2039); 2050 (mid-century, 2040-2059); 2070 (mid-late century, 2060-2079); and 2090 (end of century, 2080-2099). Value may not sum due to rounding.

	Annual expected damage ($millions)			
Region	**2030**	**2050**	**2070**	**2090**
Berkshires & Hilltowns	<$0.1	$0.1	$0.4	$0.8
Greater Connecticut River Valley	$0.1	$0.4	$1.1	$2.6
Central	$0.2	$0.5	$1.3	$3.1
Eastern Inland	$0.7	$2.2	$5.8	$13
Boston Harbor	$0.6	$2.0	$5.2	$12
North & South Shores	$0.2	$0.6	$1.5	$3.0
Cape, Islands, & South Coast	<$0.1	<$0.1	<$0.1	$0.1
Statewide	**$1.8**	**$6.0**	**$15**	**$35**

Source: Neumann et al. (2021) and project team analysis

There are additional impacts to rail that are not included in the above estimates, in particular, impacts of climate on rapid rail transit (e.g., subway and trolley systems). Martello et al. (2021) investigated measures of system resilience to exogenous climate risk and applied a resiliency model to the MBTA's rail rapid transit system; the researchers quantified system resiliency on a scale of 0 to 100 percent (low to high system resiliency), using operation levels under the disruptive condition and time of recovery back to pre-disruption. Applying this framework to the MBTA's rapid rail network found that system resiliency decreases either as sea level rise projections increase or as probability of severe coastal storms increases, as well as the interaction effect of the two. For example, under current sea level, a 100-year coastal flood would render the Silver Line and Blue Line inoperable. Under a low sea level rise scenario (which could be reached by 2030), the same flood probability would *additionally* render the Cambridge-Somerville portion of the Orange Line and all transit on the Red Line south of downtown Boston inoperable. Additional effects are found later in the century (2070), with severe flood vulnerabilities for the entirety of the Red Line, all transit on the Orange Line north of Jamaica Plain, and portions of the Green Line.[58]

Some estimates exist to characterize impacts of climate on the rail bridge network. Early estimates assessed the impacts of high river flow events on bridge support scour, and the need to incur extraordinary repair costs – these estimates suggest that up to 25 percent of bridges of all types (road and rail, but that span water) in the New England region may be vulnerable to this effect but did not provide estimates specific to Massachusetts. More detailed analyses are underway but not yet complete and suggest that bridge scour and the potential for overtopping of bridge decks at over 1,000 bridges (road and rail) in Massachusetts might increase the average annual maintenance cost per bridge by about $5,000 to $7,000, but impacts could be much greater if bridges are not regularly maintained.[59]

Disproportionality

These costs initially affect rail maintenance agencies and private owners, and could then impact riders in the areas affected – but rider impacts are addressed in the Economy sector. As a result, the location-based analysis conducted for Infrastructure sector costs, while suggestive of impacts of concern, could impact communities across the state differently because of the broader spatial scope of rail agencies such as the MBTA and Amtrak. This analysis considers the difference in rising costs to maintain the level of service necessary to compensate for damage by climate change.

From this perspective, Figure 24 shows populations living in EJ block groups defined on the basis of:

- minority population have 24 percent higher exposure to rail maintenance costs than the rest of the Commonwealth
- language isolated populations have a 32 percent higher exposure to rail maintenance costs than the rest of the Commonwealth

There is **disproportionate** exposure for this impact based on these results, and on the significant potential for disproportionate impacts on the rapid rail MBTA system as well (based

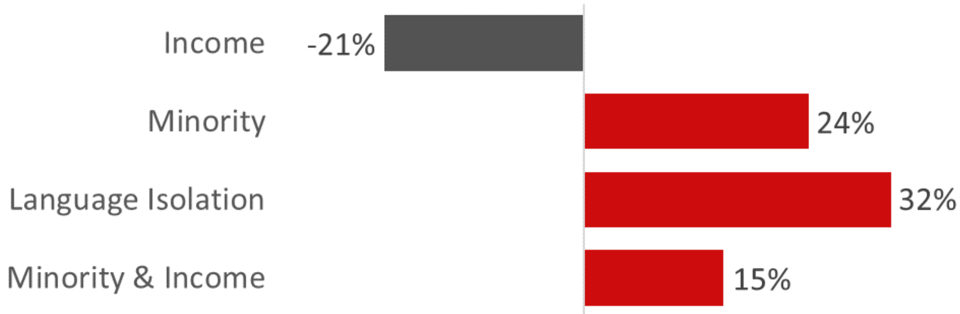
[58] Martello, M.V., Whittle, A.J., Keenan, J.M. and Salvucci, F.P., 2021. Evaluation of climate change resilience for Boston's rail rapid transit network. Transportation Research Part D: Transport and Environment, 97, p.102908, https://doi.org/10.1016/j.trd.2021.102908

[59] Wright, L., P. Chinowsky, K. Strzepek, R. Jones, R. Streeter, J.B. Smith, J. Mayotte, A. Powell, L. Jantarasami, and W. Perkins (2012). Estimated effects of climate change on flood vulnerability of U.S. bridges. *Mitigation and Adaptation Strategies for Global Change*, doi:10.1007/s11027-011-9354-2; and personal communication with Dr. Kenneth Strzepek of MIT on July 22, 2022, commenting on currently ongoing but unpublished research.

on qualitative analyses). Recent surveys have established that the rapid transit system is disproportionately relied on by EJ populations, with 29 percent of ridership among low-income groups and 34 percent among minority classifications, implying that impacts to the system could present a disproportionate burden on these groups.[60]

Figure 24. Disproportionality of Impacts on Rail Infrastructure Associated with Extreme Heat

Comparison of the rail maintenance impacts in EJ block groups defined by income, minority status, and English isolation, compared to all other block groups in the state. Positive numbers and red bars represent disproportionate exposure for the listed population segment. See Section 2.1 for further description of the EJ block group definitions.



Adaptation

There is a **moderate** adaptation gap for this impact. Little is being done to address track buckling from extreme heat, the key climate hazard modeled here. Adaptation options like train speed orders and track heat sensors do exist, but need additional consideration across the state. Flooding poses an additional risk to rail, and adaptation approaches like raising or relocating tracks out of floodplains and constructing flood barriers have been proposed in parts of the Commonwealth, but implementation is lagging. With climate hazards and transportation demand projected to increase, incorporating climate risks and adaptation actions into rail planning and management strategies in the near term will be important for preserving key transportation infrastructure.

Some progress has been made with respect to MBTA resiliency plans, however, with most of the resiliency project progress to date focused on the rapid rail transit system (e.g., floodproofing around the Aquarium station, flood door installation at Fenway Station, and sea wall construction near the Charlestown bus garage). A new project, "Greening the Blue Line", will look at natural based solutions to protecting the Blue Line infrastructure from flood risks. This project builds resiliency to a critical connection between East Boston, a part of the Commonwealth with many environmental justice areas, to downtown Boston.

Example Adaptation Plans with Actions Addressing this Impact

- MBTA Climate Change Resiliency Plans including rapid transit, bus, and commuter rail risk assessments and identified actions

[60] See MBTA 2015–17 Systemwide Passenger Survey, published May 2018 available at: https://www.ctps.org/dv/mbtasurvey2018/2015_2017_Passenger_Survey_Final_Report.pdf

Sensitivities and Uncertainty

This analysis excludes winter storm costs that may decrease in a warmer future although increases in precipitation and storm events may cause those costs to increase or remain similar to current costs. The costs presented are based on average historical costs to perform the required maintenance, repair, and reconstruction activities to maintain rails and repair the damage. As labor and material costs change over time, these costs could also change.

The response of rail governing agencies and private owners is likely to vary, depending on budgets and other constraints those agencies may have. Here it is assumed that rails are maintained so as to provide the current level of service to users, when in operation.

Related Impacts

Table 19 lists the impacts in other sectors that have a connection to this impact.

Table 19. Additional impacts related to Damage to Rails and Loss of Rail/Transit Service

Sector	Impact	Connection
Economy	Economic Losses from Commercial Structure Damage and Business Interruptions	Damage to rails and Increased construction activity causes rail delays, which impact passenger's time and the transportation of goods.
Economy	Reduced Ability to Work	Workers may experience delays or be unable to get to work during rail closures, leading to lost productivity and wages.
Governance	Increase in Demand for State and Municipal Government Services	Rail that is owned and maintained by state agencies will be more expensive to maintain, increasing expenditures for those agencies.
Infrastructure	Damage to Roads and Loss of Road Service	Road usage increases during rail outages, potentially increasing wear and tear and the need for road repairs.

Infrastructure Sector: Remaining Urgent Impacts

The following impacts are also evaluated for urgency in the Infrastructure sector. The summaries below provide a snapshot of each impact, in order of urgency. More details on each impact, as well as the sources, methods, and data used to develop results, can be found in Appendix A.

Loss of Urban Tree Cover

Urban trees are susceptible to invasive pests and high heat/drought conditions and provide many services including mitigating heat island effects, pollution removal, etc.

Moderate Level of Consequence	Disproportionate Exposure	Minimal Adaptation Gap
• Urban Tree Cover is threatened, in places their cooling services are most valuable, due to heat, drought, and increased pests.	• EJ block groups defined on the basis of minority population, language isolation, and minority population/low-income status have 39 to 45 percent less tree canopy coverage than other block groups in the Commonwealth.	• Because of their many co-benefits, many actions to increase urban tree coverage are underway across the Commonwealth but more planting and stewardship will be required.

Damage to Coastal Buildings and Ports

Sea level rise, coastal erosion, and storm surge, as well as high wind events from tropical and extra-tropical storms, will cause increased damage to coastal structures, land, and related infrastructure such as ports and marinas.

Extreme Level of Consequence	Limited Disproportionality	Moderate Adaptation Gap
• Coastal property damage reaches over $1 billion a year by the 2070s with over 70 percent of that in the Boston Harbor Region. Current annual expected damages are already $185 million per year.	• While overall, impacts do not disproportionately effect EJ populations in this analysis, communities with Minority status in a tidally affected portion of the Eastern Inland region are 60 percent more likely to experience severe impacts by the 2070s.	• Coastal resilience is a focus of many adaptation plans and projects; however, more can be done to address current impacts and the more severe impacts projected for later in the century.

Reduction in Clean Water Supply

Addresses changes in water quantity and quality for water supplied for all human uses. Changes in precipitation patterns and saltwater intrusion can lead to impaired surface and groundwater supply available for municipal, industrial, commercial, and agricultural uses.

Major Level of Consequence	Potential for Disproportionality	Minimal Adaptation Gap
• Uncertainty in groundwater recharge rates, particularly in the central and western parts of the Commonwealth could lead to increase water stress.	• Nearly half of EJ Block groups are served by MWRA which is resilient to most shocks, however shortages could be felt most severely by individuals with income constraints and towns with revenue constraints.	• Extensive monitoring of surface water sources and drinking water protection zones are effective. More attention may be needed on groundwater resources.

Damage to Roads and Loss of Road Service

Damage to roads from extreme precipitation, flooding, and temperature increases the need for repair and maintenance, and indirect effects of increased vehicle operating costs from driving on roads in poor condition. Includes effects on bridges and culverts at road crossings.

Major Level of Consequence	Limited Disproportionality	Moderate Adaptation Gap
• Increases in costs over baseline rise to $140 million a year by 2090, tripling compared to the 2050s.	• The analysis finds climate impacts are considered to be of low disproportionality.	• Culvert design, nature-based flood mitigation, and road elevation offer options for flooding, but adaptation approaches for other climate hazards are less clear.

Loss of Energy Production and Resources

Changes in temperature increase electricity demand and reduce production efficiency, requiring changes in the overall network cost of meeting electric demand. Effects on solar energy production potentially subject to flooding are also considered.

Moderate Level of Consequence	Limited Disproportionality	Minimal Adaptation Gap
• Loss of power supply overall may be minimal, as most production appears resilient to climate change, but high demand events may lead to more frequent outages during high heat events.	• There is little current evidence that loss of power during high demand events is focused on EJ populations.	• Planning has begun to increase and diversify energy production and grid flexibility.

Increased Risk of Dam Overtopping or Failure

Climate change could lead to more frequent overtopping of some, or all of the state dam safety program designated High or Significant Hazard dams, causing flooding of downstream areas.

Minimal Level of Consequence	Limited Disproportionality	Minimal Adaptation Gap
• Current safety policies are largely sufficient to mitigate future risks.	• Very few dams across the commonwealth are located in block groups designated for EJ concerns.	• Some plans address dam removals; however, the threat of dam overtopping or failure is largely addressed via existing safety procedures.

4.3 Natural Environment Sector

A changing climate will permanently alter habitats in the Commonwealth, resulting in disruptions from habitat transition, degradation of ecosystem services, and potential loss of some native ecosystems, and alteration of others. There are three unique characteristics of this sector important to highlight:

1. **Impacts in the Natural Environment Sector often represent foundational changes that influence impacts in other sectors**. For example, freshwater ecosystem health impacts clean water supply for drinking water (Infrastructure), marine water ecosystem health impacts marine fisheries productivity (Economy), and the potential loss of native species leads to diminished cultural values (Human), among others. The tables at the end of each impact summary that list these connections are particularly important in this sector.
2. **Distinct categories of impact are difficult to define in this sector.** In general, the impact categories in this sector are defined by habitat types or ecosystem types, however these categories are all interrelated. There are also specific geographic features that do not fit squarely in any one impact category. Estuaries are an example of this, as they represent the transition zones between freshwater and marine environments, and often interact with coastal wetlands. Estuaries and other transition zones represent critically important features that could be considered part of multiple impact categories.
3. **All impacts are classified as Potential for Disproportionality of Exposure.** There are several reasons why disproportionality is not differentiated in this sector. First, the focus of the Natural Environment sector is on the effects on natural resources (all flora and fauna) rather than impacts to humans. Therefore, the disproportionality metric, which measures disproportionate exposure across *people* in the Commonwealth, does not fit well with the focus of this sector. Many of the indirect effects on humans are captured in other sectors of the report (as described in the first point, above). Second, while degradation of the natural environment is linked to humans through the flow of ecosystem services, the flow of these services generally is not geographically bound to a particular place. This complicates the process of identifying people and places that may be affected by natural resource degradation. As a result, available evidence is not sufficient to support application of the place-based disproportionality metric used in the Climate Assessment. For example, the loss of an acre of wetlands not only affects those who live nearby but also those who visit the wetland and those who hold value for the knowledge of healthy wetland resources even if they do not

What are ecosystem services?

The National Ecosystem Services Partnership defines ecosystem services as "the benefits that flow from nature to people, for example, nature's contributions to the production of food and timber; life-support processes, such as water purification and coastal protection; and life-fulfilling benefits, such as places to recreate or to be inspired by nature's diversity."

visit. Because of these challenges, in this sector, all impacts are characterized as having the potential for disproportionate exposure. This ranking acknowledges that the degradation of ecosystem services may affect people in the Commonwealth differently but keeps the focus of the sector on the impacts of climate change to natural resources.

Table 20. Urgent Impacts in the Natural Environment Sector

IMPACT	DESCRIPTION	MAGNITUDE	DISPROPORTIONATE EXPOSURE	ADAPTATION GAP
Freshwater Ecosystem Degradation (MOST URGENT)	Rising temperature and changing precipitation patterns will lead to a reduction in ambient water quality and changes in water quantity, resulting in changes to habitat quality in rivers, streams, ponds, lakes and freshwater wetlands.	Extreme	Potential	Extreme
Marine Ecosystem Degradation (MOST URGENT)	Changing sea surface temperatures, ocean acidification, and increased runoff nearshore alter habitat conditions in marine environments (including submerged aquatic vegetation) leading to changing marine species distribution.	Extreme	Potential	Extreme
Coastal Wetland Degradation (MOST URGENT)	Climate impacts such as increased temperatures, increased runoff/precipitation, invasive species and drought act as stressors to coastal wetland environments. When considering coastal wetland degradation on a regional scale, sea level rise leads to the highest degree of habitat shifts and possible loss of salt marshes and important ecosystem services.	Extreme	Potential	Moderate
Forest Health Degradation (MOST URGENT)	Warming temperatures, changing precipitation, increasing pest occurrence, more frequent and intense storms, and increased wildfire risk may cause a decline in forest health (e.g., biodiversity, biomass, resiliency) along with loss of carbon sequestration and other ecosystem services. Impacts vary by forest type.	Extreme	Potential	Moderate
Shifting Distribution of Native and Invasive Species	Changing climatic conditions shift suitable habitat for native species (flora and fauna), increase the risk of new species introductions, and increases competition from established invaders, potentially causing losses in native biodiversity and loss of culturally important species.	Major	Potential	Moderate
Coastal Erosion	Climate change, is expected to increase coastal erosion, primarily driven by sea level rise, particularly in areas not protected by wetlands (e.g., dunes, banks, beaches), which has consequences for water quality, land use, and habitat quality.	Major	Potential	Moderate
Soil Erosion	Increase in extreme precipitation could result in increased erosion and potential loss in vegetation or changes in vegetation type, particularly along riverbanks but also in forests and in a number of other landscapes.	Minimal	Potential	Moderate

Natural Environment Sector: Urgent Impact #1 (tie)

Freshwater Ecosystem Degradation

Rising temperature and changing precipitation patterns lead to a reduction in ambient water quality and changes in water quantity, resulting in changes to habitat quality in rivers, streams, ponds, lakes, and freshwater wetlands.

Extreme Level of Consequence	Potential for Disproportionality	Extreme Adaptation Gap
• Some coldwater habitats expected to transition to cool- and warmwater habitats across the Commonwealth; harmful algal blooms and low dissolved oxygen threaten rivers, lakes, and ponds.	• Natural Environment sector impacts scored as "potential" because of focus on impacts on natural environments rather than the indirect impacts on humans captured in other sectors.	• Direct ecosystem restoration, green infrastructure, and land management planning are effective, but more watershed- and basin-level coordination would continue to help facilitate adaptation.

Impact Summary

Freshwater ecosystems are a critical component of connected ecosystems in the Commonwealth. Rivers, streams, lakes, ponds, and freshwater wetlands provide habitat to a variety of fish, bird, invertebrate and other species, and provide other ecosystem services such as water supply, wildlife viewing, fishing, climate resiliency and recreational opportunities. Climate change threatens freshwater ecosystems through:

- Increased nutrient loadings, particularly due to more frequent intense precipitation;
- Increased contamination concentration during drought conditions;
- Increased nutrient growth (including harmful algal blooms), particularly with warming water temperatures; and
- Shifting habitat regimes as air and water temperatures rise.

In this impact, the focus is on the habitat provision for imperiled and common species, and natural service provision (i.e., non-human uses) however there are strong linkages to human uses captured in other impacts (e.g., Reduction in Clean Water Supply, Damage to Cultural Resources).

Urgency Ranking Result

This impact is ranked as a **high priority** because of the variety of stressors threatening freshwater ecosystems across the Commonwealth. The following discussion presents examples of climate change threats to freshwater resources including projected losses of coldwater habitat, increased contaminant loading based on currently impaired waters and changes in frequency of extreme rainfall events, and changes in concentrations of cyanobacteria.

> *"Freshwater Ecosystem degradation will affect not only my health, but also the species."*
>
> - Stakeholder Survey Respondents (See Appendix C for details)

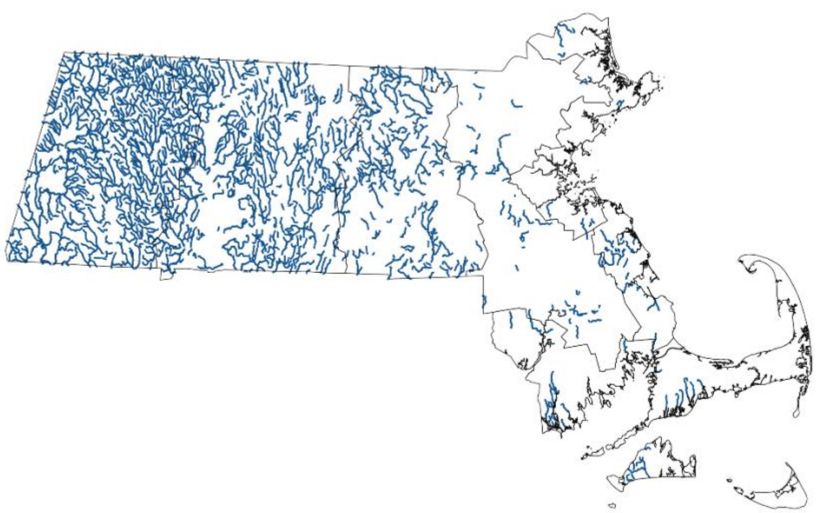
Magnitude of Consequence

The magnitude of loss of freshwater ecosystems is expected to be **extreme** due to the projected loss of coldwater habitat and threats to water quality across the Commonwealth.

Figure 25 shows current (2021) coldwater fisheries resources in the Commonwealth. Coldwater fisheries provide habitat to many species, including trout, that have relatively specific habitat requirements, including a narrow range of temperature and pollution tolerance.[61] A 2008 study found that although more than 80 percent of flowing waters in the Commonwealth likely once supported cold-water habitats, less than 50 percent of historical coldwater habitats remain in most watersheds.[62] In a study of Massachusetts coldwater habitats, Ebersole et al. 2020 find that coldwater species occurrence probability may decrease 42 to 77 percent by 2070.[63] A separate national study of freshwater fishing habitats found that although 40 percent of current hydrologic units (HUC8) support cold-water fisheries in the baseline period, all will be classified as warm or rough (species tolerant to the warmest stream temperatures) fishery guilds by end of century, and most models predict all will be warmwater habitat by 2030.[64]

Figure 25. Massachusetts Cold-water Fisheries Resources

Map of coldwater fisheries resources as of 2021, identified based on fish samples collected annually by Massachusetts Division of Fisheries and Wildlife. Coldwater fisheries resources are currently concentrated in the western and central parts of the Commonwealth but were once common throughout the state.



Source: MassGIS

[61] See the discussion of Shifting Distribution of Native and Invasive Species in Appendix B for a map of expected brook trout occurrence under future warming.

[62] Hudy M, Thieling TM, Gillespie N, et al. 2008. Distribution, status, and land use characteristics of subwatersheds within the native range of brook trout in the eastern United States. N Am J Fish Manage 28: 1069–85.

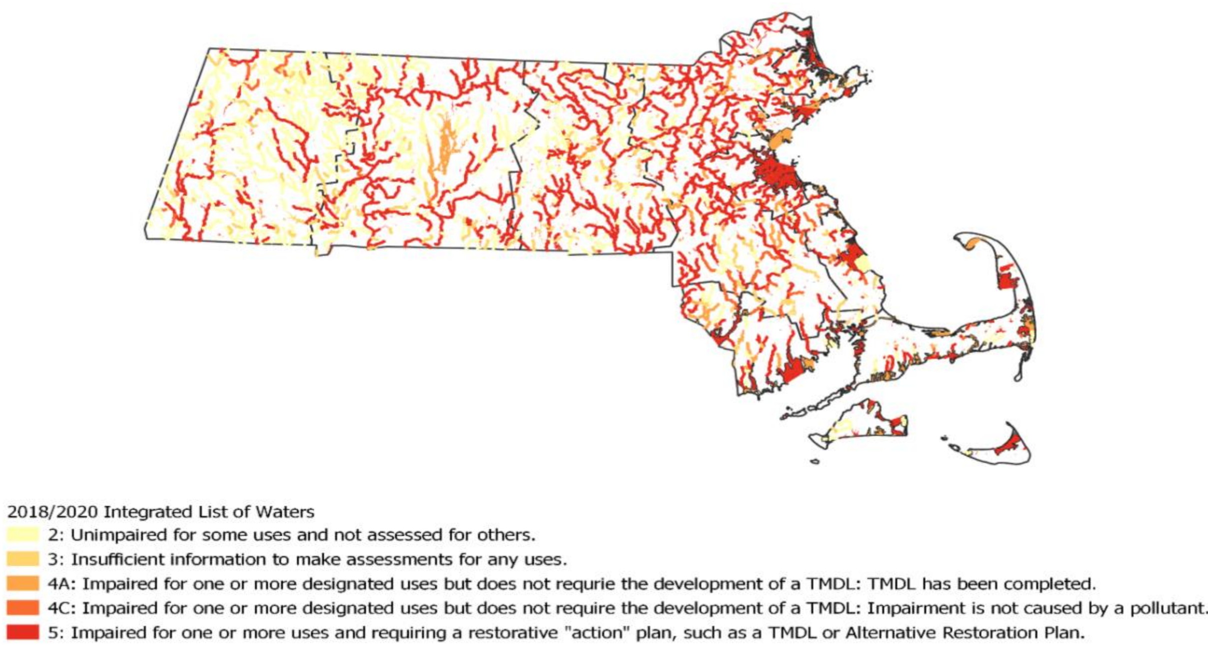
[63] Ebersole, J.L., Quiñones, R.M., Clements, S. and Letcher, B.H., 2020. Managing climate refugia for freshwater fishes under an expanding human footprint. Frontiers in Ecology and the Environment, 18(5), pp.271-280.

[64] Lane, D., R. Jones, D. Mills, C. Wobus, R.C. Ready, R.W. Buddemeier, E. English, J. Martinich, K. Shouse, and H. Hosterman, 2014: Climate change impacts on freshwater fish, coral reefs, and related ecosystem services in the United States. Climatic Change, 131, 143-157, doi: 10.1007/s10584-014-1107-2.

Intense precipitation events scour and erode stream channels, and increase nutrient and contaminant concentrations in freshwater bodies. This effect is magnified in watersheds with high levels of impervious cover, for which precipitation events increase the amount of stormwater runoff. As presented in the Soil Erosion impact (see Appendix A), the frequency of extreme rainfall event is expected to increase more in the eastern parts of the Commonwealth (Eastern Inland, Boston Harbor, North and South Shores, and Cape, Islands, and South Coast). Many of the same regions have the highest concentration of impaired waters requiring restoration action plans (see Figure 26).[65] These areas, which also have some of the highest concentrations of impervious surfaces, are particularly at risk for further impairment under a changing climate. In future years, the combination of increasing climate stress and potentially increasing development could lead to significant changes in runoff patterns.

Figure 26. Integrated List of Waters in Massachusetts by Impairment Category

Developed by MassDEP Division of Watershed Management for reporting required by the Clean Water Act. Designated uses include aquatic life, fish consumption, drinking water, shellfish harvesting, primary and secondary contact-recreation, and aesthetics.



Source: MassGIS

Dry periods can also impact freshwater ecosystem health. Insufficient flow can impact species mobility, limit habitat reaches, and increase concentration of contaminants. Although research on probability of future droughts is limited, projected increases in extreme climate conditions

[65] MassDEP compiles the Integrated List of Waters every two years in compliance with Section 303(d) of the Clean Water Act. Impaired waters on this list represent those surface waterbodies that are not expected to meet surface water quality standards after the implementation of technology-based controls. See the MassDEP website for additional details on the evaluation and listing process.

suggest this could be an issue.[66] Available projections show Massachusetts to have a relatively low risk compared to other parts of the country and the world, though there is significant uncertainty.[67]

One particular issue of concern in freshwater systems is the presence of harmful algal blooms. Climate change is expected to increase the presence of these blooms due to:

- Warming waters: which are preferential to harmful algae and reduce mixing of water layers, allowing the algae to grow faster
- Changing salinity: during droughts and low water levels. In areas in the southwest and south-central U.S., toxic marine algae have made their way into freshwater bodies.
- Higher carbon dioxide levels: that fuel rapid growth of toxic algae
- Changes in rainfall: alternating periods of rainfall and drought create ideal conditions for harmful algae; high rainfall events also increase runoff which can include a number of nutrients and contaminants.[68]

Cyanobacteria is a common form of harmful algae. Chapra et al. (2017) modeled cyanobacteria growth and the likelihood of Cyanobacteria harmful algal blooms in freshwater systems for two growth scenarios—high and low growth—which provides an uncertainty range on the change in Cyano harmful algal blooms growth patterns as temperatures rise.[69] The resulting change in cyanobacteria concentrations in Massachusetts are shown in Figure 27.

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[66] Kovach, R.P., Dunham, J.B., Al-Chokhachy, R., Snyder, C.D., Letcher, B.H., Young, J.A., Beever, E.A., Pederson, G.T., Lynch, A.J., Hitt, N.P. and Konrad, C.P., 2019. An integrated framework for ecological drought across riverscapes of North America. BioScience, 69(6), pp.418-431.

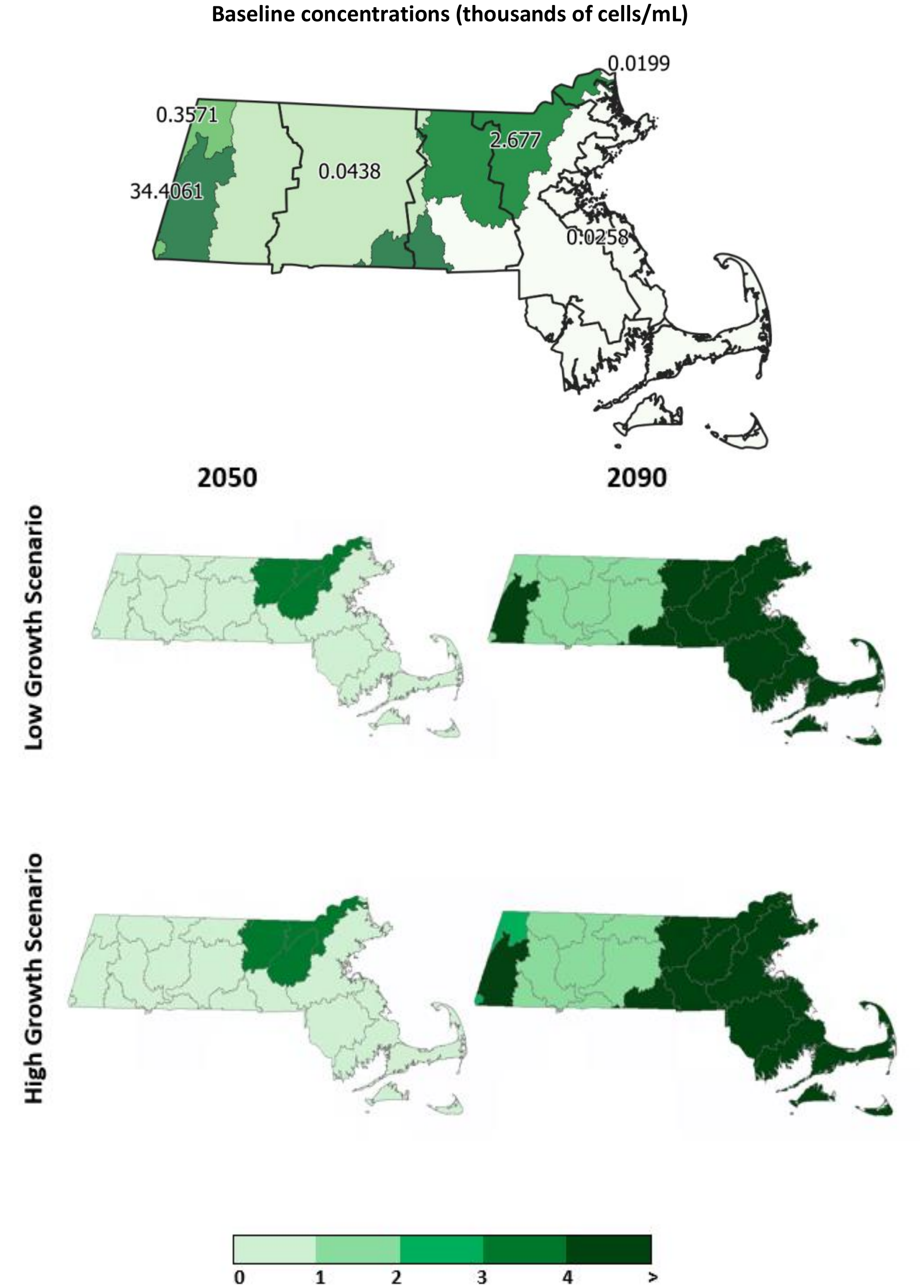
[67] Ault, T.R., Cole, J.E., Overpeck, J.T., Pederson, G.T. and Meko, D.M., 2014. Assessing the risk of persistent drought using climate model simulations and paleoclimate data. Journal of Climate, 27(20), pp.7529-7549.

[68] U.S. EPA 2022. Climate Change and Harmful Algal Blooms. Available at https://www.epa.gov/nutrientpollution/climate-change-and-harmful-algal-blooms

[69] Chapra, S. C.; B. Boehlert, C., Fant; J. Henderson, D. Mills, D. M.L. Mas, L. Rennels, L. Jantarasami, J. Martinich, K. M. Strzepek, V. J. Bierman, Jr., H. W. Paerl. Climate Change Impacts on Harmful Algal Blooms in U.S. Freshwater. Environ. Sci. Technol., 2017, 51 (16), pp 8933–8943. DOI: 10.1021/acs.est.7b01498

Figure 27. Change in Cyanobacteria Concentrations (thousands of cells/mL)

Modeled future change in cyanobacteria concentrations under two growth scenarios for 2050 (mid-century, 2040-2059) and 2090 (end of century, 2080-2099).



Source: Project Team analysis of Chapra et al. 2017

Freshwater wetlands are also at risk of climate change. Threats to freshwater wetlands include conversion to salt marshes (see Coastal Wetlands impact discussion), changes in hydrology (resulting in too much or not enough water), and temperature increases.[70] Increased presence of invasive species and land use change add stress to freshwater wetland systems.[71]

The interaction of these various threats could compound water quality issues in freshwater systems. Degradation of surrounding ecosystems (particularly riparian forest ecosystems) further endangers these resources.

Disproportionality

This impact category is classified as having a **potential** disproportionate exposure. In the Natural Environment sector, the magnitude of consequence results reflect impacts to natural assets and systems, not necessarily the impacts to humans because of the damage to natural assets and systems. Often the indirect impacts to humans resulting from changes to natural environment are captured in other sectors (see Table 21). As noted in the introduction to this section, all impacts in this sector are assigned the score of potential for disproportionate exposure, acknowledging that some groups of people may be more affected than others by the disruption of certain ecosystem service flows but that currently available data and methods can only incompletely identify the human recipients of those ecosystem services.

Adaptation

There is an **extreme** adaptation gap for responding to freshwater ecosystem degradation. This impact is particularly salient in reviewed plans, and many different approaches are being taken to combat its negative effects however the vastness of the Commonwealth's freshwater resources and the complexity of effective restoration activities requires significant attention to adequately respond to the challenges of climate change. This complexity also means that modeling and other information gathering activities (e.g., the recently updated BioMap3 which prioritizes habitats for management and restoration), along with planning activities are critical first steps towards adaptation.

Ecosystem-conscious infrastructure is being implemented across the state, many with the aim of reducing habitat fragmentation and therefore allowing fish species to travel as waters warm. Dam removal and culvert redesign and replacement are one of the methods implemented to restore natural river and stream flows and to reconnect freshwater habitats; however, many dams remain in fresh waterbodies and legal/ownership challenges make widespread removal difficult. Many plans include land acquisition, land use planning, policy restrictions to prioritize conservation and ecosystem protection; direct ecosystem restoration efforts; and measures to prevent sedimentation and nutrient loading from erosion and agricultural runoff, including stabilizing stream banks and revegetating riparian zones

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[70] Junk, W.J., An, S., Finlayson, C.M., Gopal, B., Květ, J., Mitchell, S.A., Mitsch, W.J. and Robarts, R.D., 2013. Current state of knowledge regarding the world's wetlands and their future under global climate change: a synthesis. Aquatic sciences, 75(1), pp.151-167.

[71] Erwin, K.L., 2009. Wetlands and global climate change: the role of wetland restoration in a changing world. Wetlands Ecology and management, 17(1), pp.71-84.

Many of these adaptation actions are still in the planning stages; implementation will begin to close the identified adaptation gap. Even with the plans and actions currently underway, the vastness of this resource requires even more action to protect freshwater ecosystems statewide. Adapting to climate challenges to freshwater systems requires cooperation between actors as many freshwater systems intersect multiple landowners and jurisdictions. While these actions at the municipal level can be effective, freshwater ecosystems often span towns, counties, and multiple states, so further expansion of watershed- and basin- and regional-level coordination can improve ecosystem management and facilitate effective adaptation. Private and public adaptation actions can work synergistically in some cases, and in conflict with each other in other cases, reiterating the need for effective coordination.[72] Watershed associations, non-governmental organizations, conservation commissions, and land trusts tend to fill this role in Massachusetts and can be leaders in this coordination going forward.

Example Adaptation Plans with Actions Addressing this Impact

- Merrimack River Watershed Comprehensive Plan for Diadromous Fishes, led by USFWS, Massachusetts Division of Fish and Wildlife, Massachusetts Division of Marine Fisheries, and Hew Hampshire Fish and Game Department
- Open Space and Recreation Plan Update – Amesbury: See discussion of BioMap2 and core habitats
- Horn Pond Brook Improved Fisheries Habitat and Flood Control – Woburn: See brook restoration and enhancement of fish passage
- Watershed-Based Assessment and Climate Resiliency Plan for Clesson Brook – Buckland, Ashfield, and Hawley: See comprehensive, watershed-level modeling and land management efforts

Sensitivities and Uncertainty

A large source of uncertainty in assessing the future quality of freshwater ecosystems is the future of land use patterns and site-specific impacts from climate change. More frequent intense precipitation events can increase runoff into freshwater bodies, however land usage in watersheds is a key determinant of the impact of this type of event. Impacts from warming temperatures will also vary by site, adding further complexity to understanding the effects of climate change on freshwater systems.[73]

Further, there is not a consensus among climate models on future precipitation levels, with some projecting drier conditions while others project wetter conditions, and most project changes in timing, magnitude, and duration of precipitation events. Recent experiences with

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[72] Milman, A. and Warner, B.P., 2016. The interfaces of public and private adaptation: Lessons from flooding in the Deerfield River Watershed. Global Environmental Change, 36, pp.46-55.

[73] Ebersole, J.L., Quiñones, R.M., Clements, S. and Letcher, B.H., 2020. Managing climate refugia for freshwater fishes under an expanding human footprint. Frontiers in Ecology and the Environment, 18(5), pp.271-280 and Morelli, T.L., Daly, C., Dobrowski, S.Z., Dulen, D.M., Ebersole, J.L., Jackson, S.T., Lundquist, J.D., Millar, C.I., Maher, S.P., Monahan, W.B. and Nydick, K.R., 2016. Managing climate change refugia for climate adaptation. PLoS One, 11(8), p.e0159909.

drought during the summer of 2022 have previewed some of the challenges of climate change, however wetter summers are also possible under a changing climate. There is however a general consensus that rainfall will be more unpredictable and inconsistent.

Related Impacts

Table 21 lists the impacts in other sectors that have a connection to this impact.

Table 21. Additional Impacts related to Degradation of Freshwater Ecosystems

Sector	Impact	Connection
Natural Environment	Distribution of Native and Invasive Species	Freshwater ecosystems provide critical habitat for a number of important species.
Economy	Damage to Tourist Attractions and Recreation Amenities	Freshwater resources offer many population recreation activities (swimming, fishing, etc.) that can be impacted as water quality degrades.
Infrastructure	Reduction in Clean Water Supply	Over half of the state's population receives public water supply from surface water sources. Declining water quality can cause health issues and/or increased treatment costs.
Infrastructure	Increased Risk of Dam Overtopping or Failure	Freshwater ecosystems above and below dams could be disrupted by overtopping or failure.

Natural Environment Sector: Urgent Impact #1 (tie)

Marine Ecosystem Degradation

Changing sea surface temperatures, ocean acidification, and water quality issues from increased runoff nearshore alter habitat conditions in marine environments (including submerged aquatic vegetation) leading to changing marine species distribution.

Extreme Level of Consequence	Potential for Disproportionality	Extreme Adaptation Gap
• Sea surface temperature in the Gulf of Maine is expected to rise by 5 to 10 degrees Fahrenheit by 2100.	• Natural Environment sector impacts scored as "potential" because of focus on impacts on natural environments rather than the indirect impacts on humans captured in other sectors.	• Some local plans address nearshore ecosystems and the Commonwealth has studied ocean acidification but adaptation may require more regional cooperation.

Impact Summary

Sea surface (the top 10 meters of the water column) temperature is expected to increase with ongoing climate change and ocean pH is expected to lower (become more acidic) as more carbon dioxide is absorbed from the atmosphere.

- Changing sea surface temperatures cause shifts in marine species ranges (IPCC).
- Rising sea surface temperatures impact ocean stratification, which leads to low dissolved oxygen concentrations, ocean circulation, regional climates, and storm tracks and severity (EPA).
- Increased harmful algal blooms are correlated with increases in sea surface temperatures, which may pose health hazards (IPCC).
- Ocean acidification decreases available calcium carbonate in the water column, which many marine organisms need to support their skeletal structure (shells) (IPCC).

Urgency Ranking Result

This impact is ranked as a **high priority** because of the large possible impacts and moderate adaptation gap. The effects of this impact are primarily evaluated qualitatively, based on global quantitative information on ocean conditions, due to difficulties defining measurable outcomes for marine water ecosystem health.

> *"You do not have to live on the coast to know that the effects of climate change on it will be disastrous for us all, in this area in particular."*
>
> *"The ocean is the main source of life. It's hard to explain how crucial these items are."*
>
> - Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

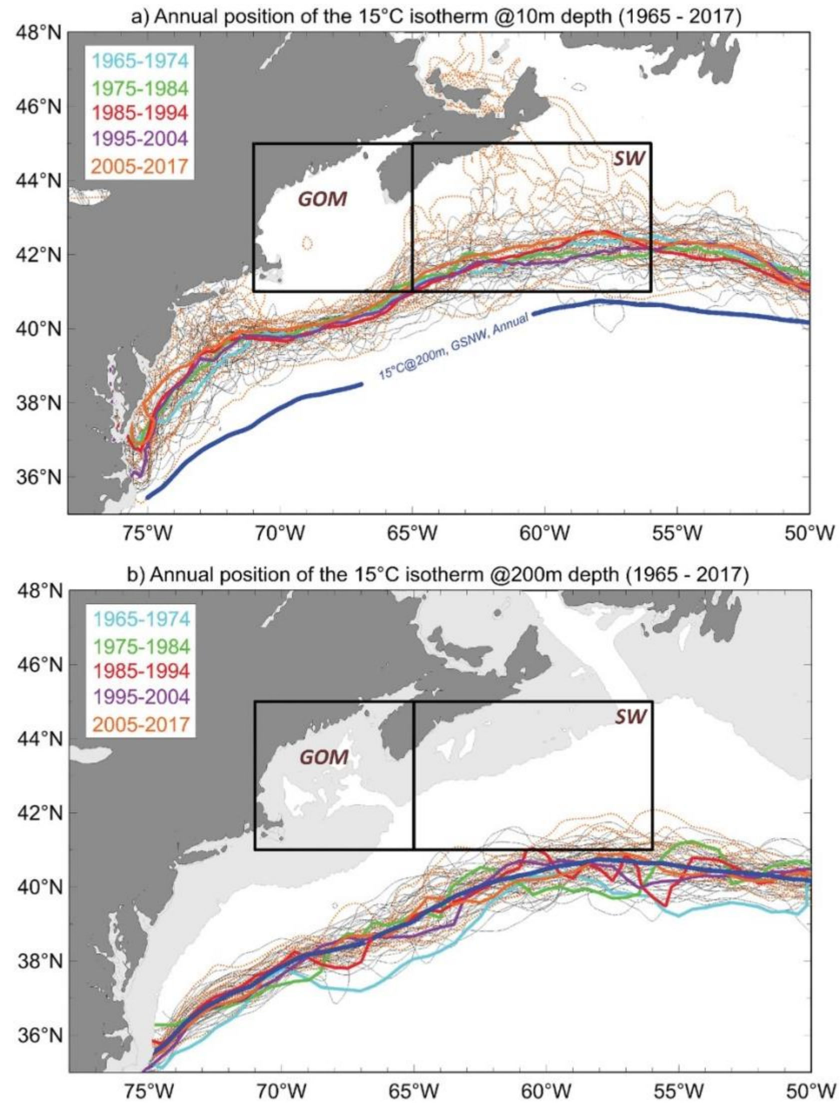
The consequences of marine ecosystem degradation are projected to be **extreme** due to the potential disruptions from warmer, more acidic waters. Sea surface temperature in the Gulf of Maine is expected to rise by 5 to 10 degrees Fahrenheit by the year 2100.[74, 75] Temperature increases of this magnitude have the potential to disrupt marine ecosystems by altering ocean chemistry in oceans, bays and estuaries (dissolved oxygen concentrations, pH), and alter ocean circulation on small (estuarine) to large (basin-wide) scales. The projected changes are a significant departure from existing conditions and also have the potential to exacerbate coastal storms and cause systemic disruptions to ecosystems found throughout Massachusetts waters. Increases in sea surface temperature force marine species beyond their historic range in search of suitable habitat and can influence weather patterns and storm tracks. Warmer waters can increase the intensity of coastal storms and the severity of heavy precipitation events.[75]

Figure 28 provides an overview of the migrating isotherm, which illustrates the northward shift of the gulf stream and warmer ocean surface temperatures from the mid-1900s to the present. On an isotherm map, the lines represent places in each year with the same temperature—in this case 15 degrees Celsius in the surface 10-meters of the water column, in the summer and winter. In the mid-1900's, the summer isotherm was located south of Cape Cod. For all subsequent years, it shifted north of Massachusetts waters entirely.

[74] Massachusetts Climate Change Adaptation Report. Accessed June 2022. https://www.mass.gov/doc/2011-massachusetts-climate-change-adaptation-report-chapter-2-the-changing-climate-and-its/download

[75] US EPA. Climate Change Indicators: Sea Surface Temperature. Accessed June 2022. https://www.epa.gov/climate-indicators/climate-change-indicators-sea-surface-temperature#:~:text=Changes%20in%20sea%20surface%20temperature%20can%20shift%20storm,risk%20of%20health%20effects.%206%20About%20the%20Indicator

Figure 28. Summer and Winter Positions of the 15-degree Celsius Isotherm



Source: Seidov et al. (2021)[76]

As sea surface temperatures have warmed, carbon dioxide (CO_2) concentrations in air and water have also increased. In ocean water, the CO_2 reacts with water (H_2O) to form HCO_3- and H+. The production of hydrogen ions (H+) resulting from this reaction decreases the pH, making oceans more acidic. Ocean water does have a natural buffering capacity, meaning a certain amount of H+ can be added without changing the pH. How much can be added varies depending on the composition of the water. Warmer saltier water has been observed to have a higher buffer capacity than cooler water[77], which means that ocean pH varies spatially. Ocean pH in the Gulf of Maine is expected to drop by 0.1 to 0.3 by the year 2100.[74]

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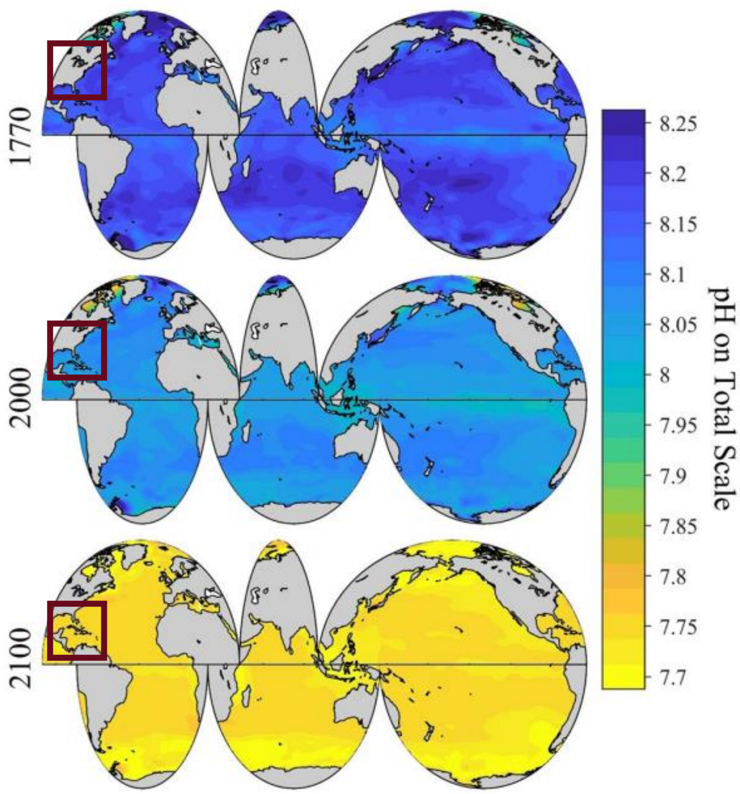
[76] Figure 3 in Seidov, D., Mishonov, A., & Parsons, R. (2021). , 66(9), 3472-3488.

[77] Xu, Y. Y., Cai, W. J., Wanninkhof, R., Salisbury, J., Reimer, J., & Chen, B. (2020). Long-term changes of carbonate chemistry variables along the North American East Coast. Journal of Geophysical Research: Oceans, 125(7), e2019JC015982.

One model, created by Jiang et al. (2019), used predictions of atmospheric CO_2, along with global patterns in temperate and salinity of ocean water to model the pH for three years: 1770, 2000, and 2100.[78] Figures from this paper show the pH in the northwest Atlantic to be around 8.05 in 2000 and falling to between 7.8 and 7.75 by 2100 (Figure 29). These drops in pH decrease the aragonite (mineral form of calcium carbonate) concentrations needed for certain marine species to build and maintain their shells, and when it drops low enough, they will begin to dissolve,[79,80] which is problematic because many of the species at greatest risk are planktonic – the foundation of the marine ecosystem.

Figure 29. Evolution and Prediction of Ocean pH from 1170 to 2100

These maps show the decrease in pH and estimate that the pH for the global oceans will drop to between 7.7 and 7.8 by 2100.



Source: Jiang et al. (2019), emphasis added

Increase in temperature and pH will affect populations of plankton, fish, and shellfish, which will have direct impacts on species distribution, the fishing industry, and populations that rely

[78] Jiang, L. Q., Carter, B. R., Feely, R. A., Lauvset, S. K., & Olsen, A. (2019). Surface ocean pH and buffer capacity: past, present, and future. Scientific reports, 9(1), 1-11.

[79] NOAA. Ocean Acidification: Saturation State. Accessed June 2022. https://sos.noaa.gov/catalog/datasets/ocean-acidification-saturation-state/

[80] US EPA. Climate Change Indicators: Ocean Acidity. Accessed June 2022. https://www.epa.gov/climate-indicators/climate-change-indicators-ocean-acidity

on the fishing industry for jobs, and the marine economies of port towns and cities (see Economy sector for discussion of these impacts).

Increases in sea surface temperatures will increase the frequency and severity of storm events, impacting populations along the coast.

Disproportionality

This impact category is classified as having a **potential** disproportionate exposure. In the Natural Environment sector, the magnitude of consequence results reflect impacts to natural assets and systems, not necessarily the impacts to humans because of the damage to natural assets and systems. Often the indirect impacts to humans resulting from changes to natural environment are captured in other sectors (see Table 22). As noted in the introduction to this section, all impacts in this sector are assigned the score of potential for disproportionate exposure, acknowledging that some groups of people may be more affected than others by the disruption of certain ecosystem service flows but that currently available data and methods can only incompletely identify the human recipients of those ecosystem services.

Adaptation

There is an **extreme** adaptation gap to addressing the effects of climate change on marine ecosystems. In 2021, the Massachusetts Special Legislative Commission on Ocean Acidification helped to author and publish the Report on the Ocean Acidification Crisis in Massachusetts[81], which includes specific recommendations to mitigate and adapt to ocean acidification; implementing these recommendations is a crucial next step.. The impact has global drivers and marine resources, even more so than other ecosystems and resources, span regional and international boundaries emphasizing the need for cooperation and action beyond Massachusetts borders.

Example Adaptation Plans with Actions Addressing this Impact

- Coastal Zone Management (CZM) habitat policies: protect coastal, estuarine, and marine habitats and advance the restoration of degraded or former habitats in coastal and marine areas
- Massachusetts Commission on Ocean Acidification Report on the Ocean Acidification Crisis in Massachusetts
- Waves of Change: The Massachusetts Ocean Management Task Force Report and Recommendations

Sensitivities and Uncertainty

Although regional (Gulf of Maine) datasets are well resolved, estimates of sea surface warming near the coast are difficult to quantify, due to the complexity of the processes at work,

[81] Commission on Ocean Acidification. Massachusetts Ocean Acidification Report. 2 February 2021. Accessed July 2022. https://malegislature.gov/Commissions/Detail/364/Documents

including atmospheric forcing, regional circulation change, and changes in radiative forcing. Despite localized uncertainty, all sources agree that sea surface temperature is increasing, the rate of change is higher than it used to be, and changes in sea surface temperature will disproportionately affect the Gulf of Maine.

The properties of coastal waters are dependent on both the large-scale ocean circulation patterns and river runoff. Surface temperature changes depend on both direct sea surface temperature warming, and on changes in large-scale ocean currents including the gulf stream and Labrador strait. Changes in pH depend on balance between oceanic buffering capacity, and the concentration of carbon in the atmosphere.

Measuring the pH of ocean water directly is possible, though collecting and comparing these measurements over large expanses of open ocean is unreliable (Jiang et al). Instead, measurements of pCO_2 or f CO_2 are used to quantify concentrations of CO_2 in the water, with higher concentrations of CO_2 corresponding with more pronounced acidification. The pCO_2 is the partial pressure of CO_2, and fCO_2 the fugacity. Partial pressure is the pressure of a component of a mixture if it were to be separated from the mixture and remain in the same volume at the same temperature. The fugacity is a related measurement, but it assumes a constant temperature. The independence of temperature makes global comparison of measurements possible. Coastal waters of Massachusetts have followed the global trend with declines in pH observed as CO_2 concentrations in the water increase.

Related Impacts

Table 22 lists the impacts in other sectors that have a connection to this impact.

Table 22. Additional Impacts related to Marine Water Ecosystem Degradation

Sector	Impact	Connection
Natural Environment	Shifting Distribution of Native and Invasive Species	Species typically found off the Massachusetts coast may migrate northwards or to deeper depths for cooler ocean temperatures and/or experience losses due to ocean acidification. Warmer waters may favor marine invasive species at the expense of native species. Shifting distributions of prey and forage species may impact predators that cannot quickly adapt.
Governance	Increase in Need for State and Municipal Policy Review and Adaptation Coordination	Regulations regarding ocean use (e.g., catch limits, pollutant concentration limits, and protected zones) may need more attention and updating as the marine ecosystem changes.
Economy	Damage to Tourist Attractions and Recreation Amenities	Recreation centered around marine habitats and marine life (e.g., recreation fishing, whale watching) could be impacted as the marine ecosystem changes.

Sector	Impact	Connection
Economy	Decrease in Marine Fisheries and Aquaculture Productivity	Revenues for the marine fisheries, aquaculture, and seafood processing industries could be affected if the supporting conditions for valuable species are not preserved in Massachusetts waters. On the contrary, shifting species distributions may present opportunities to expand marine fisheries to include species not historically found in Massachusetts waters.
Human	Damage to Cultural Resources	As a coastal state, Massachusetts has a long-held connection to the marine environment and products from marine environments, which could be disrupted as the ecosystem is degraded.

Natural Environment Sector: Urgent Impact #2 (tie)

Coastal Wetland Degradation

Climate impacts such as increased temperatures, increased runoff/precipitation, invasive species, and drought act as stressors to coastal wetland environments. However, when considering coastal wetland degradation on a regional scale, sea level rise leads to the highest degree of habitat shifts and possible loss of salt marshes and their important ecosystem services.

Extreme Level of Consequence	Potential for Disproportionality	Moderate Adaptation Gap
• 66 percent of today's total marsh area in the Commonwealth is projected to transition to other marsh types or habitats by 2070.	• Natural Environment sector impacts scored as "potential" because of focus on impacts on natural environments rather than the indirect impacts on humans captured in other sectors.	• Salt marsh restoration projects are underway across the coast; however, more restoration and planning are needed.

Impact Summary

Coastal wetlands, including freshwater tidal wetland, regularly flooded marsh, irregularly flooded marsh, transitional wetland and tidal flat provide a host of ecosystem services to coastal communities, including preservation of open space, valuable wildlife and fisheries habitat, carbon capture and added buffering capacity from coastal storms. Species such as the salt marsh sparrow, wading shorebirds, and juvenile marine fishes utilize coastal wetlands for nesting, foraging, and as nursery habitat. Salt marshes can adapt to sea level rise by building elevation (capturing sediment and organic detritus to build up the marsh plain) faster than the rate of rising sea level or by migrating inland to where conditions are suitable or into other wetland types such as transitional brackish and freshwater species die-off, providing an opportunity for salt marsh transition and expansion. In some cases, salt marshes are not able to build elevation fast enough to keep up with accelerating sea level rise rates. Additionally, inland migration is often restricted by development (roads, homes, lawns, landscaping, and parking lots) or large, naturally occurring increases in elevation. If salt marshes are not able to remain in their current locations or migrate landward, then existing salt marsh habitat will eventually transition to mudflat habitat.

Sea level rise coupled with coastal development (leading to coastal squeeze of salt marsh habitat), reduced sediment supplies, physical alteration of salt marsh hydrology (mosquito ditching, historic agricultural practices, roads and other infrastructure), and non-point source pollution have contributed to the degradation of salt marsh habitat in Massachusetts. It is important to understand the current distribution of salt marsh habitat, understand salt marsh ecology, processes (including transition), and functions now and into the future, and identify potential marsh migration areas to effectively protect and restore this important habitat. While estuaries are connected to and include salt marsh habitat, they are included as part of the Marine Ecosystem Degradation impact discussion in this Climate Assessment.

Urgency Ranking Result

This impact is ranked as a **high priority** because of the percentage of salt marsh area that is under rapid transition due to rising sea levels. Conversion of salt marsh to other habitat types, including tidal flats, will result in a loss or change of critical ecosystem services such as carbon sequestration, recreation, cultural value, storm protection, and nursery, feeding, and nesting areas for fish and wildlife. Conversion is expected to occur when sea level rises faster than marshes can build elevation, and the existing plant community is unable to adapt to increased tidal inundation.[82] This poses a particular concern for salt marsh sparrow nesting areas, a species of special concern in Massachusetts.[83]

Predicted habitat changes due to sea level rise are derived using the Sea Level Affecting Marshes Model (SLAMM) to simulate habitat transition with rising sea levels. These data were developed to evaluate projected future coastal wetland habitat conditions of the entire Commonwealth of Massachusetts.[84] SLAMM is an open-source numerical model that was developed specifically to evaluate potential impacts to coastal wetlands due to sea level rise and incorporates important parameters, such as elevation, wetland classifications, sea level rise, tide ranges, accretion, and erosion rates for various habitat types. The Climate Assessment pulls from a 2016 application of SLAMM which was run in order to determine the potential areal extent and distributions of coastal wetlands in Massachusetts as they respond to sea level rise.[85] Assumptions involved in the Massachusetts SLAMM modeling effort are described in the technical report developed in 2016. Additional information on SLAMM can be found in the technical documentation for the SLAMM source code.[86]

> *"We are putting more people at risk in the future by allowing the continued loss of these natural climate buffers."*
>
> - Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The degree of change in habitat distribution, and not the distribution itself, or the habitat types themselves, makes Coastal Wetland Degradation an **extreme** impact. Based on the results of applying SLAMM for Massachusetts in 2016, it is estimated that 8 percent, 23 percent, 77 percent, and 97 percent of the existing statewide coastal high marsh habitat will begin to transition to low marsh/tidal flat by the years 2030, 2050, 2070, and 2100, respectively under

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[82] Ganju NK, Defne Z, Fagherazzi. 2020. Are elevation and open-water conversion of salt marshes connected? Geophysical Research Letters 47(3). https://doi.org/10.1029/2019GL08670

[83] For example, see: Salt marsh Sparrow, Ammospiza caudacuta (mass.gov).

[84] See Massachusetts Office of Coastal Zone Management's SLAMM webpage.

[85] Woods Hole Group. 2016. Modeling the Effects of Sea-Level Rise on Coastal Wetlands. Prepared for Massachusetts Office of Coastal Zone Management. November 2016. Available at: https://www.mass.gov/files/documents/2018/12/07/czm-slamm-report-nov2016.pdf

[86] Warren Pinnacle Consulting, Inc. 2016a. SLAMM 6.7 Technical Documentation: Sea Level Affecting Marshes Model, Version 6.7 Beta

the IPCC A1B High Sea Level Rise Scenario.[87] Model results indicate that areas gaining salt marsh are concentrated in the Eastern Inland region. This is due to a combination of reasons such as displaced freshwater wetlands, transition of upland transitional marsh to high marsh habitat, and migration into undeveloped and developed areas.[88] Statewide, the greatest loss of high and low marsh habitat is predicted to occur between the years 2070 and 2100, with 98 percent of today's combined high and low marsh habitats transitioning to tidal flat by 2100. Proactive planning, conservation, and preservation of and connection to land where salt marsh is expected to migrate is critical to reduce the consequence of loss.

Table 23. Coastal Salt Marsh Habitat Transition by Region

Acres of habitat change by region and statewide based on the 2016 Massachusetts coastwide application of SLAMM (Woods Hole Group, 2016). Positive values (in blue) represent growth in habitat type, while negative values (in red) represent losses in habitat type. Coastal habitat transition from irregularly flooded marsh (High Marsh) to regularly flooded marsh (Low Marsh) marks a transition of habitat. Future impacts presented for four time periods identified in the table by their central year: 2030 (near-term); 2050 (mid-century); 2070 (mid-late century); and 2100 (late century).[89] The sea level rise scenario used for the 2016 SLAMM study is the IPCC A1B High Scenario, which was scaled using SLAMM to represent a relative sea level increase for each out-year.[90] Values may not sum due to rounding.

	Coastal High Marsh Habitat Loss/Gain (Acres)				Coastal Low Marsh Habitat Loss/Gain (Acres)			
Region	**2030**	**2050**	**2070**	**2100**	**2030**	**2050**	**2070**	**2100**
Eastern Inland	+ 5	+ 100	+ 150	-1	+ 1	+ 350	+ 100	+ 50
Boston Harbor	- 65	- 250	- 1,450	- 1,750	+ 60	+ 350	+ 2,150	+ 7,000
North & South Shores	- 500	- 3,850	- 18,800	-21,050	+ 600	+ 4,550	+ 19,350	+ 6,050
Cape, Islands, & South Coast	- 3,000	- 5,800	- 12,400	-18,200	+ 2,700	+ 8,200	+ 9,650	+ 3,650

[87] For more information on this scenario, please see: Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer and A.S. Unnikrishnan, 2013: Sea Level Change. 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.
[88] See discussion after the following two tables regarding the caveats associated with the modeling assumptions regarding the transition of previously developed lands to wetlands.
[89] The late century time period presented in this analysis differs from that presented in other analyses in this Climate Assessment (i.e., 2100 rather than a 20-year time period centered on 2090) due to availability of modeling results.
[90] The A1 scenario describes a future world of very rapid economic growth, a global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The following values for the high scenario sea level rise by 2100 were utilized in the SLAMM modeling study: 2.164 meters for Boston, 2.231 meters for Nantucket, and 2.166 meters for Woods Hole. These endpoint targets for 2100 were applied to the IPCC A1B High Scenario, or RPC8.5 curve.

	Coastal High Marsh Habitat Loss/Gain (Acres)				Coastal Low Marsh Habitat Loss/Gain (Acres)			
Region	**2030**	**2050**	**2070**	**2100**	**2030**	**2050**	**2070**	**2100**
Statewide Net Loss/Gain	- 3,560	- 9,800	- 32,500	-41,000	+3,360	+13,350	+31,250	+ 16,750
Note: Coastal wetland habitat does not occur in Berkshires & Hilltowns, Greater Connecticut River Valley and Central regions.								

Source: Woods Hole Group (2016) and project team analysis

Table 24. Coastal Salt Marsh Habitat Loss by Region

Acres of net salt marsh loss by region, and statewide based on the 2016 Massachusetts coastwide application of SLAMM (Woods Hole Group, 2016). Positive values (in blue) represent growth in net wetland area, while negative values (in red) represent losses in net wetland area. Future impacts presented for four time periods identified in the table by their central year: 2030 (near-term, 2020-2039); 2050 (mid-century, 2040-2059); 2070 (mid-late century, 2060-2079), and 2100 (2079-2100). Values may not sum due to rounding. The sea level rise scenario used for the 2016 SLAMM study is the IPCC A1B High Scenario.[90]

	Total Salt Marsh Habitat Loss/Gain (Acres)			
Region	**2030**	**2050**	**2070**	**2100**
Eastern Inland	+5	+450	+250	+50
Boston Harbor	-5	+100	+700	+5,250
North & South Shores	+50	+700	+550	-15,000
Cape, Islands, & South Coast	-300	+2,400	-2,700	-14,550
Statewide Net Loss/Gain	**-250**	**+3,650**	**-1,200**	**-24,250**
Note: Coastal wetlands habitat does not occur in Berkshires & Hilltowns, Greater Connecticut River Valley and Central regions.				

Source: Woods Hole Group (2016) and project team analysis

The total area of high marsh, in acres, for the entire state for the years 2008, 2030, 2050, 2070 and 2100 is 42,250; 38,700; 32,450; 9,800; and 1,250, respectively. The total low marsh, in acres, for the entire state for the years 2008, 2030, 2050, 2070, and 2100 is 6,550; 9,900; 19,350; 37,800; and 23,300, respectively. The analysis baseline, or present day for acreage of high marsh by region are as follows: 18,750 acres in the Cape, Islands, and South Coast region, 2,000 acres in the Boston Harbor region, 21,550 acres in the North and South Shore region, and 1.5 acres in the Eastern Inland region.[91] Based on the SLAMM study, nearly 77 percent of existing Massachusetts coastal high marsh and low marsh combined habitat is predicted to become more regularly inundated and transition to low marsh and/or tidal flat by the year 2070. Statewide, the largest amount of net salt marsh loss occurs over the Cape, Islands and South Coast by 2070, with the largest amount of net salt marsh loss occurring in the North and South Shore region by 2100. There is a net salt marsh gain, likely due to the submergence of transitional marsh habitat that becomes irregularly inundated high marsh habitat, and

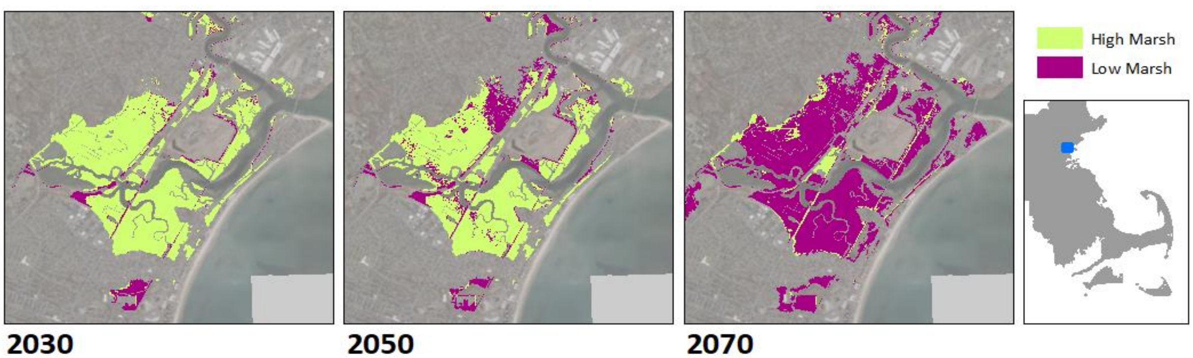
[91] The baseline period used for the 2016 SLAMM report was 2011.

migration into freshwater areas and upland regions including developed areas. These gains are focused in the Eastern Inland and North and South Shore regions.

Additionally, the gains and losses presented in these tables provide a first order assessment of the changes expected to occur in the salt marsh wetland types. For example, near to mid-term gains in salt marsh habitat result from displacement of freshwater wetlands, developed upland areas, and other upland wetland types. Over the longer term, these gains may become losses as these areas transition away from salt marsh into mud flats and subtidal resources. A key assumption in the 2016 SLAMM study was to allow salt marsh migration into developed areas to be able to identify locations where salt marsh may attempt to migrate under these changing climate conditions. This assumption likely leads to an overestimate of potential gains in wetland areas, and an underestimate of the overall losses that are likely to occur since the salt marsh will be unable to migrate into developed upland areas. Additional details on the changes in the various wetland types, beyond the low and high salt marsh habitat areas presented herein, can be found in the 2016 SLAMM study.

Figure 30. SLAMM Study Results for Salt Marsh Transition in Revere (North and South Shore Region)

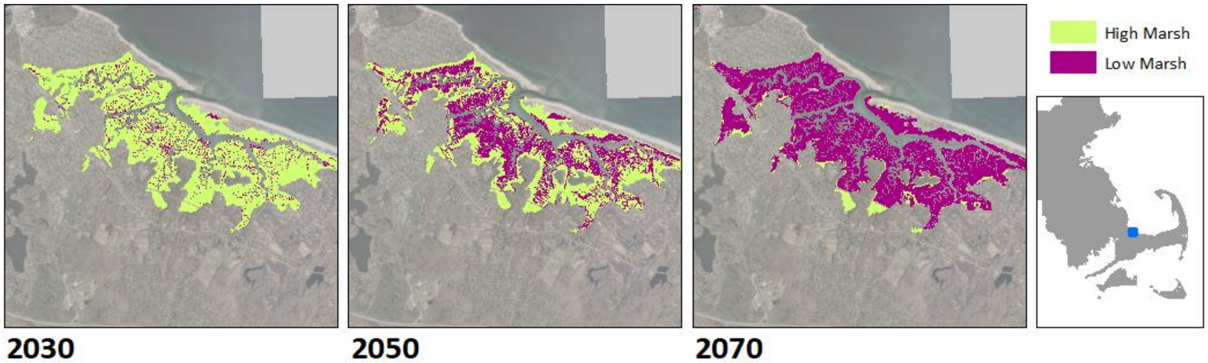
Revere's salt marsh system is predominantly high marsh in the year 2030. By 2050, this system is still predominantly high marsh, until a tipping point between the years 2050 and 2070. During this time-period the modeling results indicate that the entire marsh platform (except for a few select locations) experiences a shift from a predominantly high marsh system (irregularly flooded marsh) to a predominantly low marsh system (regularly flooded marsh). The sea level rise scenario used for the 2016 SLAMM study is the IPCC A1B High Scenario, which was scaled using SLAMM to represent a relative sea level increase for each out-year.[90]



Source: Woods Hole Group (2016) and project team analysis

Figure 31. SLAMM Study Results for Salt Marsh Transition in Sandwich (Cape, Islands, and South Coast Region)

Sandwich Harbor's salt marsh system is protected by the Town Neck barrier system, that is experiencing high rates of erosion. Over time, the modeling results indicate that the predominantly high marsh system (irregularly flooded) (2030) transitions to a predominantly low marsh (regularly flooded) system by 2070. The sea level rise scenario used for the 2016 SLAMM study is the IPCC A1B High Scenario, which was scaled using SLAMM to represent a relative sea level increase for each out-year.[90]



Source: Woods Hole Group (2016) and project team analysis

Disproportionality

This impact category is classified as having a **potential** disproportionate exposure. In the Natural Environment sector, the magnitude of consequence results reflect impacts to natural assets and systems, not necessarily the impacts to humans because of the damage to natural assets and systems. Often the indirect impacts to humans resulting from changes to natural environment are captured in other sectors (see Table 25). As noted in the introduction to this section, all impacts in this sector are assigned the score of potential for disproportionate exposure, acknowledging that some groups of people may be more affected than others by the disruption of certain ecosystem service flows but that currently available data and methods can only incompletely identify the human recipients of those ecosystem services.

Adaptation

There is a **moderate** adaptation gap for coastal wetland degradation. Salt marsh restoration projects are underway in a few coastal communities, and significant research has been done on the coastal processes impacting wetlands and how climate change might alter the state's coastal ecosystems. The Massachusetts Office of Coastal Zone Management (CZM), along with other agencies such as the Department of Environmental Protection, and the Division of Ecological Restoration (DER), coordinate to promote and implement coastal wetland protection and restoration projects. Established restoration approaches and tools include tidal flow restoration by addressing restrictions caused by roads, railroads and other types of crossings such as agricultural berms (e.g., culvert enlargement or berm removal), targeted species planting and management to supplement restoration actions. New techniques to reduce water logging and restore salt marsh hydrology through methods such as runneling and ditch remediation are currently underway. Policy approaches like rolling easements, zoning to prevent coastal development and protect existing and future salt marsh habitats, and funding for land acquisition and conservation can support these coastal wetland restoration and protection efforts. Near-term action is needed, as sea level rise is an ongoing threat to coastal wetlands.[92] (Woods Hole Group, 2016). Preserving these ecosystems and providing migration pathways is itself a form of adaptation for coastal infrastructure and economies, as coastal wetlands provide natural flood and coastal storm mitigation benefits.

Adaptation actions to maintain ecosystem services of salt marshes may include but are not limited to restoration of degraded salt marsh habitat by means of:

- Restoration of tidal flow to enhance salt marsh hydrodynamics and maintain connectivity
- Strategic actions to increase drainage of water-logged sections of the salt marsh.
- Restoration planting of salt marsh species and management of invasive plant species such as *Phragmites australis*.
- Management of point and non-point sources of pollution to reduce nutrient inputs.

These and other restoration and adaptation actions have been implemented throughout the Commonwealth. An example project is the Eagle Neck Creek Tidal and Marsh Restoration Project (MA DER, NRCS, Truro, MA).[93]

Example Salt Marsh Studies, Adaptation Plans with Actions Addressing this Impact

- Coastal Zone Management (CZM) habitat policies: protect coastal, estuarine, and marine habitats and advance the restoration of degraded or former habitats in coastal and marine areas
- Herring River Restoration Project – Wellfleet
- Sawmill Brook Central Pond Restoration – Manchester-by-the-Sea
- Documenting Effects of a Large-Scale, Natural Sediment Event on Salt Marsh

Sensitivities and Uncertainty

Uncertainty still exists regarding the exact timing and severity of sea level rise impacts and subsequently, the degree to which salt marsh habitat will be impacted by such changes. Additional impacts include reductions in open space for recreational use (shellfishing, bird watching, etc.), fish and wildlife habitat loss, and reductions in wave and storm surge buffering capacity for coastal communities. A loss of salt marsh leads to a reduction in the protection provided by the resource during storms (wave and storm surge buffering), leading to increased storm damage and the need for more frequent storm response, and asset recovery by government officials. Assumptions and modeling limitations that were directly involved in the

[92] Woods Hole Group (2016) and FitzGerald DM, Hughes Z. 2019. Marsh processes and their response to climate change and sea-level rise. Annual Review of Earth and Planetary Sciences 47:481–517. https://doi.org/10.1146/annurev-earth-082517-010255
[93] More examples of active restoration projects in Massachusetts can be found here: https://www.mass.gov/service-details/the-division-of-ecological-restoration-project-map

Massachusetts application of SLAMM, as well as a detailed sensitivity analysis, are described in detail in the technical documentation developed for the 2016 study.[94]

Related Impacts

Table 25 lists the impacts in other sectors that have a connection to this impact.

Table 25. Additional Impacts related to Coastal Wetland Degradation

Sector	Impact	Connection
Natural Environment	Distribution of Native and Invasive Species	Coastal wetlands provide critical habitat for a number of important species.
Natural Environment	Coastal Erosion	Erosion and wetlands degradation/migration are related processes along the coast.
Infrastructure	Damage to Coastal Buildings and Ports	Coastal wetlands provide flood buffering services to nearby buildings.
Economy	Decrease in Marine Fisheries and Aquaculture Productivity	Revenues for the marine fisheries, aquaculture, and seafood processing industries could be affected if the supporting conditions for valuable species are not preserved in Massachusetts waters. On the contrary, shifting species distributions may present opportunities to expand marine fisheries to include species not historically found in Massachusetts waters.
Human	Damage to Cultural Resources	As a coastal state, Massachusetts has a long-held connection to the marine environment and products from marine environments, which could be disrupted as the ecosystem is degraded.

[94] Woods Hole Group. 2016. Modeling the Effects of Sea-Level Rise on Coastal Wetlands. Prepared for Massachusetts Office of Coastal Zone Management. November 2016. Available at: https://www.mass.gov/files/documents/2018/12/07/czm-slamm-report-nov2016.pdf

Natural Environment Sector: Urgent Impact #2 (tie)

Forest Health Degradation

Warming temperatures, changing precipitation increasing pest occurrence, more frequent and intense storms, and increased wildfire risk may cause a decline in forest health (e.g., biodiversity, biomass, resiliency) along with the loss of carbon sequestration and other ecosystem services. Impacts vary by forest type.

Extreme Level of Consequence	Potential for Disproportionality	Moderate Adaptation Gap
• High temperatures, drought, pests, and wildfires lead to habitat transition and degradation of ecosystem services, with some tree species faring better than others.	• Natural Environment sector impacts scored as "potential" because of focus on impacts on natural environments rather than the indirect impacts on humans captured in other sectors.	• Actions recently identified in the Massachusetts Clean Energy and Climate Plan for 2025 and 2030 will help reduce forest degradation.

Impact Summary

Massachusetts has 62 percent forest cover, the eighth most forested state in the country in terms of percent coverage. [95] Climate change will alter the trajectory of forest succession in Massachusetts over the next century. Changes to the ranges of ambient temperature and precipitation will directly affect the lifecycles of all trees, increasing the suitability for some species while decreasing the suitability of others. In addition, climate change will introduce more threats such as new pathogens and more frequent and extreme weather events, which together create novel disturbance regimes. Altogether, these new disturbances will impact the ability of the forest to provide its ecosystem services and reflects the health of the forest. The healthier the forest, the more resilient it is to new disturbances.[96] At a landscape scale, the diversity of species, age structure of the forest, and relationships among abiotic and biotic components all play a role in the health of the forest. Some examples of the ways climate change affect forest health include:

- Northern shift in habitats as temperatures warm, growing seasons lengthen, and precipitation changes the biodiversity of the forest
- Increased mortality of tree species supporting forest health due to:
    - Increased extreme precipitation and soil erosion, intense windstorms, drought, and wildfires
    - Pests, pathogens and invasive species as warmer winters limit pest die offs and above conditions make forests more vulnerable[97]
- Potential increased growth due to longer growing seasons.

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[95] MassWoods. https://masswoods.org/massachusetts-forests

[96] MassWoods – Forest Health: https://masswoods.org/caring-your-land/forest-health

[97] Department of Conservation & Recreation Massachusetts; Massachusetts State Forest Action Plan 2020; https://www.mass.gov/doc/massachusetts-forest-action-plan/download

These stressors interact with specific species, particular forested areas, and the forest ecosystem as whole in different ways. Some hazards, such as wildfires, can be beneficial to ecosystems at low or moderate levels of burn while increasing mortality for specific trees or stands. The stressors described in this section, all projected to increase in severity, represent threats to the overall balance of forest ecosystems and the ability of forests to provide ecosystem services.

Urgency Ranking Results

This impact is ranked as a **high priority** because of its possible but uncertain level of consequence, potential for disproportionality, and moderate adaptation gap. The direct effects of climate change will increase the growing seasons and increase growth during spring and fall, though this typically favors invasive species and generalists, reducing biodiversity. Less growth is projected during summer months. The magnitude of these shifts in growing periods is uncertain, but most likely will lead to a degradation in forest health.[98] Disproportionality is difficult to assess but forests across the state will be impacted and the resulting effect on humans will be felt across the Commonwealth. Lastly, although there is an adaptation gap the Massachusetts Department of Fisheries and Wildlife, the Massachusetts Department of Conservation and Recreation (DCR) and various private and non-governmental organizations are collaborating to change forest management in the face of climate change.[99]

> *“The forest health degradation means the planet is losing its balancing and cooling systems which may also impact rainfall further damaging our ecosystem.*
>
> *“I am concerned about losing our natural beauty and environment that we are so lucky to have here in Western Mass.”*
>
> \- Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The consequences of climate change on forest health in most areas are highly uncertain in the details of expected transformation, however the scale of transition and potential for losses of ecosystem services is projected to be **extreme**. This projection takes a simplistic approach, due to limitations of data, and while forests are expected to expand in the future, the succession of forest ecosystems in Massachusetts will be rife with disturbances and unforeseen scenarios. To assess the direct effect of climate change on tree species in Massachusetts, the U.S. Forest Service uses climate models to project temperature and precipitation over the next century. From these projections they calculate further key variables such as drought severity and levels of snowpack. Using these indicators, they parameterize forest impact models to project forest community structure into the future. Among various output variables, they produce an

[98] Duveneck, M. J., & Thompson, J. R. (2017). Climate change imposes phenological trade-offs on forest net primary productivity. Journal of Geophysical Research: Biogeosciences, 122, 2298–2313

[99] Climate Change Response Framework: https://forestadaptation.org/learn/massachusetts-dcr-climate-forestry-stewardship-planning-training-foresters

indication as to the level of habitat change from 2010 to 2100 and the capability of a specific species to cope with changes to the climate.

Table 26. Climate Adaptability for Tree Species in Massachusetts

Expected habitat change for twelve most abundant tree species in Massachusetts and the American Elm (state tree) under RCP8.5 as modeled by the USFS. Forest composition reflects the abundance and area occupied. Habitat change is classified as no change, small increase or decrease (less than 20 percent change in habitat area), or large increase or decrease (over 20 percent change in habitat area). Capability is a measure of the ability of a species to cope with changes in climate based on the abundance, level of projected habitat change, and a literature review of the adaptability of that species to disturbance and other biological factors.

Species	% Forest Composition	Habitat Change	Capability
Red Maple	23.5	Small Decrease < 20%	Good
Eastern White pine	18.9	Large Decrease > 20%	Poor
Northern Red Oak	7.8	No Change	Very Good
Eastern Hemlock	7.2	Large Decrease > 20%	Poor
Black Oak	4.1	Small Increase < 20%	Good
Sugar Maple	4.1	No Change	Good
White Oak	3.3	Large Increase > 20%	Very Good
White Ash	3.2	Small Increase < 20%	Fair
Sweet Birch	3.1	No Change	Poor
Scarlet Oak	2.9	Small Increase <20%	Good
American Beech	2.7	Small Increase < 20%	Good
Black Cherry	2.6	Small Increase < 20%	Fair
American Elm (State Tree)	0.1	No Change	Fair

Source: U.S. Forest Service Tree Atlas for Massachusetts[100]

Table 26 reflects these metrics for the main tree species across the state. This analysis also included species with a likelihood to migrate into the state. 21 new species were projected to enter the state (e.g., Loblolly Pine, Black Hickory, Sweetgum, Sourwood, and Water Oak).[101] The analysis also indicates that three species (Black Ash, Pin Cherry, Black Spruce) will be completely lost by the end of the century and a third of the existing 66 species having poor ability to adapt to projected climate changes.[102] An example of how a species might shift is illustrated in Figure 32 where the USFS models projected habitat for Red Maple and Eastern White pine across the

[100] US Forest Service Tree Atlas for Massachusetts:
https://www.fs.usda.gov/nrs/atlas/combined/resources/summaries/states/Massachusetts.pdf and
https://www.fs.usda.gov/nrs/atlas/combined/resources/summaries/states/

[101] USFS Landscape Change Research Group; Climate Change Atlas Tree Species Current and Potential Future Habitat, Capability, and Migration;
https://www.fs.usda.gov/nrs/atlas/combined/resources/summaries/states/Massachusetts.pdf

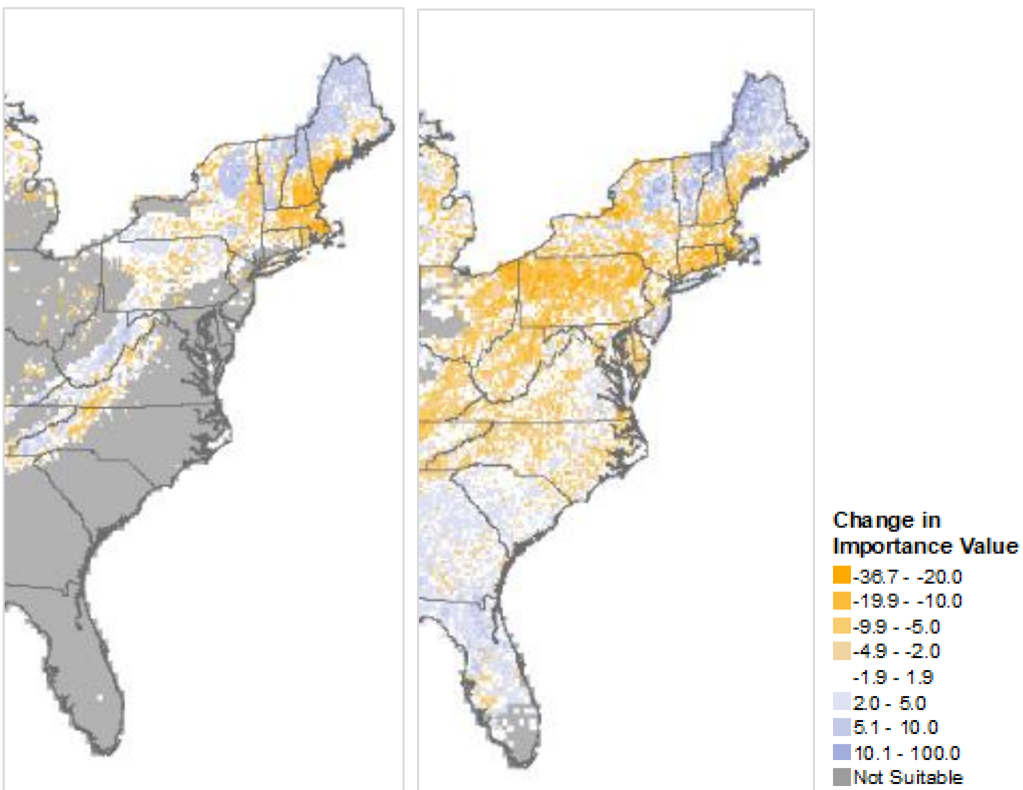
[102] US Forest Service Tree Atlas for Massachusetts:
https://www.fs.usda.gov/nrs/atlas/combined/resources/summaries/states/Massachusetts.pdf

eastern United States. Both species show a decline in relative importance under future climate in 2100.[103]

Figure 32. Projected Change in Abundance for Red Maple and Eastern White Pine by 2100

USFS models potential change in abundance (measured using 'importance values').[104] Changes in importance values over the Eastern U.S. for the two most abundant species in Massachusetts (Red Maple on the left and Eastern White Pine on the right) are shown below. Maps depict changes in habitat quality (represented as Importance Values) under RCP8.5, averaged across three GCMs (CCSM4, GFDL-CM3, and HadGEM2-ES).

Red Maple *Eastern White Pine*



Data Source: USFS Forest Atlas

Beyond the direct consequence of changes to climate on habitat suitability, climate change will induce more extreme events (i.e., wildfires, hurricanes, etc.) and an influx of pests and pathogens that will cause disruption to the health of forests in Massachusetts. The composite effect of these disturbances is difficult to model but are likely to compound in ways that could significantly change the forest ecosystems as they are today.

Since the late 1800s, global trade has driven the spread of pests and pathogens across the world. Climate change will only further exacerbate their impact by making trees more

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[103] Iverson, L.R., Peters, M.P., Prasad, A.M. and Matthews, S.N., 2019. Analysis of climate change impacts on tree species of the eastern US: Results of DISTRIB-II modeling. Forests, 10(4), p.302. https://doi.org/10.3390/f10040302.

[104] USFS Forest Atlas: https://www.fs.usda.gov/nrs/atlas/tree/316 and https://www.fs.usda.gov/nrs/atlas/tree/129

vulnerable to them and expanding the warm seasons in which these pathogens and pests thrive.[105] Some examples include:

- Spongy Moth – Eats the foliage of over 300 tree species[106]
- Dutch Elm disease – Impacts all American Elms, slowly killing the tissue of trees[107]
- Chestnut Blight—A risk to forest species such as the American Chestnut, which wiped out much of the mature chestnuts in the Eastern U.S. in the early 1900's[108]
- Wooly adelgid – Impacts Eastern Hemlock, feeds on sap of tree leading to the death of the tree[109]

Climate change will also increase the frequency and severity of extreme events such as catastrophic storms, wildfires, and floods. This further complicates modelling precise magnitudes of consequence from climate change. Examples of these impacts include:

- Storms – Physically destroys trees and alters the landscape
- Wildfire – Primarily induced by increasing drought conditions, fundamentally changes forest succession, and can introduce novel, unforeseen successional pathways
- Floods – Depending on the severity and timing of floods, floods can physically destroy trees, change landscapes, and change soil nutrient pathways[110]

As stated previously, these events may benefit certain habitats and species as natural disturbances are a part of forest health, however the uncertainty around how climate-driven disturbances could interact and intensify at levels not previously seen leads to a moderate level of consequence for this impact.

Disproportionality

This impact category is classified as having a **potential** disproportionate exposure. In the Natural Environment sector, the magnitude of consequence results reflect impacts to natural assets and systems, not necessarily the impacts to humans because of the damage to natural assets and systems. Often the indirect impacts to humans resulting from changes to natural environment are captured in other sectors (see Table 27). As noted in the introduction to this section, all impacts in this sector are assigned the score of potential for disproportionate

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[105] de la Crétaz, A.L., Fletcher, L.S., Gregory, P.E., VanDoren, W.R., Barten, P.K. 2010. An Assessment of the Forest Resources of Massachusetts. Massachusetts Department of Conservation and Recreation, United States Department of Agriculture. https://www.mass.gov/doc/assessment-of-forest-resources-of-massachusetts/download

[106] https://www.aphis.usda.gov/aphis/resources/pests-diseases/hungry-pests/the-threat/hp-egm/hp-egm

[107] https://ag.umass.edu/landscape/fact-sheets/dutch-elm-disease

[108] https://www.usda.gov/media/blog/2019/04/29/what-it-takes-bring-back-near-mythical-american-chestnut-trees

[109] https://ag.umass.edu/landscape/fact-sheets/hemlock-woolly-adelgid

[110] Janowiak, M.K., D'Amato, A.W., Swanston, C.W., Iverson, L., Thompson, F.R., Dijak, W.D., Matthews, S., Peters, M.P., Prasad, A., Fraser, J.S. and Brandt, L.A., 2018. New England and northern New York forest ecosystem vulnerability assessment and synthesis: a report from the New England Climate Change Response Framework project. Gen. Tech. Rep. NRS-173. Newtown Square, PA: US Department of Agriculture, Forest Service, Northern Research Station. 234 p., 173, pp.1-234. https://doi.org/10.2737/NRS-GTR-173

exposure, acknowledging that some groups of people may be more affected than others by the disruption of certain ecosystem service flows but that currently available data and methods can only incompletely identify the human recipients of those ecosystem services.

Adaptation

There is a **moderate** adaptation gap for this impact. While there is significant statewide focus on planting urban trees, forest health is less frequently addressed in municipal adaptation plans. Conserving large, unfragmented forests and developing forest management plans that address the key climate-driven threats to forests (e.g., shifting distributions of native plants, more frequent pest occurrence) represent the key direct adaptation strategies, and require significant resources to complete at scale.

Damage to forest ecosystems can happen far faster than restoration efforts can repair the damage, so proactive planning, and management for the range of increasing climate hazards is important for preserving the ecosystem services provided by forests across the state. An example of proactive planning and management can be seen through the Climate Change Response Framework. In collaboration with various state agencies and academic institutions, the program provides training for foresters to integrated climate change and adaptation considerations into forest management.[111]

A confounding factor for implementing adaptation plans is that 75 percent of forests are privately owned and managed by families or individuals. This poses a problem for encouraging collective action to adapt to climate change because any policy or action must be implemented by independent forest owners across the state that have different priorities for land management.[112] The Massachusetts Clean Energy and Climate Plan for 2025 and 2030 provides detailed, statewide initiatives for protecting natural and working lands, including forests, which take this ownership structure into account. The plan outlines initiatives such as the Forest Resilience Program, which will provide financial incentives to private and municipal landowners to adapt best practices on forested land, and amendments to the Massachusetts Forest Tax Law to provide additional incentives for climate smart management. All of the outlined actions are scheduled to begin before 2026.

Policy can also facilitate forest protection through incentives for protection of forests on private lands and zoning to allow for denser development and infill rather than expansion into currently forested areas.

Example Adaptation Plans with Actions Addressing this Impact

- Massachusetts Clean Energy and Climate Plan for 2025 and 2030
- Sustainable Franklin County: See Recommendations and Strategies for Forests
- Mass DCR: Climate Forestry Stewardship Planning Training for Foresters[16]

[111] https://forestadaptation.org/learn/massachusetts-dcr-climate-forestry-stewardship-planning-training-foresters

[112] MassWoods- Family Forests: https://masswoods.org/monthly-update/family-forests

Sensitivities and Uncertainty

Sensitivity and uncertainties in this impact include:

- Uncertainty in the analysis of adaptability of species to shifting climate envelopes and novel disturbance regimes.
- Uncertainty in modeling the succession of forests into the future, leads to a lack of ability to truly understand how forest composition will change into the future. The disappearance of a tree species does not always mean the appearance of a new tree species. Sometimes they will be taken over by shrubs, vines, or other vegetation types.
- Uncertainties around land use pressures from humans and management plan implementation. Migration inland from sea level rise may put pressure on forests from new urban development. Management plans are not always implemented across all forested areas, leading to a patchwork of managed land.
- Sensitivity to the choices of independent forest owners that prioritize different management styles.

Related Impacts

Table 27 lists the impacts in other sectors that have a connection to this impact.

Table 27. Additional Impacts related to Forest Degradation

Sector	Impact	Connection
Natural Environment	Distribution of Native and Invasive Species	Tree species common to the region may face increased pressure from pests and diseases new to the area. Loss of forests reduced available habitat for native species, increased opportunity for invasives to spread
Natural Environment	Soil Erosion	Loss of healthy soils in forested areas will lead to degradation of forest health, while loss of forested area could increase erosion rates.
Natural Environment	Freshwater Ecosystems	Loss of forest/trees will increase rapid runoff during intense storms; loss of groundwater recharge exacerbates impacts of droughts; loss of filtration function of forests/trees will reduce water quality and increase water temperatures, which will stress fisheries and increases algal blooms.
Human	Health and Cognitive Effects from Extreme Heat	Tree coverage, particularly in urban areas with large proportions of impervious surfaces, provides critical cooling services.
Human	Increase in Mental Health Stressors	Studies have shown access to green space and trees positively impacts mental health.
Infrastructure	Reduction in Clean Water Supply	Healthy forests filter and infiltrate precipitation, recharging surface and ground

Sector	Impact	Connection
		waters. Loss of forests will degrade both water supply quality and quantity.
Infrastructure	Damage to Coastal Buildings and Ports, Damage to Roads and Loss of Road Service, Damage to Inland Buildings, Increased Risk of Dam Overtopping or Failure	Forests capture and slow precipitation. Loss of forests and tree cover multiplies the impacts of increasingly intense storm events.
Infrastructure	Loss of Urban Tree Cover	Urban forests such as Forest Park in Springfield and Franklin Park in Boston could be affected by the dynamics discussed in this section, thought they could also be considered as urban tree cover.

Natural Environment Sector: Remaining Urgent Impacts

The following impacts are also evaluated for urgency in the Natural Environment sector. The summaries below provide a snapshot of each impact, in order of urgency. More details on each impact can be found in Appendix A.

Shifting Distribution of Native and Invasive Species

Changing climatic conditions shift and eliminate suitable habitat for native species (flora and fauna), increase the risk of new species introductions, and increases competition from established invaders potentially causing losses in native biodiversity and loss of culturally important species.

Major Level of Consequence	Potential for Disproportionality	Moderate Adaptation Gap
• Changing climate regimes may result in habitat shifts, however the extent of the impact across species varies.	• Natural Environment sector impacts scored as "potential" because of focus on impacts on natural environments rather than the indirect impacts on humans captured in other sectors.	• Conservation and restoration efforts coupled with policy support can accommodate species range shifts while managing invasive species competition.

Coastal Erosion

Climate change is expected to increase coastal erosion, primarily driven by sea level rise, particularly in areas not protected by wetlands (e.g., dunes, banks, beaches), which has consequences for water quality, land use, and habitat quality.

Major Level of Consequence	Potential for Disproportionality	Moderate Adaptation Gap
• Some parts of the Commonwealth could experience erosion rates of as much as 23 feet per year if current trends continue.	• Natural Environment sector impacts scored as "potential" because of focus on impacts on natural environments rather than the indirect impacts on humans captured in other sectors.	• Coastal habitats and vegetation provide effective nature-based solutions but all solutions require significant resource investment and planning.

Soil Erosion

Increase in extreme precipitation results in increased erosion and potential loss in vegetation or changes in vegetation type, particularly along riverbanks but also in forests and in a number of other landscapes.

Minimal Level of Consequence	Potential for Disproportionality	Moderate Adaptation Gap
• More frequent extreme precipitation events due to climate change could worsen erosion, but the highest-risk regions are expected to see the smallest increases in storm frequency.	• Natural Environment sector impacts scored as "potential" because of focus on impacts on natural environments rather than the indirect impacts on humans captured in other sectors.	• Revegetation, green infrastructure, and thoughtful development can mitigate erosion risks.

4.4 Governance Sector

State and local governments will face growing demand for the essential services they already provide as climate change increases need. Small municipalities with limited tax bases may be disproportionality burdened.

Table 28. Urgent Impacts in the Governance Sector

IMPACT	DESCRIPTION	MAGNITUDE	DISPROPORTIONATE EXPOSURE	ADAPTATION GAP
Reduction in State and Municipal Revenues (MOST URGENT)	State and municipal revenue streams impacted through property tax loss following structure damage of any type, from any hazard, and income and sales tax losses associated with business interruptions or effects on industrial activities.	Major	Disproportionate	Moderate
Increase in Costs of Responding to Climate Migration (MOST URGENT)	Costs and stresses to governments accommodating and/or preparing for forced and voluntary human migration of populations in response to climate threats or related economic pressures. Includes intra-state, inter-state, and international in- and out-migration, and generally is more abrupt than routine population changes in response to non-climate stressors (such as economic development or decline).	Major	Potential	Extreme
Increase in Demand for State and Municipal Government Services (MOST URGENT)	Climate change serves as a threat multiplier, which can increase the need for expenditures to meet existing government service. Examples include capital, equipment, or operating costs for emergency response provision and state sponsored health programs.	Major	Potential	Moderate
Damage to Coastal State and Municipal Buildings and Land	Risk to vulnerable state and municipal owned structures and other property from coastal flooding, wind, extreme heat, and extreme storms. Includes damage repair costs and service losses during closures.	Major	Limited	Moderate
Increase in Need for State and Municipal Policy Review and Adaptation Coordination	State agencies and municipalities may require additional full-time employees and specialized training to meet the challenges of climate change. Specifically, state and municipal staff will need capacity to provide adaptation planning support and to review and modify policies in response to changing conditions and uncertainty associated with climate change.	Minimal	Potential	Minimal
Damage to Inland State and Municipal Buildings and Land	Risk to vulnerable state and municipal owned structures and other property from flooding, extreme heat, and extreme storms. Includes damage repair costs and service losses during closures.	Minimal	Limited	Minimal

Governance Sector: Urgent Impact #1

Reduction in State and Municipal Revenues

State and municipal revenue streams impacted through property tax loss following structure damage of any type, from any hazard, and income and sales tax losses associated with business interruptions or effects on industrial activities.

Major Level of Consequence	Disproportionate Exposure	Moderate Adaptation Gap
• Massachusetts municipalities could experience $104 million in lost revenues from a 3 ft sea level rise (1.4 percent of current property taxes in 89 coastal municipalities).	• Lost property tax value from coastal structures is the largest category of expected impact, and could disproportionally impact municipalities with higher proportions of population in EJ block groups.	• Adaptation actions focused on reducing property damage (particularly from coastal flooding) will help to mitigate this impact.

Impact Summary

Massachusetts' fiscal health depends on both the revenues collected by the Commonwealth and other levels of government, as well as expenditures. Both could be affected by climate change, in different ways. This impact focuses on impacts of climate change on revenue streams. Existing research suggests three pathways in which revenues could be affected by climate change: personal and corporate income taxes; sales taxes; and property taxes. For example, direct revenue losses associated with personal income taxes could result from adverse health effects that reduce time at work and taxable wages. These reduced wages from climate-related health effects could also result in spillover indirect effects, if wages lost are not spent in the Massachusetts' economy to support the wages of other workers and overall economic output. Any broader statewide effect characterized in the Economy sector might also reduce overall economic activity in the state, which could reduce income to individuals and business entities, and thereby also reduce income tax revenue.

A more readily quantifiable category of the potential effect on revenues is on property taxes. In particular, effects of climate change over time, and especially sea level rise and storm surge, can be reflected in reduced sales prices and assessed values, and/or loss of land and structures, which reduces the property tax base. Property tax is usually the most important source of income for municipal entities.

Urgency Ranking Results

This impact is ranked as a **high priority** because of the assessment of potentially long term impacts on the municipal tax base, and an assessment of disproportionate exposure for municipalities with higher concentrations of designated EJ block groups. Little to no information currently exists to evaluate specific adaptation initiatives.

Potential impacts on municipal tax revenue could be linked to inundation of land and/or structures from sea level rise, as estimated in Shi and Varuzzo (2020) specifically for

Massachusetts.[113] The estimate in the literature is based on the 2015 tax base and is based on a 3-feet of sea level rise estimate. The 3-foot scenario used in the paper is within the range of uncertainty for the Commonwealth's projection of the not-to-exceed estimate for sea level rise through 2050, as applied in the Climate Assessment.

> *"Our local communities rely on municipal programs and decisions that are funded by revenues from tax collection, etc."*
>
> *"If property values drop on Cape Cod due to climate change impacts, such as rising sea levels that eliminate beaches and flood coastal homes and businesses, there will be a reduction in tax revenues and that will reduce our ability to respond to climate change and try to adapt to it."*
>
> *"If the governments revenues are reduced it could be devastating to our department that already is understaffed."*
>
> - Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The consequences of climate change on state and municipal revenues are projected to be **major** due to projected impacts on property and income tax revenue, particularly in the late century period but perhaps sooner. The evaluation of property tax impacts is based on the Shi and Varuzzo (2020) analysis which is specific to Massachusetts municipalities but uses a different timing assumption for sea level rise changes than that adopted for the Climate Assessment. Massachusetts municipalities could experience $104 million in lost revenues by the time 3 feet of sea level rise is reached, which represents 1.4 percent of current property taxes in 89 coastal municipalities. The Massachusetts sea level rise scenario projects that level of sea level rise could be reached in the mid-century period. Projected losses could increase to $946 million per year with 6-feet of sea level rise (12.5 percent of current property taxes in 99 coastal municipalities).

Estimating potential losses of state income tax is more difficult. Some estimates exist at a national level. In general, as researchers expect climate change to trigger lost global GDP, researchers have begun to quantify the impact of climate-induced lost GDP on country-level, national government revenues.[114] Under a commonly cited statistic that the global economic loss from 4°C is four percent of global GDP, as well as assumptions that (1) U.S. Federal income tax and other revenue can be characterized as closely correlated as a share of U.S. GDP and that (2) all economic losses occur via lost GDP, the White House Office of Management and Budget predicts late-century lost Federal revenue to range from $343 to $685 billion per year, depending on whether the U.S. share of global economic loss is between 10 percent and 20 percent. This lost revenue is equivalent to approximately $56 to $111 billion per year using

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[113] Shi, L. and Varuzzo, A.M. 2020. Surging seas, rising fiscal stress: Exploring municipal fiscal vulnerability to climate change. Cities, 100, p.102658.

[114] International Monetary Fund (IMF). 2019. Fiscal Monitor: How to Mitigate Climate Change. Washington, October. Available at https://www.imf.org/en/Publications/FM/Issues/2019/09/12/fiscal-monitor-october-2019

2016 GDP values.[115] Similar estimates for Massachusetts do not yet exist, but it is not implausible that lost revenue to the state treasury could exceed $100 million per year by end century, if Massachusetts GDP drops by a similar amount as the national GDP reduction used in the OMB analysis. A $100 million reduction in tax revenue would represent only about 0.4 percent of the FY2022 Income Tax revenue reported by the State Treasurer's Office – income tax revenue is the single largest component of state revenue, accounting for almost 60 percent of total revenue for the Commonwealth.[116]

Disproportionality

Based on currently available information, this impact is classified as having **disproportionate** exposure. The major quantified effect for property tax revenues is focused on coastal communities, and the specific vulnerable properties are those identified as most at risk of storm surge and sea level rise damage from the Infrastructure sector – Damage to Coastal Buildings and Ports impact. For that sector, detailed analysis showed the coastal impacts to buildings had limited to no disproportionate effects, however, the effects of revenue loss are on the municipal budgets as a whole, not on individual properties. This different perspective, more relevant for this Governance sector impact, implies that the correct metric for assessing disproportionality for this impact is the distribution of estimated municipal revenue loss compared to the share of populations in that municipality resident in EJ block groups. That analysis shows the revenue impacts are 13 percent higher than proportional based on the distribution of total population in minority designated EJ block groups; and 8 percent higher for minority and income designated EJ block groups. The degree of disproportionality is higher for the Boston Harbor region, at the municipal scale it is 14 percent higher than proportional for minority designated EJ block groups and 21 percent higher than proportional for minority and income designated block groups.

For other revenue effects, Commonwealth income tax effects, if they materialize as substantial, might not show a disproportionate impact because while income tax rates are the same across income brackets, the effective state income tax incidence can be considered progressive when deductions and exemptions are considered, which provides a state-wide buffering effect of potential impacts to specific EJ block groups. For potential sales tax revenue impact, not enough evidence exists to conclude whether potential revenue effects could fall disproportionately on local governments in areas with a concentration of EJ population block groups.

Adaptation

There is a **moderate** adaptation gap to preventing a climate-driven reduction of state and municipal revenues. Statewide climate planning documents do outline plans to integrate climate projection data into state capital planning (see for example, EEA's Climate Resilience Design Standards Tool), but similar planning efforts at the municipal and regional scales are

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[115] Office of Management and Budget and Council of Economic Advisors (2016). Climate Change: The Fiscal Risks Facing The Federal Government; A Preliminary Assessment. Available at: https://toolkit.climate.gov/reports/climate-change-fiscal-risks-facing-federal-government

[116] See https://www.mass.gov/news/fiscal-year-2022-revenue-collections-total-41105-billion

needed. Some climate adaptation actions that do not target revenue reduction directly will still likely have spillover benefits for this impact, including flood mitigation, road infrastructure improvements, and resiliency planning and retrofitting for municipal buildings. Coastal infrastructure adaptation in particular is being actively pursued statewide and provides a cost-effective and direct approach to preventing many of the potential property tax base impacts identified here.

That said, climate change is already inflicting costly damage across the state that municipal funds are largely responsible for fixing, so continuing to expand the consideration of climate impacts in future planning at all levels of government will be important for preventing unnecessary losses.

Sensitivities and Uncertainty

Existing information to quantify impacts of climate change on state and municipal revenue streams is limited. There remain large uncertainties in assessing the impact on overall economic activity and the income tax base in particular. Further, the magnitude of impacts for this category depends critically on adaptation actions focused on other related impacts, such as effects of sea level rise on coastal infrastructure, impacts on the agriculture and marine fisheries sectors, and impacts on business interruption and individuals' ability to work in a hotter climate. The authors of the Massachusetts focused study on impacts of sea level rise on property tax base also acknowledge that their vulnerability assessment relies on a flood risk tool, the NOAA Sea Level Rise viewer, that does not take into account all existing infrastructure, such as the Charles River dam, in assessing properties at risk. For these reasons the impact on property tax base assessed here is likely to overstate the magnitude of impact.

Related Impacts

Table 29 lists the impacts in other sectors that have a connection to this impact.

Table 29. Additional Impacts related to Reduction in State and Municipal Revenues

Sector	Impact	Connection
Economy	All	Impacts in the Economy sector could affect overall economic activity in the Commonwealth, which would in turn affect the income and sales tax revenue bases.
Infrastructure	Damage to Coastal and Inland Buildings	Damage to buildings and risks to continuing uses of land vulnerable to coastal or inland flooding affects the value of residences and commercial structures, which in turn affects the property tax base for Commonwealth municipalities.

Governance Sector: Urgent Impact #2

Increase in Costs of Responding to Climate Migration

Costs and stresses to governments accommodating and/or preparing for forced and voluntary human migration of populations in response to climate threats or related economic pressures. Includes intra-state, inter-state, and international in- and out-migration, and is generally more abrupt than routine population changes in response to non-climate stressors (such as economic development or decline).

Major Level of Consequence	Potential for Disproportionality	Extreme Adaptation Gap
• Global and national concern for climate migration is appropriately high, and while the impact for Massachusetts is uncertain, several studies suggest Massachusetts could be a "receiving zone" because of its more northerly location in the U.S. and less extreme summer climate than other locations.	• Unable to estimate – current experience suggests areas with current concentrations of ethnic groups may be receiving areas for climate migration.	• Adaptation action to prepare communities for a possible influx of climate migrants is very limited, to date.

Impact Summary

The elevated incidence and intensity of extreme weather outcomes associated with climate change projections has forced displacement among many global communities who are victims of environmental disruption, and has prompted relocation to other, unfamiliar regions – a phenomenon known as "climate migration".[117] In Massachusetts, costs and stresses to governments accommodating and/or preparing for forced and voluntary human migration of populations in response to climate threats or related economic pressures could be significant, as climate migration pressures could result from intra-state, inter-state, and international in- and out-migration. Massachusetts' more northern location within the U.S., and milder summer climate, has led some researchers to suggest it could be a net receiving zone for climate migrants.

Though climate migration can bring benefits to receiving communities, there are also often associated costs due to the abrupt nature of population changes, rather than the more typically encountered population changes that governments encounter in response to non-climate stressors (such as generally more gradual economic development or decline). The costs of climate migration could include specialized housing provision, both short-term and medium-term, for migrants; social services; increased educational costs to school systems; and pressure on existing public infrastructure. Housing provision is a particular challenge for Massachusetts in the context of the current imbalance between growing housing demand and limited expansion of housing supply.

[117] Burson, B. 2021. Displacement in a Changing Climate: IFRC. ifrc.org. Retrieved July 18, 2022, from https://www.ifrc.org/document/displacement-in-a-changing-climate

Urgency Ranking Results

This impact is ranked as a **high priority** because of the assessment of potentially major long-term impacts. Qualitative information and historical anecdotal evidence suggest the potential for disproportionate impacts in municipalities with higher concentrations of populations in EJ block groups. There is little evidence of specific adaptation initiatives at the current time.

Unfortunately, there are currently no quantitative estimates of the population that might seek refuge in Massachusetts from climate disasters, so this impact is evaluated qualitatively based on available information, literature, and anecdotal information. In particular, the Massachusetts town of Holyoke recently experienced a rapid population influx in 2017 connected to Hurricane Maria's consequences in Puerto Rico. Other information suggests that Massachusetts may be a "receiving zone" for climate migrants, owing to a milder summer climate and potentially increasingly mild winters. In addition, a large portion of the population of Massachusetts which is connected to the Massachusetts Water Resource Authority water supply has a higher degree of water security than much of the western U.S., based on national studies of projected future water shortages.[118]

> *"What happens when people start to bump up against new ideas, new people, etc. that are not otherwise a piece [of] a community? We need to be preparing people for this, now, with the goal of making the transition warm, kind and accepting."*
>
> \- Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The consequences of climate migration are difficult to assess. Consequences may be minimal based on currently limited evidence of significant climate migration to Massachusetts to date, but this impact is classified as **major** based on review of existing literature on climate migration prospects and the likelihood that Massachusetts could be a receiving zone for climate migrants based on a relative assessment of climate hazards. In addition, stakeholder survey information indicates concern among the public about this impact. Climate migration remains an emerging risk for Massachusetts, which could accelerate in the future based on changes in trends of global, interstate, and in-state migration patterns.

From a global perspective, a recent World Bank report acknowledges that while migration is a complex decision influenced by many, cross-sectoral factors, climate change can either directly influence mobility – in cases of displacement under extreme-weather-induced distress – or indirectly, through climate change's impacts on economic and political landscapes. Specifically,

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[118] See for example Strzepek, K., J. Neumann, J. Smith, J. Martinich, B. Boehlert, M. Hejazi, J. Henderson, C. Wobus, R. Jones, K. Calvin, D. Johnson, E. Monier, J. Strzepek, and J. Yoon (2014). Benefits of greenhouse gas mitigation on the supply, management, and use of water resources in the United States. *Climatic Change*, 131, 127–141, doi:10.1007/s10584-014-1279-9. Available online at https://link.springer.com/article/10.1007/s10584-014-1279-9

"hotspots" of climate out-migration can include low-lying cities and coastlines, as well as areas of water and agricultural stress.[119]

While existing studies remain limited in focus, and dependent on specific assumptions about warming projections in different parts of the world and potential adaptation efforts, one study which focused on immigration across the Mexico/U.S. border found that climate change could prompt the migration of an additional 1.4 to 6.7 million adults to the United States by 2080.[120] While migration in aggregate is most visible in large metropolises, Marandi & Main (2021) find that "recipient cities" of climate migration tend to be small- or mid-size cities; thus, the Influx of residents from migration has the potential to dramatically alter a locale's social and economic outlook.[121]

Climate change has rendered Massachusetts increasingly vulnerable to coastal flooding and hurricanes, but its reputation as a cold region has marked the state, along with other Northeastern and Northwestern U.S. regions as suitable destinations for those affected by environmental disasters, within the U.S. and abroad.[122]

Most notably, in 2017 and 2018, Holyoke – a Massachusetts city with the highest concentration of people of Puerto Rican descent in the contiguous U.S.– welcomed 142 Puerto Rican households permanently but just under 1,000 households initially, displaced by Hurricane Maria, largely because of the existing Puerto Rican population; in fact, most people interviewed mentioned that they were primarily attracted to Holyoke in particular because of the presence of family or friends there.

Latin America is among the regions currently hit hardest by extreme weather phenomena, and the United States is one of the most proximal nations high in income and with higher proportions of migrants.[123,124] As such, Massachusetts cities such as Lawrence, Chelsea, Holyoke, Springfield, Lynn, Revere, Fitchburg, Everett, and Worcester – each with an existing Hispanic population of at least 20 percent (with Lawrence and Chelsea above 60 percent) – could be regarded as sites for relocation for Latin American climate migrants.

With respect to the potential for out-migration of population from Massachusetts in response to climate stressors, Hauer et al. (2020) predict that Massachusetts is home to anywhere between 300 to 500 thousand individuals vulnerable to displacement due to rising sea levels, either because they reside in low elevation coastal zones or in the 100-year projected

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[119] Rigaud, K.K., De Sherbinin, A., Jones, B., Bergmann, J., Clement, V., Ober, K., Schewe, J., Adamo, S., McCusker, B., Heuser, S. and Midgley, A. 2018. Groundswell: Preparing for Internal Climate Migration. World Bank, Washington, DC. https://openknowledge.worldbank.org/handle/10986/29461

[120] Feng, S., Krueger, A. B., & Oppenheimer, M. 2010. Linkages among climate change, crop yields and Mexico-US cross-border migration. *PNAS*, 107(32), 14257–14262. https://doi.org/10.1073/pnas.1002632107

[121] Migration Policy Institute. (2021, March 26). U.S. Immigrant Population by State and County. migrationpolicy.org

[122] Marandi and Main (2021).

[123] Rigaud et al. (2018)

[124] World Immigration Report (2022)

floodplain.[125] Hauer reports that most American households displaced due to environmental phenomena migrate to nearby urban job-growth centers; within Massachusetts, this outcome may be observed as a growth of small cities in western Massachusetts, or interstate migration to nearby growing cities such as Buffalo.

A comprehensive picture of the risks of displacement *within* and *to* Massachusetts can help policymakers and local communities balance climate adaptation efforts and climate migrant welcome efforts. However, in order to make any quantitative estimates, more research is necessary on the frequency of international migration to the United States in response to climate change events – as opposed to intranational movement within impacted countries–- as well as the distribution of movement within the United States attributable to extreme weather events.

One other factor in the consequence assessment is the current housing context in which climate migration might occur. The Commonwealth's Partnership for Growth plan identifies that "*Massachusetts is in a housing crisis. Over the past 30 years, housing production in Massachusetts has plummeted. Between 1960 and 1990, Massachusetts communities permitted almost 900,000 new housing units, but between 1990 and 2017, communities permitted less than 435,000 units…The combination of a growing economy, with nearly 400,000 new jobs created between 2010 and 2017, and a slowing rate of production, with barely over 100,000 new housing units created in the same period, has created massive market pressure on home prices and rents.*"[126]

In this context, there is less flexibility across the state to respond to new housing pressure, and climate migration could exacerbate the crisis by adding to market pressure.

Disproportionality

Based on currently available information, this impact is classified as having the potential for disproportionate exposures. Not enough evidence exists to conclude whether the costs of responding to climate migration would fall disproportionately on local governments in areas with a concentration of EJ population block groups, however recent experience suggests areas with existing concentrations of recently immigrated populations may be more likely receiving areas for future international climate migrants because of shared culture and community.

Adaptation

There is an **extreme** adaptation gap to addressing the increased costs of responding to climate migration.

Massachusetts' major towns and cities are taking some steps to plan for these population migrations (both in-migration and out-migration in terms of managed retreat), but only in certain municipalities. Robust preparation and implementation should begin sooner than later, as population increases will place stress on the already overburdened systems for housing, food, job training, and education, all of which face their own additional climate threats.

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[125] Hauer, M.E., Fussell, E., Mueller, V. et al. 2020. Sea-level rise and human migration. Nat Rev Earth Environ 1, 28–39. https://doi.org/10.1038/s43017-019-0002-9

[126] See https://www.mass.gov/info-details/partnerships-for-growth#respond-to-the-housing-crisis-

Example Adaptation Plan with Actions Addressing this Impact

- Meeting an Immediate Need by Learning from Hurricane Maria Survivors in Holyoke

Sensitivities and Uncertainty

Existing information to quantify impacts of climate migration is limited – because migration in general is a complex decision influenced by many, cross-sectoral factors as well as non-climate influenced factors, there remain large uncertainties in assessing the impact of climate migration on Massachusetts.

Related Impacts

Table 30 lists the impacts in other sectors that have a connection to this impact.

Table 30. Additional Impacts related to the Increase in Costs of Responding to Climate Migration

Sector	Impact	Connection
Economy	Reduction in the Availability of Affordably Priced Housing	Growing demand for housing in places with relatively low climate risks may cause housing prices to increase.
Natural Environment	Forest Health Degradation	Development pressure in areas receiving climate migrants may result in sprawl to currently forested areas.

Governance Sector: Urgent Impact #3

Increase in Demand for State and Municipal Government Services

Climate change serves as a threat multiplier, which can increase the need for expenditures to meet existing government service. Examples include capital, equipment, or operating costs for emergency response provision and state sponsored health programs.

Major Level of Consequence	Potential for Disproportionality	Moderate Adaptation Gap
• Demand for MassHealth, food security support, and emergency response could be most significantly affected by climate impacts in the Commonwealth	• MassHealth and food security support are generally at the state level and therefore not specific to local incidence, but emergency service support could be disproportionately higher in EJ block groups.	• No identified adaptation actions are underway to address this impact, however the options for direct action are minimal. Adaptation actions directed towards other sectors (e.g., Human and Infrastructure) will also mitigate this impact.

Impact Summary

State and municipal governments make expenditures and provide services in a broad range of areas which are not directly linked to climate change adaptation expenditures and policies, but which could nonetheless change as a result of impacts to government owned and maintained infrastructure, the health of residents in the relevant jurisdictions, the impact of climate on food supply and distribution, or disruption of ordinary economic activity.

The need to increase expenditures to maintain the current level of governmental services is a component of estimating the overall fiscal impact of climate change on government entities, through methods established in recent U.S. Office of Management and Budget reports on the fiscal impact of climate change on the U.S. Federal Government.[127] The other component of fiscal impact is impacts on revenue sources, including income, sales, property, and other taxes are considered in a separate impact category of the Governance sector. In addition, expenditures specifically focused on the coordination among various levels of government for efficient adaptation, including human resources needed for those tasks, or for supporting climate migration are not considered in the scope of this impact, but are considered in separate categories of the Governance sector.

Urgency Ranking Results

This impact is ranked as a **medium priority** because of potentially large impacts, with potential for disproportionality and moderate adaptation gap.

Impacts are evaluated based on the share of quantified Infrastructure sector costs which can be reliably attributed to a need for funding from municipal or state government, for road

[127] U.S. Office of Management and Budget, 2016, Climate Change: The Fiscal Risks Facing the Federal Government - A Preliminary Assessment; and U.S. Council Of Economic Advisers and Office Of Management And Budget, 2022, White Paper on Climate-Related Macroeconomic Risks and Opportunities, published April 4, 2022.

maintenance, and based on a review of current and possible increasing need for expenditures by government to maintain services such as health care support for residents or economic support to specific sectors important to the Commonwealth.

> *"When we need to respond to storms and damage constantly, it will leave less funding for schools and services."*
>
> - Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

This impact is categorized as a **major** level of consequence based on review of possible changes in municipal and state expenditures to maintain government services.

A wide range of state and municipal expenditures could be affected by climate change. One well-understood impact is the need to address changes in road maintenance and repair costs to address changes in temperature (which affects the useful life of asphalt road binders); precipitation (which affects roadways and can also wash-out unpaved dirt roads); and freeze-thaw cycles (which in the most recent history have been more severe as warming climate causes multiple freeze-thaw cycles every winter rather than just one). Table 31 summarizes these expected road maintenance and repair cost changes for municipally owned (left panel) and state-owned (right panel) road inventory. Costs in 2030 are small and, in some regions, can be negative if precipitation or the effects of freeze-thaw cycles moderate. By 2050 any benefits of a warming climate are dissipated and costs for municipal and state-owned roads together exceed $32 million per year; by 2090 this grows to over $100 million per year. As shown in Table 31, the majority of these costs fall on municipal budgets, rather than state budgets, because of the large road/lane-mile inventory maintained at the municipal level. Costs for municipally owned roads are smallest in the Boston Harbor region and largest in the Eastern Inland area.

It is important to note that the regional distribution of costs is not correlated with regional population – which means the cost per resident is likely to be highest in the sparsely populated Berkshires and Hilltowns region, which will reduce the ability to pay of municipal governments in that region. Many municipalities rely on Chapter 90 funding for road work, and the existing Chapter 90 formula allocates funding based on a community's road mileage, population, and employment. These latter two factors can put smaller communities in a disadvantaged position. Additional discussion of this point can be found in a 2021 report by the Office of the State Auditor.[128]

[128] See https://www.mass.gov/info-details/recommendations-public-infrastructure-in-western-massachusetts

Table 32. Changes in road maintenance and repair costs attributed to climate change for municipally owned and state-owned roads

Change in road maintenance and repair costs compared to a 1986-2005 baseline (million$). Future impacts presented for four time periods identified in the table by their central year: 2030 (near-term, 2020-2039); 2050 (mid-century, 2040-2059); 2070 (mid-late century, 2060-2079); and 2090 (end of century, 2080-2099). Totals may not sum due to rounding.

	Municipally Owned Roads				State-Owned Roads			
Region	**2030**	**2050**	**2070**	**2090**	**2030**	**2050**	**2070**	**2090**
Berkshires & Hilltowns	$0.9	$3.1	$4.5	$8.5	<$0.1	$0.2	$0.3	$0.6
Greater Connecticut River Valley	$0.2	$4.3	$8.8	$16	-$0.1	$0.2	$0.5	$1.1
Central	$0.1	$8.0	$12	$17	<$0.1	$0.6	$0.9	$1.3
Eastern Inland	-$2.7	$6.1	$12	$21	-$0.2	$0.5	$1.0	$1.7
Boston Harbor	-$0.1	$2.7	$4.0	$6.9	<-$0.1	$0.3	$0.5	$0.9
North & South Shores	$0.2	$2.6	$5.0	$8.1	<$0.1	$0.4	$0.8	$1.2
Cape, Islands, & South Coast	-$0.8	$3.3	$11	$16	$0.1	$0.5	$1.3	$1.8
Statewide	**-$2.2**	**$30**	**$58**	**$94**	**-$0.1**	**$2.6**	**$5.3**	**$8.5**

Source: Adapted from Neumann et al. 2021 and Project Team analysis[129]

Other possible categories of impact on expenditures, excluding expenditures accounted for in other Governance sectors, such as costs to repair and maintain state buildings and land damaged by coastal or inland flooding, are summarized in Table 33 below. The total of potentially increased expenditures included in Table 33 might be in the $10s of millions by 2050.

Disproportionality

Exposure to this impact has a **potential** for disproportionate exposure based on qualitative analysis of the increase in demand for government services. The incidence of road repair expenditures summarized in Figure 33 below does not support a finding of disproportionality, but indicate the most of the demand for road repair costs, while large in magnitude, is estimated to be borne outside of EJ block groups.

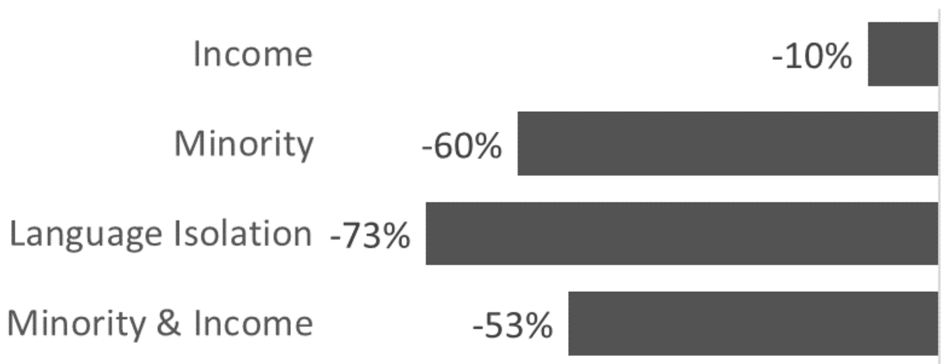
The finding of the potential for disproportionate Impact are based on the mostly qualitative analysis of the increased demand for other services. In particular, an increased demand for medical treatment, and therefore expenditures on health care, from impacts in the Human sector, could lead to additional pressure on the MassHealth program or could potentially result in an increasing share of health care costs being shared with low-income health insurance policy-holders – in that case impacts could fall disproportionately on low-income populations. In the Health sector additional health care expenditures for asthma medical care, vibriosis, and Lyme disease could be $40 million, $54 million, and $45 million, respectively, by 2050.

[129] Neumann, J.E., Chinowsky, P., Helman, J., Black, M., Fant, C., Strzepek, K., and Martinich, J. (2021) Climate effects on US infrastructure: the economics of adaptation for rail, roads, and coastal development. Climatic Change 167, 44 (2021). https://doi.org/10.1007/s10584-021-03179-w

MassHealth spending of $19.2 billion is about 1/3 of the total Massachusetts health care spending of $61 billion,[130] implying that MassHealth could see demand for an additional roughly $50 million of these cost increases in 2050.

Figure 33. Disproportionality of Municipal Road Maintenance and Repair Costs Attributed to Climate Change

Comparison of municipal road repair costs attributed to climate change by income, minority status, language isolation and minority status and income combined, compared to all other block groups in the state. Negative numbers and gray bars represent a negative correlation between the block groups meeting the EJ criteria on the basis listed and the magnitude of consequence. See Section 2.1 for further description of the EJ block group definitions.



Adaptation

There is a **moderate** adaptation gap to mitigate or lessen demand for government service expenditures. There are limited available actions to directly adapt to the potential need for increased demand for expenditures. Instead, the available actions address the causes of increased demand (e.g., flooding mitigation, infrastructure resilience, and climate adaptation strategy development). Acting sooner in these areas should, in the long term, reduce overall demand for additional government services. However, as evidenced by the number of plans expressing a desire for additional funding, adequately adapting to climate change now and preventing future increases in government service expenditures suggests that an adaptation gap remains.

Example Adaptation Plans with Actions Addressing this Impact

- Metro Boston Regional Climate Change Adaptation Strategy Report - See plans to increase support for green infrastructure funding mechanisms
- Building a Resilient Scituate – See section on Adaptive Management planning

130 https://www.chiamass.gov/report-health-care-costs-in-massachusetts-are-growing-slowly-as-out-of-pocket-costs-rise/

Sensitivities and Uncertainty

Sensitivities and uncertainties around this impact include a limited ability to quantify all state and municipal expenditure changes in response to climate change, to allocate costs to specific regions, or to estimate impacts on specific populations. When evaluating disproportionality, the analysis relies on where municipal road maintenance costs might be incurred, rather than direct effects on individuals in those location.

Related Impacts

Table 33 lists the impacts in other sectors that have a connection to this impact.

Table 33. Additional Impacts related to Increase in State and Municipal Expenditures on Government Services

Sector	Impact	Connection
Infrastructure	Damage to Roads and Loss of Road Service	Most costs associated with road maintenance and repair fall on municipal and state governments.
Economy	Reduction in the Availability of Affordably Priced Housing	Some state programs provide support and subsidies for income restricted affordable housing – any increase in the need for affordably priced housing support could lead to demand to increase those expenditures.
Economy	Decrease in Agricultural Productivity	Reductions in agricultural productivity could increase the need for state government support of programs for agricultural extension for climate-resilient farming and livestock management practices.
Economy	Damage to Tourist Attractions and Recreation Amenities	Costs to repair damages to municipally or state-owned tourist and recreation areas could increase expenditures for agencies that manage and maintain these assets.
Human	Health and Cognitive Effects from Extreme Heat; Health Effects from Degraded Air Quality; and Increase in Vector Borne Disease Incidence and Bacterial Infections	Increased medical costs are shared in part by the state government subsidies provided through MassHealth
Human	Reduction in Food Safety and Security	Food security support is provided in part through the state budget, which could be affected in particular by any increase in food prices.
Infrastructure	Dam Overtopping or Failure	An increased cost for maintenance and repair of dams that are overtopped or breached could be borne in whole or in part by state expenditures.
Natural Environment	Freshwater and Marine Ecosystem Degradation	Costs for restoration of damaged ecosystems might be borne in part by state expenditures.

Governance Sector: Remaining Urgent Impacts

The following impacts are also evaluated for urgency in the Governance sector. The summaries below provide a snapshot of each impact, in order of urgency. More details on each impact can be found in Appendix A.

Damage to Coastal State and Municipal Buildings and Land

Risk to vulnerable state and municipally owned structures and other property from coastal flooding, wind, extreme heat, and extreme storms. Includes damage repair costs and service losses during closures.

Major Level of Consequence	Limited Disproportionality	Moderate Adaptation Gap
• Damage to buildings is estimated to gradually increase to over $40 million per year relative to baseline by the 2070s.	• Potential for disproportional exposure in low-income block groups is moderate (10 percent).	• Infrastructure adaptation measures are being widely implemented along the coast, but larger, more effective adaptations such as rezoning policies are less common.

Increase in Need for State and Municipal Policy Review and Adaptation Coordination

Costs and stresses to governments accommodating and/or preparing for forced and voluntary human migration of populations in response to climate threats or related economic pressures. Includes intra-state, inter-state, and international in- and out-migration and is generally more abrupt than routine population changes in response to non-climate stressors (such as economic development or decline).

Minimal Level of Consequence	Potential for Disproportionality	Minimal Adaptation Gap
• A large proportion of municipal budgets and staff are allocated to building inspection and code enforcement – so even a small increase could have major impacts on municipal expenditures.	• Small local governments, which may include more low-income EJ block groups, could also have a higher cost for addressing the need for building code changes and associated enforcement, relative to their overall budgets.	• The Municipal Vulnerability Preparedness program is a key example of the work in this area already underway, which will need to be expanded as needs continue.

Damage to Inland State and Municipal Buildings and Land

Risk to vulnerable state and municipal owned structures and other property from flooding, extreme heat, and extreme storms. Includes damage repair costs and service losses during closures.

Minimal Level of Consequence	Limited Disproportionality	Minimal Adaptation Gap
• Less than 10 state-owned major facilities fall in areas expected to experience significant inland flooding by the end of the century.	• None of the potentially impacted buildings are located in EJ block groups.	• Current facilities siting decisions are adequately addressing the risk of inland flooding.

4.5 Economy Sector

Extreme events, dangerous heat, and transportation delays will all affect business and people's ability to work. Less productive fisheries and changing agricultural yields cause direct impacts to farm workers and indirect impacts through the Commonwealth's economy.

Table 34. Urgent Impacts in the Economy Sector

IMPACT	DESCRIPTION	MAGNITUDE	DISPROPORTIONATE EXPOSURE	ADAPTATION GAP
Reduced Ability to Work (MOST URGENT)	More frequent extreme heat days leads to lost wages and decreased productivity, as do increasing incidence of climate-induced health effects (e.g., asthma, allergies, vector borne disease, extreme heat). Weather-induced disruptions to transportation and ability to work may also lead to lost wages and worker productivity. Impacts are felt most by workers in outdoor industries, those who rely on public transportation, and those who care for others at home.	Extreme	Disproportionate	Moderate
Decrease in Marine Fisheries and Aquaculture Productivity (MOST URGENT)	Changes in water temperature regimes and acidification in the marine environment change fish habitat and alter commercial landings and revenue, including effects on related industries.	Major	Disproportionate	Moderate
Reduction in the Availability of Affordably Priced Housing (MOST URGENT)	An increase in demand for housing that is affordable and a decrease in supply worsens the scarcity of affordably priced housing. Demand for housing that is affordable can result if people are forced to relocate either due to direct damage to existing housing or because of climate-related economic pressures. The supply of affordably priced housing is reduced due to direct physical damage from climate impacts and potentially higher construction costs to increase resilience to threats from climate change.	Major	Disproportionate	Moderate
Economic Losses from Commercial Structure Damage and Business Interruptions	Reduction in economic outputs during closures resulting from flooding and storm damage to places of business, as well as reductions in economic output due to extreme weather shutdowns, utility and infrastructure disruptions, and climate-driven supply chains issues.	Extreme	Potential	Moderate

IMPACT	DESCRIPTION	MAGNITUDE	DISPROPORTIONATE EXPOSURE	ADAPTATION GAP
Damage to Tourist Attractions and Recreation Amenities	Changes to revenues in the tourism and recreation industry, particularly those associated with distinct New England seasons (e.g., winter recreation, foliage viewing), recreational fishing, beach recreation (i.e., reduction in beach width due to sea level rise and coastal erosion), and tourism related to vulnerable historical landmarks.	Moderate	Disproportionate	Moderate
Decrease in Agricultural Productivity	Reduction in crop yields for major agricultural products including field crops and tree products due to changing temperature and precipitation patterns, extreme weather, loss of pollinators, saltwater intrusion, and others.	Major	Limited	Moderate

Economy Sector: Urgent Impact #1

Reduced Ability to Work

More frequent extreme heat days leads to lost wages and decreased productivity, as do increasing incidence of climate-induced health effects (e.g., asthma, allergies, vector borne disease, extreme heat). Weather-induced disruptions to transportation and ability to work may also lead to lost wages and worker productivity. Impacts are felt most by workers in outdoor industries, those who rely on public transportation, and those who care for others at home.

Extreme Level of Consequence	Disproportionate Exposure	Moderate Adaptation Gap
• Workers in Massachusetts could lose over 10 million hours of work and associated wages per year by 2090 due to high heat conditions plus additional losses due to transportation delays.	• Calculated disproportionality scores are relatively small; however, people earning lower incomes are less likely to have flexibility for remote work to mitigate commute issues during extreme weather.	• Flood and heat mitigation strategies will help improve workforce resilience indirectly but direct planning, such as increased worker protections, have yet to be adopted on a large scale.

Impact Summary

Climate change impacts can make it difficult for people to work because of dangerous conditions (i.e., extreme heat), transportation disruptions, and illness. These impacts are felt particularly by workers in industries that perform work outdoors (e.g., construction, agriculture, transportation, utilities), those who do not have the option to work from home, those who rely on public transportation, and those who care for others at home.

About 20 percent of the Commonwealth's workforce (nearly 700,000 people) work in industries such as agriculture, fishing, construction, manufacturing, transportation and warehousing, and utilities in which workers are often exposed to the heat and other weather conditions. These industries are critical for economic growth in the Commonwealth. Manufacturing and/or construction are mentioned as priority industries in nearly all Regional Labor Market Blueprints updated in 2020.[131] Construction work will also be critical to responding to the challenges of climate change on infrastructure as well as growing the housing stock to meet demand (see all impacts in the Infrastructure sector and Reduction in Availability of Affordably Priced Housing in the Economy sector).

Urgency Ranking Results

This impact is ranked as a **high priority** because of potentially large impacts, with potential for disproportionality and moderate adaptation gap.

[131] https://www.mass.gov/service-details/view-your-regions-blueprint. Greater Boston, the only region to not include a high-risk industry as priority, listed priority industries as Health Care and Social Assistance and Professional and Technical Services.

Impacts are evaluated based on:

- Reduced hours of work and lost wages on high heat days for high-risk workers (following Neidell et al. 2021) and increased risk of injury (from Park et al. 2021)[132];
- Reduced productivity due to illness from childhood asthma and Lyme disease (following analyses presented in the Health sector); and
- Reduced productivity due to delays during road and rail disruptions (following analyses presented in the Infrastructure sector).

> *"If people can't go to work, they can't receive wages necessary to purchase life goods"*
>
> *"As [a] farmer, my ability to work in the field (heat/storms) and economic sustainability are at risk"*
>
> *"Winter storm severity, coastal storm, hurricanes and other damaging storms slow everything down and make it hard to work"*
>
> - Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

This impact is categorized as an **extreme** level of consequence due to the various ways climate change could reduce people's ability to work and earn wages and affect economic productivity of the workforce.

High-risk workers (in agriculture, fishing, construction, manufacturing, transportation and warehousing, and utilities), tend to work fewer hours on high heat days, particularly on days over 90 degrees. Table 35 presents the results of a 2021 study of lost hours and wages for high-risk workers (analyzed by county based on number of high-risk workers and projected number of days over 90 degrees). Most regions stand to lose more than the equivalent of 1,000 full-time employees each year by 2090 due to reduced hours during high heat events. Statewide, those lost hours represent over $775 million in lost earnings for high-risk workers. Although this analysis focuses primarily on workers in outdoor settings, workers in indoor work environments lacking cooling systems (e.g., restaurant kitchens) can also experience unsafe conditions during high-heat events. Current Massachusetts laws set minimum heating guidelines for workplaces, but no such regulation is in place for maximum temperatures.[133]

[132]Park, J. and Pankratz, N.M. C. and Behrer, A., Temperature, Workplace Safety, and Labor Market Inequality. IZA Discussion Paper No. 14560, Available at SSRN: https://ssrn.com/abstract=3892588 or http://dx.doi.org/10.2139/ssrn.3892588

[133] https://www.mass.gov/doc/minimum-workplace-heating-guidelines/download

Table 35. Annual Lost Hours and Wages

Annual lost hours per high-risk worker and lost full-time employee equivalents by region, where full-time employees are assumed to work 2,080 hours per year. Future impacts presented for four time periods identified in the table by their central year: 2030 (near-term, 2020-2039); 2050 (mid-century, 2040-2059); 2070 (mid-late century, 2060-2079); and 2090 (end of century, 2080-2099). Total may not sum due to rounding.

	Lost Hours per High-Risk Worker				Lost Full Time Employee Equivalents			
Region	**2030**	**2050**	**2070**	**2090**	**2030**	**2050**	**2070**	**2090**
Berkshires & Hilltowns	4	12	33	58	15	40	110	200
Greater Connecticut River Valley	12	28	70	114	150	340	840	1,370
Central	13	31	78	128	180	440	1,000	1,700
Eastern Inland	15	34	80	127	390	910	2,140	3,400
Boston Harbor	15	35	79	123	250	570	1,300	2,020
North & South Shores	12	28	67	108	120	270	640	1,040
Cape, Islands, & South Coast	4	12	33	54	50	140	380	620
Statewide	12	29	69	111	**1,140**	**2,680**	**6,430**	**10,330**
Lost Wages ($millions)					**$39**	**$123**	**$382**	**$778**

Source: Adapted from Neidell et al. 2021[134]

Workers who continue to work in high heat conditions experience higher levels of injury directly from heat stress and from other accidents, likely due to cognitive performance in the heat.[135] Additional temporary labor losses could result from increased extreme weather closures of business and schools (requiring caregivers to be present at home).

Other climate induced health outcomes (discussed in greater detail in the Human sector) also have impacts on productivity and people's ability to work:

- Incremental Lyme disease incidence is projected to result in $29 million productivity losses and indirect costs and nonmedical costs (productivity losses are not reported separately) per year in 2050, more than double current losses, and $82 million per year by 2090.[136]
- Total loss in lifetime productivity from children diagnosed with asthma attributable to climate change is projected to reach $25 million per year. New cases diagnosed in 2090 are associated with $93 million of lost lifetime productivity.[137]

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[134] Neidell, M., Graff Zivin, J., Sheahan, M., Willwerth, J., Fant, C., Sarofim, M. and Martinich, J., 2021. Temperature and work: Time allocated to work under varying climate and labor market conditions. PloS one, 16(8), p.e0254224.

[135] Park, J., Pankratz, N. and Behrer, A., 2021. Temperature, workplace safety, and labor market inequality.

[136] Based on an analysis of data from Couper, L.I., MacDonald, A.J., and Mordecai, E.A. 2020. Impact of prior and projected climate change on U.S. Lyme disease incidence. Global Change Biology, 27(4), 738-754 and Zhang, X., Meltzer, M. I., Peña, C. A., Hopkins, A. B., Wroth, L., and Fix, A. D. 2006. Economic impact of Lyme disease. Emerging infectious diseases, 12(4), 653.

[137] Based on an analysis of data from Fann, N., C. Nolte, M. Sarofim, J. Martinich, and N. Nisokolas (2021). Associations between simulated future changes in climate, air quality, and human health. *JAMA Network Open*, doi:10.1001/jamanetworkopen.2020.32064

Finally, climate disruptions to transportation systems[138] (discussed in greater detail in the Infrastructure sector) would make it more difficult for people to get to work, particularly those workers who do not have the option to work from home.

- Road delays due to high tide flooding could result in over 4 million vehicle hours of delay by 2030 and 40 million vehicle hours of delay by 2050. While not all vehicle trips are work commutes, this could still represent a significant increase in commuting times, either resulting in lost wages and productivity, or loss of leisure time.
- Road delays due to other climate stressors (e.g., freeze-thaw cycles and precipitation), valued at the wage rate, are expected to decrease in the near term but increase to over $9 million in 2050 and nearly $30 million in 2090.
- Rail delays, both rapid transit and commuter rail, could significantly hamper people's ability to get to work in a timely fashion. Infrastructure damage and closures could cause more long-term employment issues, particularly for people with limited alternative transportation options. A 2018 study of MBTA passengers found that about 70 percent of rapid transit and bus trips and 90 percent of commuter rail and ferry trips were commutes between home and work. 30 percent of rapid transit users and five percent of commuter rail and ferry users did not have a useable household vehicle, leaving limited alternatives during shutdowns.[139]

Reduced work hours impact individuals earned income as well as overall economic production (e.g., GDP output) in the Commonwealth.

Disproportionality

This impact has a **disproportionate** exposure because minority workers are overrepresented in high-risk industries and high-risk workers in EJ block groups identified on the basis of minority population and minority and income status experience slightly more losses per worker than other block groups in the Commonwealth. Further, individuals with limited income would be disproportionately affected by marginal changes in earned wages.

According to U.S. Equal Employment Opportunity Commission (EEOC) data compiled by the University of Massachusetts Amherst Center for Employment Equity, in Massachusetts non-Asian minority workers make up an outsized share of the "laborer" category of employment, which includes physical work in construction, carpentry, agriculture, and landscaping—all of which are at risk of extreme heat exposure. The share of non-Asian minority workers in the

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[138] Neumann, J.E., Chinowsky, P., Helman, J., Black, M., Fant, C., Strzepek, K., and Martinich, J. (2021) Climate effects on US infrastructure: the economics of adaptation for rail, roads, and coastal development. Climatic Change 167, 44 (2021). https://doi.org/10.1007/s10584-021-03179-w; Chinowsky P, Price J, Neumann J (2013) Assessment of climate change adaptation costs for the U.S. road network. Glob Environ Chang 23(4):764–773, http://www.sciencedirect.com/science/article/pii/S0959378013000514; and Neumann, J.E., J. Price, P. Chinowsky, L. Wright, L. Ludwig, R. Streeter, R. Jones, J.B. Smith, W. Perkins, L. Jantarasami, and J. Martinich, 2014: Climate change risks to US infrastructure: impacts on roads, bridges, coastal development, and urban drainage. *Climatic Change,* 131, 97-109.

[139] Central Transportation Planning Staff. 2018. MBTA 2015-17 Systemwide Passenger Survey. Directed by the Boston Region Metropolitan Planning Organization. Available at: https://www.ctps.org/dv/mbtasurvey2018/2015_2017_Passenger_Survey_Final_Report.pdf

laborer occupation group is 160 percent of the same group's representation in the Massachusetts workforce.[140]

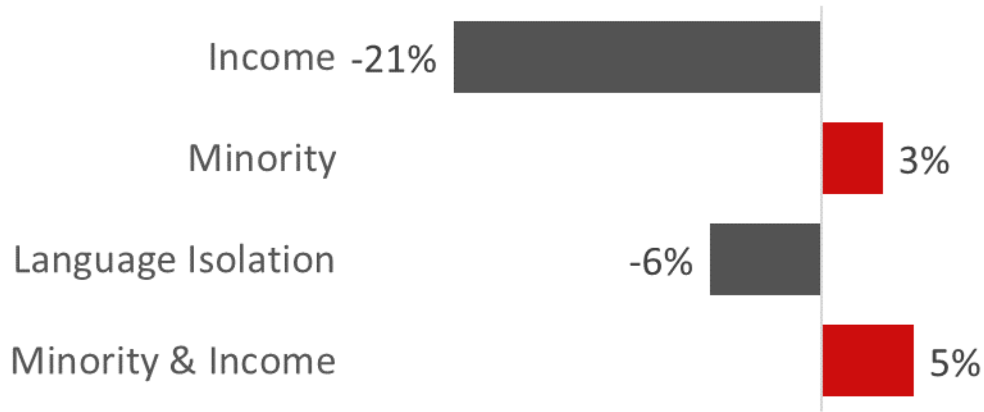
When comparing lost labor hours due to high heat per high-risk worker (i.e., controlling for the number of high-risk laborers per block group), high-risk workers living in EJ block groups defined on the basis of:

- minority population have three percent more lost work hours compared to the rest of the Commonwealth, and
- minority population and income have five percent more lost work hours compared to the rest of the Commonwealth.

This shows some disproportionate exposure, but at lower levels discrepancies relative to some of the more disproportionate impacts in the Climate Assessment. A 2021 EPA report covering this issue nationwide found that disproportionality in labor hours lost due to extreme heat is lower in the Northeast compared to other regions.[141]

Figure 34. Disproportionality of Lost Labor Hours due to Extreme Heat

Comparison of lost work hours for high-risk workers due to heat by income, minority status, language isolation and minority status and income combined, compared to all other block groups in the state. Positive numbers and red bars represent disproportionate exposure for the listed population segment. See Section 2.1 for further description of the EJ block group definitions.



Disproportionate impacts from transportation delays and closures are supported by the literature. During disruptions, some workers may be able to avoid delays by working from home but not all workers have that option available. In May 2020, following the initial COVID-19 breakout, nearly 40 percent of white workers telecommuted from home, compared to 25 percent of Black workers and 23 percent of Hispanic workers. While 46 percent of workers from

[140] Center for Employment Equity. Diversity Analytics: Compare Within State. University of Massachusetts Amherst. Available at https://www.umass.edu/employmentequity/diversity-analytics/visualization/Compare%20within%20State.

[141] EPA. 2021. Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. U.S. Environmental Protection Agency, EPA 430-R-21-003.

high-income households worked from home, only 31 percent of middle-income earners and 18 percent of low-income earners did the same.[142,143]

Adaptation

There is a **moderate** adaptation gap to addressing the hazards that threaten workforce resilience. Workers' ability to work will benefit from the many actions being taken to combat extreme heat and inland and coastal flooding, especially on roadways and in cities (see discussion of general extreme heat adaptation measures in the Human sector discussion earlier in this chapter). That said, few actions were found that focus directly on improving conditions for workers as climate change makes their jobs more difficult. Boston and Medford are two exceptions as climate plans in these cities seek to develop guidelines for outdoor workers in extreme heat conditions. The region plans to build new community telecommuting centers to improve worker resilience. Additional potential actions include updates to worker safety regulations to mandate intermittent breaks and provide shade and water on high heat days (see, for example, the California Heat Illness Prevention in Outdoor Places of Employment standard).

Example Adaptation Plans with Actions Addressing this Impact

- Equity Centered Process for Climate Action and Adaptation Planning – Medford – See plan to develop guidelines for outdoor workers in extreme heat conditions
- Pioneer Valley Climate Action and Clean Energy Plan – Identifies possibly building telecommuting centers which would build resiliency again travel delays

Sensitivities and Uncertainty

Sensitivities and uncertainties around this impact include limited ability to quantify indirect labor effects of climate change and labor effects of larger shifts in industries (e.g., moves away from winter recreation to other industries). When evaluating disproportionality, the analysis relies on where workers live, not where workers are employed, where each location may experience different climate conditions.

Related Impacts

Table 36 lists the impacts in other sectors that have a connection to this impact.

[142] Income bins defined by household income: High-income (> $100k); middle-income ($50-100k); low-income (<$50k).

[143] Bick, A., Blandin, A. and Mertens, K., 2020. Work from home after the COVID-19 Outbreak. Federal Reserve Bank of Dallas Working Paper #2017. https://doi.org/10.24149/wp2017.

Table 36. Additional Impacts related to Reduced Ability to Work

Sector	Impact	Connection
Human	Health and Cognitive Effects from Extreme Heat	Physical and mental stresses stemming from extreme heat affect workers and non-workers.
Human	Health Effects from Degraded Air Quality	Increase in childhood asthma rates leads to decreased lifetime productivity (captured in the Reduced Ability to Work impact).
Human	Increase in Vector Borne Disease Incidence and Bacterial Infections	Increase in Lyme disease cases leads to decreased lifetime productivity (captured in the Reduced Ability to Work impact).
Infrastructure	Damage to Roads and Loss of Road Service	Disruptions and delays on commuting routes lead to loss of work and productivity.
Infrastructure	Damage to Rails and Loss of Rail/Transit Service	Disruptions and delays on commuting routes lead to loss of work and productivity.
Economy	All impacts	Disruptions and downturns in economic activity (particularly tourism) lead to reduced hours and wages.

Economy Sector: Urgent Impact #2 (tie)

Decrease in Marine Fisheries and Aquaculture Productivity

Changes in water temperature regimes and acidification in the marine environment change fish habitat and alter commercial landings and revenue, including effects on related industries.

Major Level of Consequence	Disproportionate Exposure	Moderate Adaptation Gap
• Changing species distributions may result in a decrease in marine industry revenue of nearly $70 million per year by 2090.	• Populations with low incomes live in areas with 203 percent higher projected impacts to marine fishery landings compared to the rest of the coast.	• Little action has taken place to date to address the climate-related damages caused to marine fisheries and aquaculture despite the industries being major contributors to many coastal economies.

Impact Summary

Rising ocean temperatures associated with climate change have been associated with decreased commercial harvests because of geographic shifts in species distributions poleward, altered seasonality of the fishing season, and changes to stock productivity, especially at middle and lower latitudes. Changes in catch composition toward lower-value species may lead to significant revenue loss among marine fisheries in Massachusetts. Climate change impacts will create more economic pressure on coastal towns and communities that rely on the marine fisheries industry and associated revenue. A healthy marine ecosystem is critical to support commercial fishing and the "blue economy", or all sustainable economic activities related to the ocean and shore. New Bedford was the top port in the U.S. by value of seafood landed in 2020, driven by landings of sea scallops, lobsters, and other high value commercial species.[144] With annual landings of approximately $650 million, marine fisheries are a significant driver of the economy in coastal regions of the state. A substantial portion of the total annual value of landings is accounted for by aquaculture, although there is not yet a comprehensive estimate of the total value of aquaculture landings. The value of landings for eastern oyster alone, however, a large portion of which is aquaculture, was more than $25 million in 2018.[145]

Urgency Ranking Results

This impact is ranked as a **high priority** because of its large and disproportionate impacts. This impact is evaluated by estimating changes in thermally available habitat for economically

[144] National Marine Fisheries Service. 2022. Fisheries of the United States, 2020. U.S. Department of Commerce, NOAA Current Fishery Statistics No. 2020. Available at: https://www.fisheries.noaa.gov/national/sustainable-fisheries/fisheries-united-states

[145] Massachusetts Division of Marine Fisheries, Urban Harbors Institute at the University of Massachusetts Boston, and the Cape Cod Commercial Fishermen's Alliance for the Massachusetts Division of Marine Fisheries. Port by Port: Profiles and Analysis of the Massachusetts Commercial Fishery. https://www.mass.gov/doc/port-by-port-profiles-and-analysis-of-the-massachusetts-commercial-fishery/download

important commercial fish species and connecting changes in fish species population with projected landings, valued using economic damage estimates from a previous study.[146,147] State-level impacts were allocated to Massachusetts towns using current distribution of ex-vessel value by town.[148]

> *"Cape Ann's fishing industry has been struggling for years and climate change is exacerbating an already challenging situation."*
>
> *"I have a part-time job as a fry cook in a local seafood restaurant and these impacts have made a huge impact on the restaurant. Different seafood has become harder to find and therefore costs a lot more to get."*
>
> \- Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The consequences of climate change on marine fisheries landings are projected to be **major** due to substantial loss of fishery revenue associated with species migration in response to changing ocean temperatures.[149] In 2018, landings totaled $650 million in Massachusetts.[150] These are projected to decrease by nearly $70 million by the end of the century because of climate change.

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[146] Morley, J.W., Selden, R.L., Latour, R.J., Frolicher, T.L., Seagraves, R.J., and Pinsky, M.L. 2018. Projecting shifts in thermal habitat for 686 species on the North American continental shelf. PLoS ONE, 13(5), e0196127

[147] Moore, C., Morley, J.W., Morrison, B., Kolian, M., Horsch, E., Frolicher, T., Pinsky, M.L., and Griffis, R. 2021. Estimating the Economic Impacts of Climate Change on 16 Major US Fisheries. Climate Change Economics, 12(1), 2150002.

[148] Massachusetts Division of Marine Fisheries, Urban Harbors Institute at the University of Massachusetts Boston, and the Cape Cod Commercial Fishermen's Alliance for the Massachusetts Division of Marine Fisheries. Port by Port: Profiles and Analysis of the Massachusetts Commercial Fishery. https://www.mass.gov/doc/port-by-port-profiles-and-analysis-of-the-massachusetts-commercial-fishery/download

[149] This impact, within the Economy sector, focuses on the revenues and economic activity associated with marine fisheries and aquaculture productivity. Effects on food supply and cultural value of seafood are captured in the Human sector.

[150] Port by Port Report. Moore et al. estimated a baseline of $390 million based on a partial list of ports in the state, therefore this analysis uses the baseline value from the more comprehensive and Massachusetts-focused Port by Port Report.

Table 37. Economic Impact of Climate Change on Marine Fisheries

Decrease in landings due to climate change. Future impacts presented for four time periods identified in the table by their central year: 2030 (near-term, 2020-2039); 2050 (mid-century, 2040-2059); 2070 (mid-late century, 2060-2079); and 2090 (end of century, 2080-2099). Values may not sum due to rounding.

	Decrease in landings ($millions)			
Region	**2030**	**2050**	**2070**	**2090**
Boston Harbor	$0.5	$0.5	$1.1	$2.0
North & South Shores	$2.6	$2.8	$5.7	$10.8
Cape, Islands, & South Coast	$13.1	$14.3	$29.2	$55.5
Statewide	**$16.2**	**$17.7**	**$35.9**	**$68.4**

Note: There are no losses in the Berkshire & Hilltowns, Greater Connecticut River Valley, Central, or Eastern Inland regions.

Source: Project Team analysis based on Morley et al. (2018) and Moore et al. (2021)

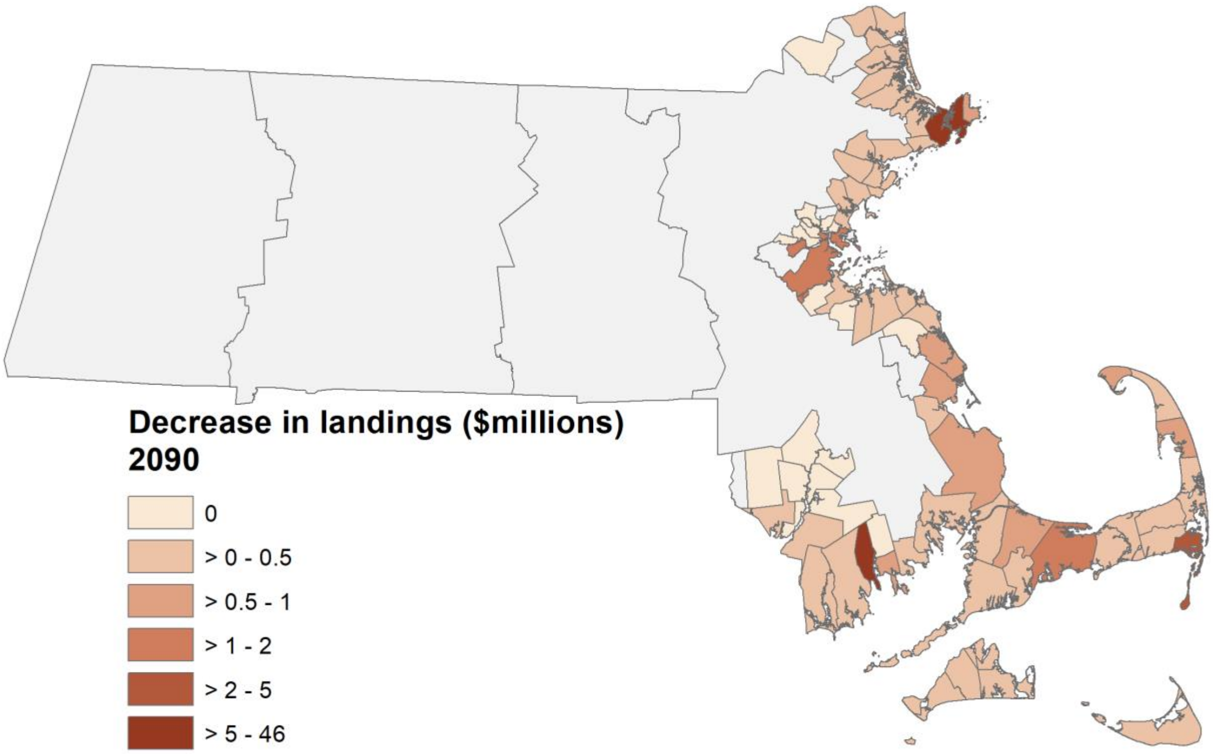
Direct impacts of marine fisheries productivity declines (measured as revenues from landings) are exclusive to the coastal regions of the state, with approximately 80 percent of impacts falling in the Cape, Islands, and South Coast region. This spatial distribution of impacts reflects the predominance of the New Bedford port, which accounts for two thirds of the total ex-vessel value in Massachusetts in 2018 – and is also the single largest port in the U.S., ranked by value of ex-vessel landings. Impacts to economic activity associated with marine fisheries landings may be experienced beyond coastal communities: a 2019 study estimates commercial fishing and seafood processing activities in New Bedford/Fairhaven Harbor support $11 billion in total economic activity in Massachusetts, or about two percent of the total gross domestic production (GDP) of the Commonwealth.[151, 152]

Figure 35 shows the distribution of impacts among coastal towns in Massachusetts. The largest impacts are concentrated in New Bedford, Gloucester, and Chatham ($46 million, $5.6 million, and $2.0 million in 2090, respectively). Impacts in Boston and Barnstable are also of comparable magnitude to Chatham.

[151] Martin Associates and Foth-CLE Engineering Group. 2019. Economic Impact Study of the New Bedford/Fairhaven Harbor. Prepared for the New Bedford Port Authority. March 2019.
[152] U.S. Bureau of Economic Analysis, Gross Domestic Product: All Industry Total in Massachusetts [MANGSP], retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/MANGSP, September 24, 2022.

Figure 35. Projected Decrease in Landings ($millions) in 2090

Results shown by coastal city/town, with largest impacts seen in New Bedford, Gloucester, Chatham, Boston, and Barnstable.



Source: Project Team analysis based on Morley et al. (2018) and Moore et al. (2021)

A related impact of climate change is associated with the impact of higher marine water temperatures on the abundance of *Vibrio* species and other pathogens which can infect shellfish and particularly, shellfish typically served raw such as oysters. As described in more detail in the Increase in Vector Borne Diseases Incidence and Bacterial Infections impact in the Human sector, the risk of bacterial infection of raw seafood is elevated as a result of climate change, and may require additional measures for the seafood industry to ensure food safety, potentially raising costs of production for this industry.

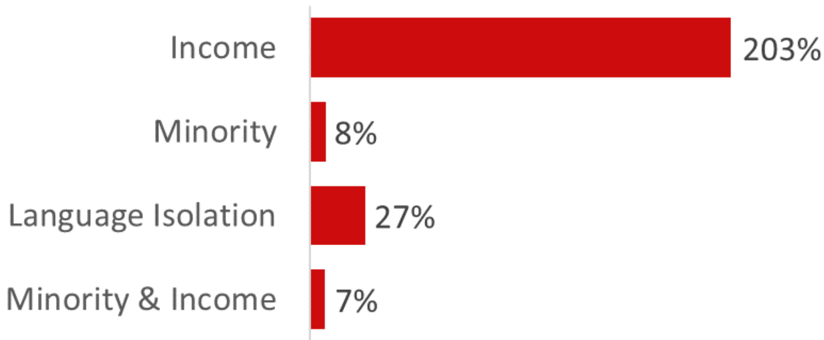
Disproportionality

Exposure to this impact is highly **disproportionate**. Populations living in EJ block groups defined on the basis of:

- low-income experience 203 percent higher impacts to marine fishery landings compared to the rest of the coast;
- language isolation experience 27 percent higher impacts to marine fishery landings compared to the rest of the coast.

Figure 36. Disproportionality of Marine Fisheries Impacts

Comparison of the decrease in landings in EJ block groups defined by income, minority status, language isolation and minority status and income combined, compared to all other coastal block groups in the state. Positive numbers and red bars represent disproportionate exposure for the listed population segment. See Section 2.1 for further description of the EJ block group definitions.



The extreme disproportionality seen among all subgroups of interest but mostly individuals with low income can be attributed largely to the prevalence of the New Bedford port, which is located in a town with high percentages of households with incomes below the state median. A total of 64 percent of block groups in New Bedford are designated as EJ due to the proportion of households with low income, while only 22 percent of the block groups across the state are designated as low-income. It is also important to acknowledge that the disproportionality analysis is based on alignment of the port of marine fisheries landings and the location of EJ block groups, rather than the home location of those employed directly in the occupations of marine fishing, processing of landings, or ancillary/related business activity (e.g., wholesale and retail trade of seafood). New Bedford in particular is such a significant Atlantic port that many of the boats landing seafood there are from outside of Massachusetts. A precise match of the prospective impacts of climate change with the home locations of those affected is unfortunately beyond the scope of this work – however the significance of the marine fishing industry and related business activity in New Bedford (and to a lesser extent in Gloucester and smaller Massachusetts port cities), combined with the high density in the city of EJ block groups, provides support for the result of disproportionate impacts to the residents of EJ block groups.

Adaptation

The adaptation gap to address the projected climate-related damages to marine fisheries and aquaculture productivity is **moderate**. Despite fisheries, and increasingly aquaculture, being major economic producers in Massachusetts many coastal communities, few available plans address marine fisheries and aquaculture specifically, and those that do tend to be studies aiming to assess the situation (e.g., the 2021 "Report on the Ocean Acidification Crisis in Massachusetts", Department of Marine Fisheries Habitat Program's climate change strategy).[153]

[153] Massachusetts Special Legislative Commission on Ocean Acidification, 2021. Report on the Ocean Acidification Crisis in Massachusetts. Available at: https://www.mass.gov/files/documents/2021/12/15/massachusetts-ocean-acidification-report-feb-2021.pdf

Research on the effects of acidification and temperature regime shifts on key species will continue to be important, but focused action is also needed. Updating pollution regulations to mitigate nutrient runoff and eutrophication can help to protect the coastal and marine ecosystems that support fisheries and aquaculture. Strengthening and expanding local and regional food systems can bolster the markets that support fisheries. Direct support and outreach to the fishing community is also a potential solution, for example, providing education and resources about adapting practices to pivot and accommodate new species as they move northward (i.e., updating permitting regulations and the subsidizing the cost of re-rigging a boat for catching a different species).

Example Adaptation Plan with Actions Addressing this Impact

- MAPC's 2014 Metro Boston Regional Climate Change Adaptation Strategy Report includes actions such as researching techniques for maintaining viability of at-risk fishing and aquaculture industries and researching impacts to aquaculture and fishing industry.

Sensitivities and Uncertainty

Impacts for the Northeast region of the U.S. were allocated to the state-level based on the proportion of damages occurring in Massachusetts during the baseline period. This analysis assumes the proportion of damages across states within the Northeast region remains constant throughout the century.

The studies underlying this analysis exclude factors that may influence species abundance and commercial landings, including potential changes in primary productivity, species interactions, population dynamics, and fisheries management. They also do not account for the development of new fisheries in response to increased abundance of different species, which would offset economic losses.

Related Impacts

Table 38 lists the impacts in other sectors that have a connection to this impact.

Table 38. Additional Impacts related to Decrease in Marine Fisheries and Aquaculture Productivity

Sector	Impact	Connection
Infrastructure	Damage to Coastal Buildings and Ports	Damage to port infrastructure may impact the ability to land and process marine catches – smaller scale docks and marinas are also directly threatened by sea level rise.
Natural Environment	Marine Ecosystem Degradation	Marine fisheries production is closely tied with general marine ecosystem health.
Economy	Economic Losses from Commercial Structure Damage and Business Interruptions	Processing facilities located in the coastal zone are at risk of coastal storm damage,

Sector	Impact	Connection
		which can inhibit the ability to get catches to market.
Economy	Reduced Ability to Work	Individuals working in the fishing industry may be exposed to extreme weather conditions and face job losses due to decreases in productivity.
Human	Increase in Vector Borne Diseases Incidence and Bacterial Infections	Actions necessary to reduce the risk of vibriosis associated with higher concentrations of certain marine bacteria which cause health effects and present elevated risk under climate change, can raise the costs of production for shellfish aquaculture in particular.
Human	Damage to Cultural Resources	Local seafood (e.g., lobsters, oysters, cod) is a part of the Commonwealth's identity.

Economy Sector: Urgent Impact #2 (tie)

Reduction in the Availability of Affordably Priced Housing

An increase in demand for affordably priced housing and a decrease in supply worsens the scarcity of housing that is affordable, further exacerbating the known inequities in access to affordably priced and healthy housing. Demand for affordably priced housing can result if people are forced to relocate either due to direct damage to existing housing or because of climate-related economic pressures. The supply of affordably priced housing is reduced due to direct physical damage from climate impacts and potentially higher construction costs to increase resilience to threats from climate change.

Major Level of Consequence	Disproportionate Exposure	Moderate Adaptation Gap
• Direct impacts on specific structures are difficult to identify, but among block groups up to 25th percentile for residential structure value, in 2030 up to 6,500 households could experience 0.5 percent or more of expected annual damage to structures from flooding, increasing to 36,000 by 2090.	• Impacts are focused on low-income populations living primarily in housing with the lowest value in the state.	• Actions and plans are underway outside of climate planning processes to address housing affordability but more work is needed, particularly to address the specific risks of climate change on subsidized affordable housing.

Impact Summary

Climate change could affect the availability of affordably priced housing in multiple ways, including through coastal and inland flood risks which can directly or indirectly affect both publicly owned housing and the market for housing that is affordable. An increase in demand for high-quality housing and a decrease in supply worsens the scarcity of affordably priced housing. Increasing demand for affordably priced housing can result if people are forced to relocate either due to direct damage to existing housing or because of climate-related economic pressures ("Climate Gentrification"). The supply of affordably priced housing is reduced due to direct physical damage from climate impacts and potentially higher construction costs for all housing to improve resiliency to threats from climate. Both demand and supply effects raise rental and ownership prices, which can effectively limit options for affordably priced housing.

Urgency Ranking Results

This impact is ranked as a **high priority** because of its large and disproportionate impacts.

This impact is evaluated by assessing coastal and inland flood risk to structures which may contribute to the supply of affordably priced housing in the state, to the extent these properties can be identified for this purpose. Coastal flooding has been identified as a potentially major risk factor for the availability of subsidized and income restricted affordable housing at the national level, and Massachusetts is ranked second in the nation by a recent study in the percentage of Federally subsidized affordable housing units vulnerable to coastal flood risk, with a concentration of units affected by 2050 in Boston (3,189 units exposed per year); Quincy (668 units); Cambridge (510 units); and Revere (266 units). These four cities are ranked in the top 20 cities nationally for this metric – Boston is third in the nation in expected number of exposed subsidized affordable housing units, trailing only New York (4,774 units) and Atlantic City, NJ (3,167 units).[154]

This Climate Assessment identifies impacts to affordably priced housing in two steps. First, state-owned affordable housing that is income restricted which might be at risk from coastal or inland flooding is identified using the DCAMM state owned property database and coastal and inland flooding projections. This method is described in greater detail in the Governance sector. Damage to Inland and Coastal State and Municipal Buildings and Land impacts, as well as the Infrastructure sector, Damage to Inland and Coastal Buildings and Ports impacts.

The analysis finds no state-owned public housing at high risk of flood damage. However, publicly owned housing is only one part of the overall supply of affordably priced housing units. The other two components are subsidized housing (assessed in the study summarized above, for coastal risks) and relatively less expensive private market rate housing, in more affordable communities (there may be significant overlap within these two categories).

Unfortunately, it is infeasible to comprehensively identify the most affordable housing units in the state at the building level, within the limits of currently available data. Instead, the analysis is run at the block group level. For the second step of the analysis, all block groups within the lowest 25 percent (25th percentile) for median per household structure value are identified and the projected annual expected flood damage (from both coastal and inland sources) for all structures throughout the Commonwealth within these block groups is calculated.[155] This is the primary metric used to assess the magnitude of consequence and potential for disproportionate exposure.

> *"I do not own a house and am at the mercy of the market."*
>
> *"The impact on housing as people are forced to relocate will be substantial, particularly in a region already struggling with housing stock."*
>
> *"To provide housing for all, we need to change our vision, attitudes, and expectation of what housing looks like."*
>
> - Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The consequences of flood risk on affordably priced housing are projected to be **major** due to widespread and substantial increases in flood risks to housing in block groups in the 25th percentile for median per household structure value. Table 39 below provides a summary of

[154] Buchanan, M.K., Kulp, S., Cushing, L., Morello-Frosch, R., Nedwick, T. and Strauss, B., 2020. Sea level rise and coastal flooding threaten affordable housing. Environmental Research Letters, 15(12), p.124020.

[155] The range of per household structure value in these block groups is $87,900 at the minimum (in a block group in Berkshire country) to $289,100 at the 25th percentile (in a block group in Worcester County).

results for flood risk to lower structure value per household block groups in the Commonwealth. The results show an increase in impacts from $44 million to $150 million statewide, from 2030 to 2090.

Table 39. Estimated Impact of Flooding in Block Groups at 25th Percentile for Median Per Household Structure Value

Current total residential structure value for properties in the 25th percentile of block groups for median household structure value, and estimated impact of climate change on expected annual damages from inland and coastal flooding. Future impacts presented for four time periods identified in the table by their central year: 2030 (near-term, 2020-2039); 2050 (mid-century, 2040-2059); 2070 (mid-late century, 2060-2079); and 2090 (end of century, 2080-2099). All results in millions of 2020 dollars. Totals may not sum due to rounding. Negative values represent reductions in projected residential flood risk relative to current damage ratios.

Region	Current total residential structure value ($millions)	Annual Total Expected Damages from Inland and Coastal Flood Risk			
		2030	2050	2070	2090
Berkshires & Hilltowns	$11,000	$5	$4	$7	$10
Greater Connecticut River Valley	$48,000	$13	$10	$17	$29
Central	$31,000	-$0.8	$0.1	-$0.2	-$0.4
Eastern Inland	$22,000	$3	$14	$19	$25
Boston Harbor	$1,000	$0.4	$0.8	$2	$3
North & South Shores	$3,600	$7	$14	$19	$25
Cape, Islands, & South Coast	$23,000	$16	$25	$40	$54
Statewide	**$140,000**	**$44**	**$68**	**$100**	**$150**

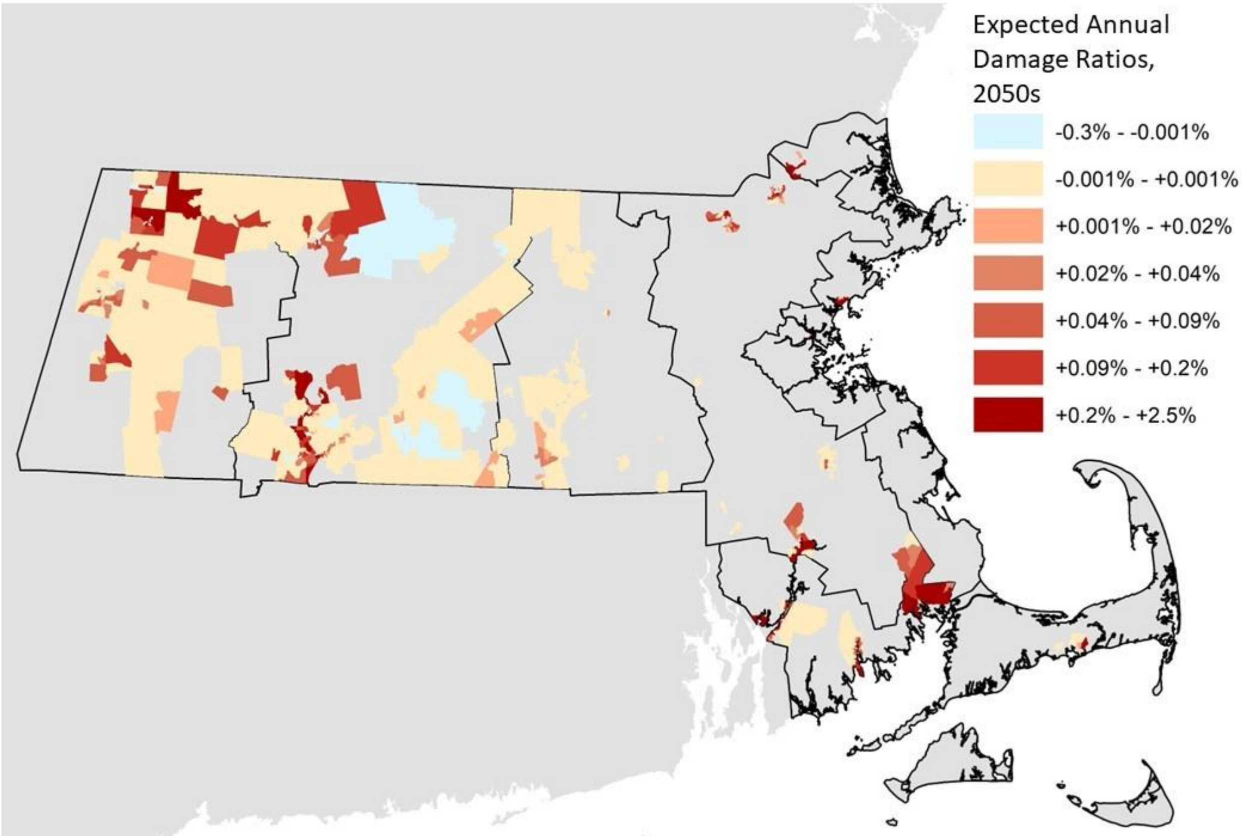
Source: ACS property and structure value; U.S. EPA data at www.epa.gov/CIRA; and Project Team Analysis

The spatial distribution of the results shows damages are largest in the Cape and Islands/South Coast, Connecticut River Valley, and Eastern Inland regions. As a percentage of the total current residential structure value in these regions, however, the largest effects are on the Cape and Islands/South Coast region (see Figure 37 and accompanying text, the greatest impacts are in the South Coast portion of this region) and can be attributed to coastal flooding risks. Large impacts in the Greater Connecticut River Valley and Eastern Inland regions are associated with increase in inland flood risks. In the Central region, where inland floods are the only source of flood risk, a projected decrease in river flows in the 2030, 2070, and 2090 time periods in the relevant 25th percentile structure value block groups could result in a slight decrease in expected damages.

Figure 37 shows a map of all the 25th percentile block groups and their expected annual damage ratios (damages as a percentage of total structure value) in the 2050s time period. Although it appears there are few block groups of interest in the Cape, Islands, and South Coast region, the relevant 25th percentile block groups are small and densely populated and concentrated in the South Coast portion that includes Fall River and New Bedford. Other concentrations of interest in Figure 37 are in the Connecticut River Valley, particularly the Springfield area but also near the Vermont border, and in mostly northern portions of the Berkshire and Hilltowns region.

Figure 37. Expected Annual Damage Ratios in 2050s Relative to Current Ratios

Map shows block groups falling within the 25th percentile of expected annual damage rations in 2050s. Negative values represent reductions in projected residential flood risk relative to current damage ratios.



Source: U.S. EPA data at www.epa.gov/CIRA and Project Team analysis

The Massachusetts specific results of the previously summarized coastal risk to Federally subsidized affordable housing add a second dimension to the magnitude of consequence assessment, which reflects high risk to another type of affordably priced housing, focused on building-scale pockets of coastal flood risk vulnerability in the generally higher structure value block groups in the Boston, Cambridge, Quincy, and Revere areas of the Boston Harbor region. That analysis finds that those four cities are among the 20 cities nationally with the greatest number of subsidized housing units vulnerable to coastal flood risks.

Finally, there are dimensions of indirect risk concern that amplify the findings from these other, more direct damage implications of flood risks to affordably priced housing. Some analysts argue that efforts to insure properties against coastal hazards, and that aim to keep the National Flood Insurance Program solvent by moving away from subsidized premiums, could harm low- and middle-income populations through premium rate increases.[156] The complexities of balancing amenity and risk in the coastal zone have motivated an emerging literature on "climate gentrification," a process which leads to displacement of low-income populations as

[156] Shively D. 2017. Flood risk management in the USA: implications of the national flood insurance program changes for social justice. Reg. Environ. Chang. 17:1663–1672. https://doi.org/10.1007/s10113-017-1127-3

wealthier residents seek higher ground and safety from coastal hazards;[157] new conceptual models of housing location decisions that suggest low-income and minority populations will be pushed into higher hazard areas of the coastal zone.[158] The combination of direct and indirect risks of climate change on affordably priced housing support the finding of a major magnitude of consequence.

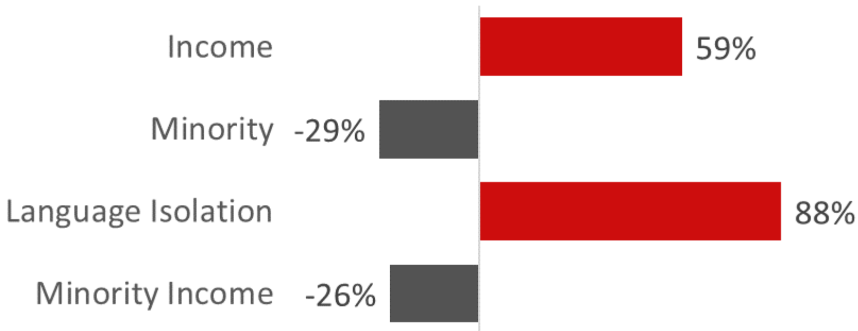
Disproportionality

Exposure to this impact is highly **disproportionate**. Populations living in EJ block groups defined on the basis of:

- low-income status have 59 percent higher flood impacts to the most affordably priced housing than the rest of the Commonwealth
- language isolated populations have 88 percent higher flood impacts to the most affordably priced housing than the rest of the Commonwealth

Figure 38. Disproportionality of Climate Impacts on Affordably Priced Housing

Comparison of flood impacts to the most affordable housing in EJ block groups defined by income, minority status, language isolation and minority status and income combined, compared to all other block groups in the state. Positive numbers and red bars represent disproportionate exposure for the listed population segment. See Section 2.1 for further description of the EJ block group definitions.



In concept, one would expect that impacts on affordably priced housing, particularly subsidized affordable housing, would have the largest impacts on low-income populations, so these results are not surprising. Figure 38 shows disproportionality results for the 2070s time period, but higher rates of disproportionality are seen more immediately, in the 2030s time period. For example, in the 2030s, only 12 block groups state-wide have an annual damage ratio (damages per unit of total structure value) of 0.5 percent or higher – but 58 percent of these block groups are EJ block groups, and 48 percent of the 106 block groups projected to see a 0.1 percent annual damage ratio are EJ block groups. In other words, it is expected that the most

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[157] Anguelovski I, Connolly JJT, Pearsall H, Shokry G, Checker M, Maantay J, Gould K, Lewis T, Maroko A, and Roberts JT. 2019. Why green "climate gentrification" threatens poor and vulnerable populations. PNAS 116(52): 26139–26143. https://www.pnas.org/cgi/doi/10.1073/pnas.1920490117

[158] Bakkensen L and Ma L. 2020. Sorting over flood risk and implications for policy reform. Journal of Environmental Economics and Management, 104:102362. https://doi.org/10.1016/j.jeem.2020.102362

immediate impacts in terms of more intense flooding will be first experienced in many EJ block groups.

This quantitative analysis cannot forecast indirect impacts such as climate gentrification effects, but that literature universally acknowledges that the complex market effects of climate gentrification effects fall disproportionally on low-income populations as well, who are least able to afford the higher housing and rental prices that climate gentrification causes.

Adaptation

There is a **moderate** adaptation gap to addressing the climate hazards that reduce the availability of high-quality housing that is affordable. Protecting the most affordable housing is not a primary focus in the plans reviewed, but this issue has received significant attention outside of the climate sphere. Actions identified include designing and retrofitting existing buildings to expand the availability of income restricted and subsidized affordable housing, addressing political barriers to multi-family/mixed-use housing, and training housing authority members and other municipal staff on equity issues. Discussion of income restricted and/or subsidized affordable housing and climate risks appears in plans for some municipalities (e.g., Palmer, Devens, Medford, Somerville, etc.), but most actions are still in the early stages of planning. Few plans address losses of affordably priced housing caused directly by climate-related hazards like flooding, sea level rise, and reduced land availability for new development caused by conservation acquisitions. The two-pronged challenge of retrofitting existing housing that is income restricted or subsidized while also building additional new housing strains already limited municipal and state budgets. Considering the path dependencies built into the systems that impact the availability of affordably priced housing, action should be taken soon.

Example Adaptation Plans with Actions Addressing this Impact

- Comprehensive Master Plan – City of Palmer. The plan expands affordable housing through the Community Preservation Act, provides equity training to housing authority members, and reduces zoning barriers to multi-family/mixed-use housing

Sensitivities and Uncertainty

The metrics used to estimate impacts on affordably priced housing remain incomplete and likely underestimate the full extent of both direct and indirect impacts of climate change, through omission of some types of income restricted housing, complex pathways of impact, or other data and methodology limitations.

In addition, uncertainties that apply for the coastal and inland flood risk estimation processes that this housing affordability impact category draws on also apply here. These include, for example, the concern that increasing degrees of sea level rise and storm surge risks over time are likely to trigger changes in the demographics of the population at risk. For example, the owners of properties that are repeatedly damaged by storm surge may choose to sell. Those who have more limited access to information or the necessary social connections to understand the risks of purchasing near-coast property may move into these areas once the property values drop, changing the demographics of the properties at risk, especially at higher levels of rise. Such demographic changes are not accounted for in the modeling approach used in this analysis. In addition, demographics within the Census block group are not considered because that information is not available. However, there are likely differences in demographics between, for example, shore-front property-owners and property-owners a few streets away from the shoreline. These are not captured in this analysis conducted at block group level resolution.

Related Impacts

Table 40 lists the impacts in other sectors that have a connection to this impact.

Table 40. Additional Impacts related to the Reduction in the Availability of Affordably Priced Housing

Sector	Impact	Connection
Infrastructure	Damage to Inland Buildings; Damage to Coastal Buildings and Ports	Incorporates the same methodologies used here to assess the projected expected annual damage from inland and coastal flood risks to residential structures.
Governance	Damage to Inland State and Municipal Buildings and Land; Damage to Coastal State and Municipal Buildings and Land	Identifies state and municipally owned buildings, which could include state or municipally owned public housing, which may be affected by inland or coastal flood risks associated with climate change.
Governance	Increase in Costs of Responding to Climate Migration	Increase in displacement of residents of affordable housing in response to climate risks could increase the number of climate migrants seeking intrastate or interstate relocation.
Governance	Damage to Coastal/Inland State and Municipal Buildings and Land	Although this analysis does not find that state-owned public housing is significantly affected by coastal and inland flood risk, municipal owned public housing was not comprehensively reviewed, and flood risks may raise costs of maintenance and repair for potentially vulnerable municipally owned public housing

Economy Sector: Remaining Urgent Impacts

The following impacts are also evaluated for urgency in the Economy sector. The summaries below provide a snapshot of each impact, in order of urgency. More details on each impact can be found in Appendix A.

Economic Losses from Commercial Structure Damage and Business Interruptions

Reduction in economic outputs during closures resulting from flooding and storm damage to places of business, as well as reductions in economic output due to extreme weather shutdowns, utility and infrastructure disruptions, and climate-driven supply chains issues.

Extreme Level of Consequence	Potential for Disproportionality	Moderate Adaptation Gap
• Direct damage of future expected flooding on commercial structures is substantial but less than that for residential structures - largest effects are associated with business interruption.	• Exposure is not necessarily disproportionate; however, effects may be concentrated among small and disadvantaged businesses with less ability to pay for repairs.	• Extreme weather and sea level rise mitigation strategies will help improve commercial infrastructure resilience but business-focused planning and implementation strategies, with few exceptions, are lagging.

Damage to Tourist Attractions and Recreation Amenities

Changes to revenues in the tourism and recreation industry, particularly those associated with distinct New England seasons (e.g., winter recreation, foliage viewing), recreational fishing, beach recreation (i.e., reduction in beach width due to sea level rise and coastal erosion), and tourism related to vulnerable historical landmarks.

Moderate Level of Consequence	Disproportionate Exposure	Moderate Adaptation Gap
• Loss of winter recreation and impacts to nature-based recreation opportunities (e.g., harmful algal blooms in swimming spots and beach erosion) may limit some types of recreation and travel; however, studies show warmer shoulder seasons could lead to increased outdoor recreation for residents.	• Although all residents should experience increases in recreation, the potential impacts on the tourism industry are disproportionate based on the demographic characteristics of workers in this industry.	• There is limited action being taken to understand or address the hazards that directly threaten tourism and recreation but adaptations that address flooding in parks and recreation areas offer some hazard mitigation.

Decrease in Agricultural Productivity

Reduction in crop yields for major agricultural products including field crops and tree products due to changing temperature and precipitation patterns, extreme weather, loss of pollinators, saltwater intrusion, and others.

Major Level of Consequence	Potential for Disproportionality	Moderate Adaptation Gap
• Climate change brings unpredictability and disruption to the agriculture industry, although the magnitude of impact is uncertain.	• Agricultural activity in the Commonwealth is not located in areas identified as EJ block groups. Local agriculture is a small but growing source of food for people participating in Commonwealth food assistance programs.	• Statewide investment in research and outreach (e.g., Coordinated Soil Health Program and the upcoming Farmland Action Plan) provide important guidance that could be supplemented with more local planning efforts.

5. Conclusion and Next Steps

5.1 Conclusion

This Massachusetts Climate Change Assessment (Climate Assessment) has been designed to answer three basic questions for top climate impacts that may face the Commonwealth:

- How large of an impact do we expect from projected climate hazards on potentially vulnerable human populations, natural environment, and built infrastructure assets?
- Do we expect populations living in environmental justice communities to be affected more than the rest of the population? [159]
- Are we currently doing enough to adapt to these impacts or are there gaps in effective adaptation actions? How soon is action needed?

Information presented in Chapters 1 through 4 of this report, and summarized in the accompanying Executive Summary, seeks to answer these three questions for 37 impacts across five sectors selected through a robust stakeholder process, within the limits of currently available evidence across the Commonwealth and the uncertainty of how future climate change will unfold in ways that put people, infrastructure, natural and cultural assets, and governance activity and resources at risk.

The report establishes a priority for 16 of these impacts that were determined to be of highest urgency in the Commonwealth, representing the top three ranked impacts in each of the five sectors, and four within the Natural Environment sector. All of the 37 impacts assessed warrant risk mitigation action, and the adaptation action review establishes that the Commonwealth's state and municipal governments and a wide range of non-government organizations and private sector actors are already engaged in substantive action across the full scope of this Climate Assessment report. The quantitative and qualitative analysis and broad stakeholder input on climate hazard science and asset vulnerability addressed in this report, however, support the identification of a subset of 16 impacts for specific and ongoing focus.

5.2 Next Steps

The findings of this report will be incorporated and serve to directly inform the 2023 update to the State Hazard Mitigation and Climate Adaptation Plan (SHMCAP), the Commonwealth's strategic plan for hazard mitigation and climate risk reduction action. Findings will be utilized as the primary component of the detailed risk assessment, as they meet the federal requirements for State Hazard Mitigation Planning documents. Because the Climate Assessment was

[159] As used in this report, environmental justice (EJ) communities are block groups defined by EEA based on US Census data, for more information see: https://www.mass.gov/info-details/environmental-justice-populations-in-massachusetts

designed in part to inform the SHMCAP, all information provided in this report is being considered for inclusion in the 2023 SHMCAP update. However, one of the most important purposes of the Climate Assessment is to provide the Commonwealth with the ability to implement risk prioritization within the Statewide Mitigation Strategy. This means that the SHMCAP will identify additional risk mitigation actions, including and beyond those documented in the Climate Assessment, that the Commonwealth will support in order to augment and update the 2018 SHMCAP. The 2023 update will be released in September 2023, following a stakeholder engagement process to identify and prioritize statewide action in response to the Climate Assessment findings.

The Climate Assessment draws on the best available climate and impact assessment science, active public stakeholder engagement, and broad state agency perspectives to answer the three key questions that begin this chapter. It is also important to recognize that knowledge of climate hazards and impacts is constantly evolving and expanding. Some of these advances expand the scope of impacts – suggesting that the 37 impacts assessed here will need to continue to evolve over time. Other anticipated advances will increase the Commonwealth's understanding of relevant climate science and hazards. Still others will better align the complex and uncertain outputs of climate projections with the processes used to assess impacts in detail. In addition, new information may become available which informs the efficacy and cost-effectiveness of risk reduction action. The Commonwealth's best available statewide climate data will be reevaluated and updated on a 5-year cycle to align with future updates of the Climate Assessment and SHMCAP. EEA will also work to invest in staff capacity and expertise in climate science to ensure the continued development, maintenance, and cross-government application of statewide climate change data and information. In addition, there is continual evolution in the nature and resilience of potentially vulnerable people, built assets, infrastructure, and the natural environment which will affect the size and timing of future climate impacts.

The Commonwealth of Massachusetts, and in particular the Executive Office of Energy and Environmental Affairs which led the development of this report, in close coordination with the Massachusetts Emergency Management Agency, are committed to continued attention to improve the understanding of the impact of climate change to the people, places, and resources of the Commonwealth. The Commonwealth is also committed to making updated and improved information available to facilitate risk reduction; to partnering with communities to improve their resilience to climate change now and in the future; and to continuing the leadership role the Commonwealth has taken to significantly reduce the greenhouse gas emissions that cause global climate change.

Glossary

The entries below reflect key terms defined and used within the document and also are consistent with definitions of terms to be used in the 2023 State Hazard Mitigation and Climate Adaptation Plan.

Term	Definition	Source
Adaptation gap	A measure of the need for further effective adaptation measures to address the expected effects of a particular impact of climate change. The adaptation gap is evaluated by the Climate Assessment team and considers how much action has already been done relative to the availability of known solutions and any timing pressures for action (e.g., high levels of near-term damages are expected or potential adaptation actions require a long lead time).	Defined for this document, see Chapter 2
Agencies and stakeholders	State, local and tribal agencies; colleges and universities; private entities, including private nonprofit organizations; or quasi-governmental authorities and special districts like port authorities or utility districts that perform critical functions.	FEMA State Mitigation Planning Policy Guide, 2022
Annualized frequency	The expected frequency or probability of a hazard occurrence per year. It is a natural hazard incidence factor for Expected Annual Loss, the natural hazards component of the National Risk Index. A higher annualized frequency value results in higher Expected Annual Loss and Risk Index scores. Annualized frequency is derived from either the number of recorded hazard occurrences each year over a given period or the modeled probability of a hazard occurrence each year.	FEMA, National Risk Index
Climate Adaptation	Actions taken at the individual, local, regional, and national levels to reduce risks from today's changed climate conditions and to prepare for impacts from additional changes projected for the future.	USGCRP National Climate Assessment Online Glossary
Consequence	The effect of a hazard occurrence. Consequence is demonstrated by the impact on population, physical property (e.g., state facilities, local jurisdiction assets and general building stock, and critical facilities), responders, operations, the environment, the economy, and public confidence in state governance. A consequence analysis meets the Emergency Management Accreditation Program standard for hazards identified in state plans.	2018 SHMCAP

Term	Definition	Source
Critical Infrastructure	Systems and assets, whether physical or virtual, so vital that the incapacity or destruction of such may have a debilitating impact on the security, economy, public health or safety, environment, or any combination of these matters, across any local, State, Tribal and Federal jurisdiction. Some examples of critical infrastructure include: • Public water systems serving large population centers. • Primary data storage and processing facilities, stock exchanges or major banking centers. • Chemical facilities located in close proximity to large population centers. • Major power generation facilities exceeding 2,000 MW and supporting the regional electric grid. • Hydroelectric facilities and dams producing power in excess of 2,000 MW that could cause catastrophic loss of life if breached. • Nuclear power plants. • Major underground gas, water, phone and electrical supplies affecting a large population.	FEMA Online Glossary
Development	Any man-made change to improved or unimproved real estate, including but not limited to buildings or other structures, mining, dredging, filling, grading, paving, excavation or drilling operations or storage of equipment or materials.	FEMA Online Glossary
Disproportionate exposure	A measure of the likelihood that individuals living in areas identified as Environmental Justice areas (at the Census block group scale) by the Commonwealth currently live in areas where climate and hazard risks are high, relative to individuals in reference populations (e.g., for socially vulnerable low-income households, the reference population would be households that are not included in the definition of low-income). The resulting values are measures of the potential risks of socially vulnerable populations being exposed to future impacts of climate change.	Defined for this document, see Chapter 2
Ecosystem Services	The benefits that flow from nature to people, for example, nature's contributions to the production of food and timber; life-support processes, such as water purification and coastal protection; and life-fulfilling benefits, such as places to recreate or to be inspired by nature's diversity.	National Ecosystem Services Partnership
Environmental Justice	Environmental Justice (EJ) is based on the principle that all people have a right to be protected from environmental hazards and to live in and enjoy a clean and healthful environment. EJ is the equal protection and meaningful involvement of all people with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies and the equitable distribution of environmental benefits.	Mass.gov definition
Environmental Justice Population	In Massachusetts, an environmental justice population is a neighborhood where one or more of the following criteria are true: the annual median household income is 65 percent or less of the statewide annual median household income, minorities make up 40 percent or more of the population, 25 percent or more of households identify as speaking English less than "very well", minorities make up 25 percent or more of the population and the annual median household income of the municipality in which the neighborhood is located does not exceed 150 percent of the statewide annual median household income.	Mass.gov definition

Term	Definition	Source
Exposure	The extent to which physical and non-physical assets, functions, and population groups are in direct contact with natural hazards or their related climate change impacts. Exposure is often determined by examining the number of people or assets that lie within a geographic area affected by a natural hazard or by determining the magnitude of the climate change impact. For example, measurement of flood depth outside a building or number of heat waves experienced by a county are measurements of exposure.	2018 SHMCAP
Floodplain	Any land area susceptible to being inundated by floodwaters from any source.	FEMA Online Glossary
Hazard mitigation	Hazard mitigation is any sustained action taken to reduce or eliminate the long-term risk to human life and property from hazards. An example of hazard mitigation is elevating or strengthening a bridge to reduce damage, disruption, or loss from a flood or an earthquake. It also includes the development of new regulations to require new construction to include new methods and procedures to reduce risks from current hazards and increasing risks from climate change.	SHMCAP Survey 2022
High hazard potential dams	Dams where failure or mis-operation will probably cause loss of human life, according to the Hazard Potential Classification System for Dams (FEMA/ICODS, 2004).	FEMA State Mitigation Planning Policy Guide, 2022
Impacts	The consequences of climate change and natural and other hazards on lives, livelihoods, health, ecosystems and species, economic, social and cultural assets, services (including environmental) and infrastructure. Impacts result from the interaction of vulnerability, exposure and hazard.	Defined for this document, see Chapter 2
Magnitude of consequence	An estimate of the level of climate risk to exposed people, resources, or assets, where risk is defined as the product of severity and frequency of occurrence, or the impact resulting from the combination of vulnerability and exposure. Magnitude of consequence is rated by an expert panel(s) in one of five categories, from “Minimal” to “Extreme” and converted to a scale of 0 to 100, with reference to the results of quantitative risk analysis (where feasible) and other available evidence, and with review by relevant subject matter experts and stakeholders.	Defined for this document, see Chapter 2
Natural hazard	Sources of harm or difficulty created by meteorological, environmental, or geological events. Natural hazards, such as flooding and earthquakes, affect the built environment, including dams and levees.	FEMA State Mitigation Planning Policy Guide, 2022
Natural resources	Land, fish, wildlife, biota and water. Water means salt and fresh water, surface and ground water used for drinking, irrigation, aquaculture and recreational purposes, as well as in its capacity as fish and wildlife habitat.	FEMA Online Glossary
Recurrence interval	A recurrence interval is how often a hazard event of specific severity is likely to occur in a particular location. A recurrence interval is often referred to as the "X-year" or "Y% annual chance" event.	FEMA Student Manual-Recurrence Interval

Term	Definition	Source
Regions	Results are presented for seven regions across the Commonwealth. The seven regions were developed by grouping cities and towns with the goals of aligning with existing planning regions and jurisdictions and grouping areas that face similar climate risks, have similar vulnerabilities, and share affinity with other cities and towns in the region. Although results are summarized by region, results for specific risk analyses will be available at finer spatial scales, where the resolution is defined by the underlying sector model(s) used to characterize the risk.	Defined for this document, see Chapter 2
Resilience	Resilience is the capacity of individuals, communities, businesses, institutions, and governments to adapt to changing conditions and to prepare for, withstand, and rapidly recover from disruptions to everyday life, such as hazard events.	FEMA Planning for Resilient Communities Fact Sheet
Risk	The potential for an unwanted outcome resulting from an incident, event, or occurrence, as determined by its likelihood and the associated consequences. With respect to continuity, risk may degrade or hinder the performance of essential functions and affect critical assets associated with continuity operations.	FEMA Online Glossary
Risk assessment	Evaluates where populations, infrastructure and critical facilities are vulnerable to hazards, and to what degree injuries or damage may occur.	FEMA State Mitigation Planning Policy Guide, 2022
Sectors	Defined by EEA as the major categories of projected impacts of climate change, or groupings of individually defined risks with a common set of exposed individuals, assets, or resources, as well as a common set of stakeholders. Five sectors included in this study are: Human; Infrastructure, Natural Environment, Economy, and Governance.	Defined for this document, see Chapter 2
State assets	Include state-owned or operated buildings, infrastructure, community lifelines, and critical facilities.	FEMA State Mitigation Planning Policy Guide, 2022
Vulnerability	The vulnerability from a hazard is considered by assessing the assets and services owned, managed, and implemented by a community or organization and the populations and stakeholders who are served by those assets and services. Vulnerability assessments often include conducting an exposure analysis to determine which hazards may affect the assets, services and issues that your agency is responsible for. Once exposure is determined, the vulnerability of agency assets, services, and populations served to damage, disruption, or loss is assessed to determine the consequences to community and society, economy and jobs, public health and safety, natural environment and ecology, and governance.	SHMCAP Survey 2022
Notes on Sources	*2018 SHMCAP*: Massachusetts Integrated State Hazard Mitigation and Climate Adaptation Plan, September 2018**,** available online here. *SHMCAP Survey 2022*: Developed as part of the ongoing planning and completion of 2023 update to Massachusetts SHMCAP *FEMA State Mitigation Planning Policy Guide, 2022*: State Mitigation Planning Policy Guide, FP 302-094-2, Released April 19, 2022, Effective April 19, 2023, OMB Collection #1660-0062, available online here.	