Appendix A | Full Statewide Impact Rankings and Scores by Sector

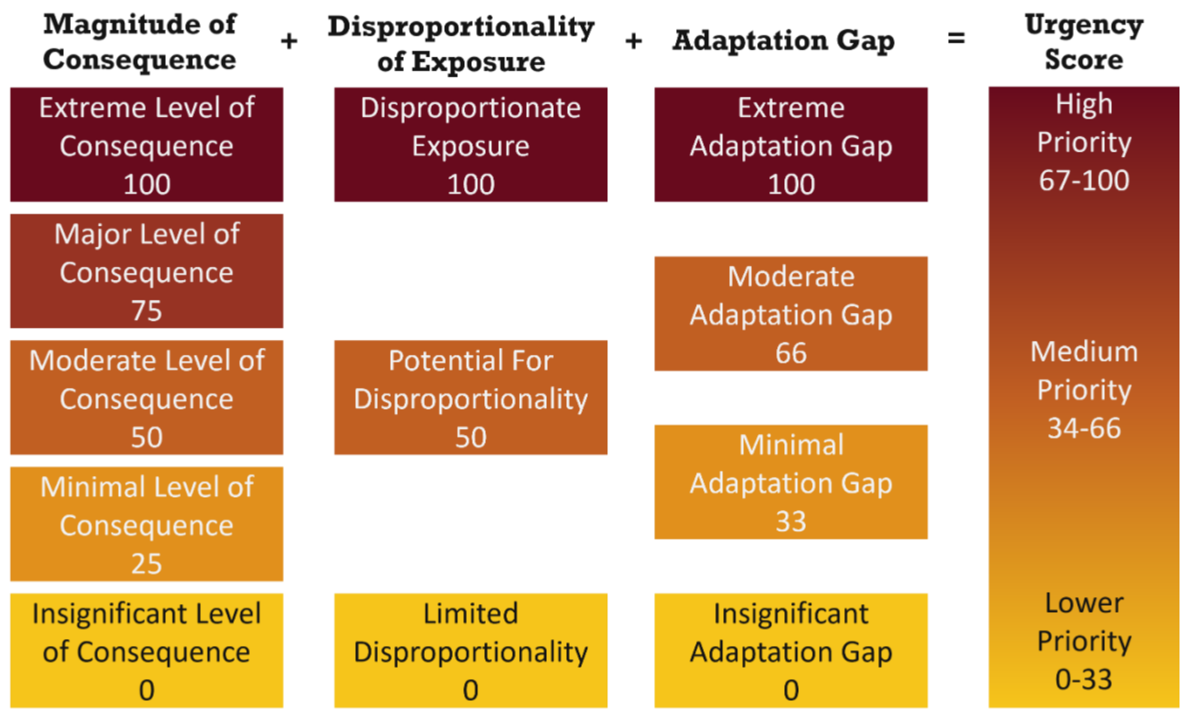
Appendix A Contents

Urgency Scoring Procedures

This Appendix provides full urgency rankings by sector and additional details for the impacts not highlighted in the main report (i.e., the impacts ranked fourth or lower per sector).

Rankings per sector are determined by urgency scores for each of the three components analyzed: Magnitude of Consequence, Disproportionality of Exposure, and Adaptation Gap. The classifications within each component are assigned a score from 0 to 100, as shown in Figure A1, and averaged to calculate the urgency score. A description of the methods used to calculate component and overall urgency scores is provided in the main report, with additional methodological details and data sources included in Appendix B.

Figure A1. Urgency Ranking Framework with Scores



Human Sector

The Human sector includes impacts to people's health, welfare, and safety. 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 for populations living in Environmental Justice blocks groups.

Table A1. Health Sector Impacts Ranked by Urgency Score

IMPACT	MAGNITUDE	DISPROPORTIONATE EXPOSURE	ADAPTATION GAP	URGENCY SCORE
Health and Cognitive Effects from Extreme Heat (MOST URGENT)	Extreme	Disproportionate	Moderate	89
Health Effects from Degraded Air Quality (MOST URGENT)	Major	Disproportionate	Moderate	80
Emergency Service Response Delays and Evacuation Disruptions (MOST URGENT)	Major	Disproportionate	Moderate	80
Reduction in Food Safety and Security	Moderate	Disproportionate	Moderate	72
Increase in Mental Health Stressors	Major	Potential	Moderate	64
Health Effects from Aeroallergens and Mold	Moderate	Potential	Moderate	55
Health Effects of Extreme Storms and Power Outages	Moderate	Potential	Moderate	55
Damage to Cultural Resources	Moderate	Potential	Moderate	55
Increase in Vector Borne Diseases Incidence and Bacterial Infections	Major	Limited	Moderate	47

Human Sector: Urgent Impact #4

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.

Impact Summary

At the global scale, climate change has been identified as a major concern with respect to food security, mainly linked to challenges associated with global primary food production (crops and livestock) and the potential for high temperatures and changes in precipitation patterns to affect crop and livestock yields. In the U.S. in general, as well as in Massachusetts, the impact of climate change on food security is typically associated with food access in rural counties, where local agricultural supplies and local economies are more heavily dependent on local food production,[1] but food insecurity may also be linked to vulnerability of food distribution networks to extreme event risks. Food insecurity is an existing problem in the Commonwealth that could be further exacerbated by climate change. In Massachusetts, 32 percent of adults experienced food insecurity in 2021, with even higher rates for households with children (40 percent), and adults who identify as Black (53 percent) or Latino/a (61 percent).[2] Food safety, particularly associated with spoilage and bacterial contamination, is also associated with high temperature events and risk of power outages.[3]

[1] Raj, S., Roodbar, S., Brinkley, C. and Wolfe, D.W., 2022. Food Security and Climate Change: Differences in impacts and adaptation strategies for rural communities in the Global South and North. Frontiers in Sustainable Food Systems, 5. doi: 10.3389/fsufs.2021.691191

[2] The Greater Boston Food Bank. 2022. Opportunities to Improve Food Equity and Access in Massachusetts. Available at https://www.gbfb.org/wp-content/uploads/2022/06/GBFB_Food-Access_Report22_V08c_singles.pdf

[3] A potentially related effect on food security involves effects of more variable streamflow on freshwater fish guilds which may contribute to subsistence food stocks. There is some evidence of climate change potentially leading to a change in predominant fish species (see Jones, R., C. Travers, C. Rodgers, B. Lazar, E. English, J. Lipton, J. Vogel, K. Strzepek, and J. Martinich (2012). Climate change impacts on freshwater recreational fishing in the United States. *Mitigation and Adaptation Strategies for Global Change*, doi:10.1007/s11027-012-9385-3. Available online at https://link.springer.com/article/10.1007/s11027-012-9385-3), Unfortunately there is currently very limited evidence on the impact of those changes on fish available as food for subsistence.

Urgency Ranking Results

This impact is ranked as a **high priority** because of its expected moderate magnitude of impact and moderate adaptation gap, and disproportionate impact based on qualitative assessment.

This impact is evaluated qualitatively using a combination of available literature on risks of climate change to food security, consideration of potential local crop and livestock yield impacts conducted from the Economy sector impact category, and mapping of Massachusetts food distribution networks relative to risk of extreme event flooding.

> *"I get concerned about food going bad, and prices continuing to rise for groceries which will disproportionally affect folks."*
>
> *"If we continue to have shipping issues due to pandemics, gas prices, production, and labor challenges we will need to have more local food grown."*
>
> \- Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The consequences of climate change on food safety and security in Massachusetts are projected to be **moderate** due to the lack of evidence of widespread and substantial losses of major food sources for Massachusetts attributable to climate change. Most of the food consumed in Massachusetts is derived from out-of-state sources, for the majority of the population. As described in the Economy sector, Agriculture impact, key commodity crop yields in Massachusetts could decline by 10 percent in 2030, and by 18 percent by 2070, with the potential for losses concentrated in the Berkshire and Hilltowns and Greater Connecticut River Valley regions. In these regions, effects on local food security and the viability of local agriculture could be substantial, but the broad network of food supply would likely be sufficiently robust to compensate for these losses through imports from other U.S. states or internationally, in northern areas which may be expected to see higher yields for agricultural production over time. Impacts on individual plots or small collectives which supply consumers throughout the state may also be affected – anecdotal evidence from stakeholder outreach, particularly from the western regions of the state, suggests that small-scale farming viability in the face of increased weather fluctuations and insecure irrigation water sources are of great concern to Massachusetts residents. In addition, loss of local crop sources may affect the quality and nutritional value of food stocks to a greater extent than the overall quantity of commodity crops assessed here.

Other analyses have identified climate change yield losses as a cause of commodity food crop price increases,[4] which could in turn lead to increases in prices for consumers for a large portion of a typical food basket. For example, for the climate change scenario used in the Assessment, by 2035 there could be a 7 percent increase in overall crop prices relative to a no climate change scenario. This estimate considers only U.S. domestic agricultural production –

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[4] USEPA. 2017). Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. U.S. Environmental Protection Agency, EPA 430-R-17-001. See Figure 21.5 on page 163 for price forecasts.

the price increase could be worse if losses to global agriculture production from climate change are considered. The same analysis also shows that, in order to counteract yield losses, additional land would need to be put into production in the U.S. – if those land areas prove to be not available for agricultural production it could put additional pressure on crop and food security globally, in the U.S., and in Massachusetts.

Three other types of risks to food security are relevant to review and continue to monitor over time as potentially of concern. The first involves the potential for high temperature events to lead to bacterial infections of food stocks. Dominianni et al. (2018) reviewed 65,000 food safety inspections across 30,000 New York City restaurants across summer-weather months and found a significant positive association between hotter temperatures and the incidence of both cold food holding violations as well as insufficient refrigeration/hot holding equipment violations.[5] Lin et al. (2016) found a significant increase in daily gastrointestinal (GI) infection count following a 1 degree Celsius increase in a variety of temperature measures (e.g., daily maximum and minimum), particularly one day following the temperature rise. Bacterial GI infections are commonly waterborne or foodborne, and they occur through the consumption of foods that have been spoiled or contaminated, likely due to insufficient cooling in food storage – these include some forms of fresh seafood such as oysters (see Human sector, Increase in Vector borne Illness impact). Projected increases in the frequency and severity of extreme heat can cause food spoilage that can lead to more widespread GI illness. Lin et al. also reported higher incidences of GI infections amongst socially vulnerable strata such as women and Black and Hispanic individuals.[6]

The second involves the potential for power outages to affect food spoilage. Following New York City's August 2003 power outage, Marx et al. (2006) reported a 70 percent increase in diarrhea-related emergency department visits and a 29 percent increase in the proportion of worker absences attributable to gastrointestinal illness. As power outages are projected to become more frequent with rising extreme weather, the consumption of foods spoiled due to lost refrigeration poses a potential risk to Massachusetts food safety.[7]

The third involves the resilience of major food distribution centers throughout Massachusetts to impacts from extreme events – a storm or flood related shutdown of a major distribution facility may temporarily but perhaps severely impact local food availability during and after the event. Figure A2 below shows the major wholesale food distribution centers located in Massachusetts, based on industry trade group research, with their locations plotted in proximity to the FEMA 100-year floodplain.[8] Four of the 32 on the list are located within the FEMA 100-year floodplain – 29 of the 32 are within 1,000 meters of this floodplain. The map

[5] Dominianni, C., Lane, K., Ahmed, M., Johnson, S., McKelvey, W., & Ito, K. (2018). Hot Weather Impacts on New York City Restaurant Food Safety Violations and Operations. *Journal of food protection*, *81*(7), 1048–1054.

[6] Lin, S., Sun, M., Fitzgerald, E., and Hwang, S.A. 2016. Did summer weather factors affect gastrointestinal infection hospitalizations in New York State? Sci Total Environ, 550, 38-44.

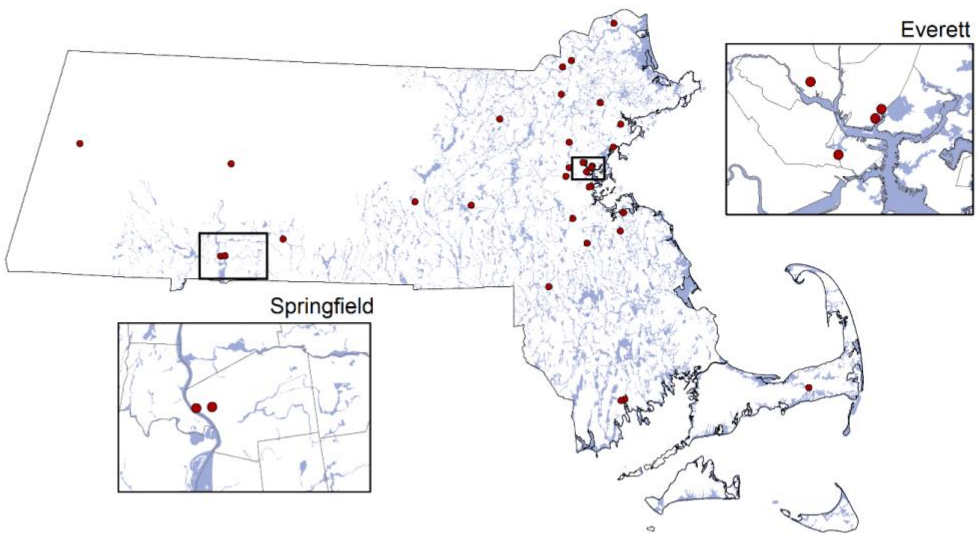
[7] Marx, M. A., Rodriguez, C. V., Greenko, J., Das, D., Heffernan, R., Karpati, A. M., Mostashari, F., Balter, S., Layton, M., & Weiss, D. (2006). Diarrheal illness detected through syndromic surveillance after a massive power outage: New York City, August 2003. *American journal of public health*, *96*(3), 547–553.

[8] List available at: https://www.foodcodirectory.com/2020/09/wholesale-food-distributors-in_31.html

shows two of these, along with others, in the Everett/Chelsea and Springfield areas which may be both vulnerable to flood risk and may be important in supplying groceries in EJ population areas. While no flood modeling is yet available to more comprehensively assess extreme event risks to these facilities and their operations, the critical role of distribution centers suggests more detailed climate risk analysis may be needed.

Figure A2. Location of Major Wholesale Food Distribution Centers in Massachusetts Relative to the current FEMA 100-year Floodplain

Red dots show the location of major wholesale food distribution centers – see text for source. Blue shaded areas are the current FEMA 100-yr floodplain. Insets show two centers near Springfield, and four near Everett which are among those located within and/or nearest the current 100-year floodplain.



Source: Distribution locations from Food Co. Directory; FEMA Flood layer from MassGIS

Disproportionality

Exposure to this impact is expected to have a significantly **disproportionate** exposure.

While quantitative assessment of disproportionality is not available, other qualitative information is useful in assessing the potential for disproportionate effects of climate on food safety and security. Two key factors in the evaluation of significantly disproportionate exposure are the current and rising trend of incidence of food insecurity among low-income populations,[9] and the role of climate change in forecast food price increases, which would fall disproportionately among low-income populations without the ability to absorb prices increases for what is an already large component of their monthly budget.

The food distribution center map above also suggests that flood risks to these facilities in some areas of the Commonwealth may be disproportionately near EJ block groups. In addition, several sources including the stakeholders engaged for this Climate Assessment indicate that small-scale farming, typically with partial and/or low-income attributable to farming activity,

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[9] See for example Feeding America's county-level dashboard of food insecurity among specific demographic groups, available here: https://www.feedingamerica.org/research/map-the-meal-gap/by-county

and which is prevalent in the western part of the state and in rural areas in general in the U.S., may be particularly vulnerable to climate and weather shocks.[10]

Adaptation

There is a **moderate** adaptation gap between current action and what could be done to address the impact of climate change on food safety and security at the state level. From EEA's Food Security Infrastructure Grant Program to free meal programs that are already implemented in public school systems and other Supplemental Nutrition Assistance Program, SNAP, benefits, food security is a focus of many programs in the Commonwealth. Since 2012, the Division on Marine Fisheries and the Department of Public Health have issued annual control plans to reduce vibrio incidence, which include requirements for storage and shipping. An additional focus on food safety will be important looking forward.

Within adaptation plans, actions underway to adapt to the climate-driven stress on food security include creating regional food hubs, farm-to-school food programs, and restructuring policies on food access programs to allow the use of food stamps at farmers' markets.

Example Adaptation Plans with Actions Addressing this Impact

- Medford Climate Action and Adaptation Plan includes actions such as creating a community food hub, creating a platform for grocery business continuity planning, and increasing the number of providers accepting food assistance.
- New Bedford Resiliency Plan also creates a regional food hub and expands community garden programs.

Sensitivities and Uncertainty

Substantial declines in overall food production, food security, and food safety, particularly linked to climate change, have not been prevalent to date in the U.S., although in specific regions, crops, and livestock types have experienced drought related declines. The U.S. is a net exporter of food, and food storage and distribution systems are generally well developed and responsive to shortages, with good availability of substitutes in response to shortages. While historically a climate-related food security concern in the U.S. has not been in evidence, owing to a generally resilient food system, there remain substantial uncertainties in the current ability to forecast climate-related instances of multiple or cascading crop/livestock/region combinations of effects either locally, domestically, or globally which could lead to more substantial concerns.

Related Impacts

Table A2 lists the impacts in other sectors that have a connection to this impact.

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[10] USDA. 2017. 2017 Census of Agriculture State Profile: Massachusetts. Available at: https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/County_Profiles/Massachusetts/index.php; Raj, S., Roodbar, S., Brinkley, C. and Wolfe, D.W. 2022. Food Security and Climate Change: Differences in Impacts and Adaptation Strategies for Rural Communities in the Global South and North. *Front. Sustain. Food Syst.* 5:691191. doi: 10.3389/fsufs.2021.691191

Table A2. Additional Impacts related to Food Safety and Security

Sector	Impact	Connection
Economy	Reduced Agricultural Productivity and Reduced Marine Fisheries and Aquaculture Productivity	Reduced in-state production of food increases the Commonwealth’s reliance on the global supply chain for food provision.
Governance	Increase in Demand for State and Municipal Government Services	Increased food insecurity can lead to an increased demand for the SNAP program.
Infrastructure	Damage to Inland Buildings and Damage to Coastal Buildings and Ports	Critical distribution centers may be vulnerable to inland and coastal flooding, causing unreliable deliveries.

Human Sector: Urgent Impact #5

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.

Impact Summary

Researchers have begun to look at the association between climate change exposure and a range of mental illnesses, from ambient stress to clinical psychological disorders. The best-documented and most readily quantified measure of mental health which has been linked to climate change is an association between extreme temperature and an increase in suicide incidence specific to the U.S. at county scale.[11] The causative factors that increase suicide during high temperature periods is not well understood, but data more closely connect suicide by violent means to elevated temperature, and hypothesized factors include sociological (e.g., increased alcohol use during heat waves); biological (e.g., effects on neurotransmitters such as serotonin which affect impulsivity and aggression); and psychological (e.g., temperature links to increased disinhibition, aggressiveness, and propensity for violence).[12] Research on other effects is still in infancy due in part to the difficulty of defining metrics of impact and the incremental effect of complex climate stressors, but an emerging set of findings links psychological effects on different impacts of climate change, such as extreme heat, long-term temperature change, and extreme weather disasters – wildfires, floods, droughts, storms, etc.[13]

Urgency Ranking Results

This impact is ranked as a **medium priority** because of its large impact, potential for disproportionate impact based on qualitative assessment, and moderate adaptation gap.

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[11] See, for example, Belova, A., Gould, C. A., Munson, K., Howell, M., Trevisan, C., Obradovich, N., & Martinich, J. (2022). Projecting the Suicide Burden of Climate Change in the United States. *GeoHealth*, *6*(5), e2021GH000580. https://doi.org/10.1029/2021GH000580

[12] See Page, L.A., S. Hajat, and R.S. Kovats, (2007). Relationship between daily suicide counts and temperature in England and Wales. *The British Journal of Psychiatry.* 191(2):106 – 112. https://doi.org/10.1192/bjp.bp.106.031948

[13] Ebi, K.L., J.M. Balbus, G. Luber, A. Bole, A. Crimmins, G. Glass, S. Saha, M.M. Shimamoto, J. Trtanj, and J.L. White-Newsome, 2018: Human Health. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 539–571. doi: 10.7930/NCA4.2018.CH14

This impact is evaluated using a combination of available USEPA-sponsored literature on quantitative links between extreme heat and suicide incidence,[14] and qualitative evidence on a broad range of other connections between climate change and mental health.

> *"No one knows how to talk about this issue with children. I have kids. I struggle, all the time, with how to make them aware but not terrified of what is going on."*
>
> - Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The consequences of climate change on mental health are projected to be **major** due to widespread and substantial increases in heat-related suicide, and the severity of increases in mortality. The effects of climate change phenomena on mental health are of particular importance when contextualized by the physical and economic impacts of psychological distress in the United States; in 2019, suicide claimed 13.9 lives per 100,000 (CDC 2021). Belova et al. (2022) found that 1 to 6 degrees Celsius of rising temperatures could result in 283 to 1,660 additional annual suicide cases in the U.S. (the portion in Massachusetts and by region below are estimated by aggregating from the county level results made available by the authors); the annual economic value of avoiding these impacts for a 3- to 4-degree warming could be in the range of $8.5 to $11 billion (2015$, 3 percent discount rate) at a national scale. Impacts are valued based on individual values for avoiding the risk of premature death.

Table A3 below summarizes estimated impacts on incidence of climate-related suicide by year and region. The baseline shown is for all suicides – climate change could be anticipated to increase the rate of suicide statewide by as much as 5 percent by the end of the century.

Table A3. Effects of Extreme Heat on Incidence of Suicide

Cases of suicide attributable to climate change (increasing extreme temperatures). Statewide economic costs (in millions of dollars) are based on individual 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.

Region	Baseline	2030	2050	2070	2090
Berkshires & Hilltowns	18	0	0	1	1
Greater Connecticut River Valley	78	1	2	3	3
Central	80	1	2	3	3
Eastern Inland	166	2	4	7	9
Boston Harbor	110	1	3	5	6
North & South Shores	60	1	2	2	3
Cape, Islands, & South Coast	69	1	1	2	2
Statewide	**581**	**8**	**14**	**22**	**28**

[14] Belova et al. (2022), see prior footnote for full reference.

Region	Baseline	2030	2050	2070	2090
Economic Costs ($millions)	$6,300	$90	$190	$320	$470

Source: Author's analysis based on Belova et al. 2022

There are many other impacts of climate change on mental health, but these can be assessed only qualitatively at this time. Flooded communities have been found to experience greater depression, anxiety, and PTSD one year after flooding than communities affected by but not directly flooded, with the odds of each psychological morbidity being significantly and positively associated with floodwater depth; displacement by flooding increased the odds of each mental disorder.[15,16] Questionnaires completed by Florida Department of Health workers following the 2004 hurricane season revealed probable depression, probable PTSD, and increased alcohol and/or tobacco use, with incidence of these being higher among workers with greater exposure to the hurricanes and/or greater work demand.[17] Studies conducted in the New York City area as follow-up to the impacts of Superstorm Sandy found that iincreased exposure to Hurricane Sandy was statistically significantly associated with a greater likelihood of depression, anxiety, and probable post-traumatic stress disorder, even after controlling for demographic factors known to increase susceptibility to mental health issues.[18]

Mental health consequences may also be linked to anxiety over climate change itself, and not focused on a specific stressor or associated with the magnitude of a stressor. In the United States, 75 percent of 1000 surveyed young adults between the ages of 16 and 25 reported being at least "moderately worried" about global climate change projections, with 29 percent being "moderately worried," 27 percent being "very worried," and 19 percent being "extremely worried".[19] "Eco-anxiety" -- a non-clinical term used to describe anywhere from a "chronic fear of environmental doom" to "mental distress or anxiety associated with worsening environmental conditions" -- seems to affect younger, active populations to a greater degree.[20] More quantitative research on mental health diagnoses related to eco-anxiety can help understand its potentially widespread implications among Massachusetts' youth demographic.

[15] Munro, A., Kovats, R. S., Rubin, G. J., Waite, T. D., Bone, A., Armstrong, B., & English National Study of Flooding and Health Study Group (2017). Effect of evacuation and displacement on the association between flooding and mental health outcomes: a cross-sectional analysis of UK survey data. *The Lancet. Planetary health*, *1*(4), e134–e141. https://doi.org/10.1016/S2542-5196(17)30047-5

[16] Waite, T.D., Chaintarli, K., Beck, C.R. *et al.* The English national cohort study of flooding and health: cross-sectional analysis of mental health outcomes at year one. *BMC Public Health* **17,** 129 (2017). https://doi.org/10.1186/s12889-016-4000-2

[17] Fullerton, C., McKibben, J., Reissman, D., Scharf, T., Kowalski-Trakofler, K., Shultz, J., & Ursano, R. (2013). Posttraumatic Stress Disorder, Depression, and Alcohol and Tobacco Use in Public Health Workers After the 2004 Florida Hurricanes. *Disaster Medicine and Public Health Preparedness, 7*(1), 89-95. doi:10.1017/dmp.2013.6

[18] Schwartz, R.M., Sison, C., Kerath, S.M., Murphy, L., Breil, T., Sikavi, D. and Taioli, E., 2015. The impact of Hurricane Sandy on the mental health of New York area residents. American journal of disaster medicine, 10(4), pp.339-346. doi: 10.5055/ajdm.2015.0216.

[19] Marks, E., Hickman, C., Pihkala, P., Clayton, S., Lewandowski, E. and Mayall, E., & van Susteren, L.(2021). Young people's voices on climate anxiety, government betrayal and moral injury: A global phenomenon. The Lancet.

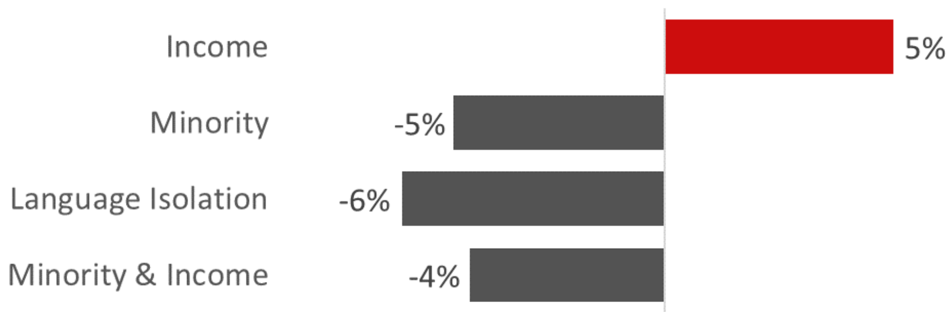
[20] Coffey, Y., Bhullar, N., Durkin, J., Islam, M.S. and Usher, K., 2021. Understanding eco-anxiety: A systematic scoping review of current literature and identified knowledge gaps. The Journal of Climate Change and Health, 3, p.100047.

Disproportionality

This impact is expected to have **potential** for disproportionate exposure. Analysis of suicide rates shows low disproportionality of exposure, as indicated Figure A3. Populations living in EJ block groups defined on the basis of income could have 5 percent higher rates of climate-induced suicide than the rest of the Commonwealth, based on the analysis described above and the results in Belova et al. (2022).

Figure A3. Disproportionality of Climate Impact on Extreme Heat-Associated Suicide

Comparison of the incidences of suicides 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.



However, other qualitative information is useful in assessing the potential for disproportionate effects of climate on mental health. For example, extreme weather events exacerbated by climate change can interact with existing psychological conditions such as PTSD, depression, and anxiety, and in certain cases cause chronic mental illnesses.[21] Research compiled in support of the Fourth National Climate Assessment shows that certain sectors of the population, namely children, elderly people, women, members of Indigenous communities, people of color, first responders, and the economically-disadvantaged face a disproportionate burden of the post-traumatic stress and other mental health conditions from ecological events connected to climate change; some of these demographics are also more likely to be located in risk-prone areas and/or have previously existing conditions.[22,23] Basu et al. (2018) found that in California, a 10-degree Fahrenheit increase in same-day mean apparent temperature was associated with a 4.8 percent, 5.8 percent, and 7.9 percent increase in Emergency Department (ED) visits for mental health disorders, self-injury, and homicide, respectively; Hispanics, whites, children, and

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[21] Dodgen, D., D. Donato, N. Kelly, A. La Greca, J. Morganstein, J. Reser, J. Ruzek, S. Schweitzer, M.M. Shimamoto, K. Thigpen Tart, and R. Ursano, 2016: Ch. 8: Mental Health and Well-Being. The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment. U.S. Global Change Research Program, Washington, DC, 217–246. http://dx.doi.org/10.7930/J0TX3C9H

[22] Gronlund C. J. (2014). Racial and socioeconomic disparities in heat-related health effects and their mechanisms: a review. *Current epidemiology reports*, *1*(3), 165–173. https://doi.org/10.1007/s40471-014-0014-4;

[23] Lowe SR, Sampson L, Gruebner O, Galea S (2015) Psychological Resilience after Hurricane Sandy: The Influence of Individual- and Community Level Factors on Mental Health after a Large-Scale Natural Disaster. *PLoS ONE* 10(5): e0125761. doi:10.1371/journal.pone.0125761

females were at greatest risks of these outcomes.[24] Higher temperatures during the cold season were also found to be positively associated with these psychological and social effects.

Adaptation

There is a **moderate** adaptation gap between current action and what could be done to address the impact of climate-related mental health stressors. Actions to directly adapt to mental health consequences of climate change have generally not been identified or implemented and discourse on climate-related mental health degradation is almost entirely absent in municipal- and state-level climate resiliency planning. Plans that do directly address climate-related mental health impacts do so only in conjunction with physical health risks related to climate change.

Indirect effects of other actions and trends, however, may serve to increase resilience to these consequences. For example, the recent general trend to increase recognition of mental health diagnoses, reduce stigma, and increase access to mental health treatment could all serve to reduce overall levels of mental health morbidity and mortality as well as those attributed to climate-related triggers. For example, the Executive Office of Health and Human Services launched the [Roadmap for Behavioral Health Reform] in 2021. Overall support for treatment of mental health remains a priority for the Commonwealth. In addition, efforts to reduce the incidence of extreme heat, such as urban greening and funding to increase air conditioning penetration, could also decrease heat-related incidence of mental health morbidity and mortality.

Example Adaptation Plans with Actions Addressing this Impact

- Resilient Boston: An Equitable and Connected City
- Devens Climate Action and Resilience Plan

Sensitivities and Uncertainty

The quantitative results for suicide are the primary basis for both the magnitude of consequence and social vulnerability assessments for this impact. There is some possible overlap in premature deaths of any type attributable to extreme heat (addressed in the Health and Cognitive Effects of Extreme Heat impact) and suicide deaths attributed to high heat days. The effect is likely to be small primarily because the "high heat day" metrics differ substantially, with the threshold of high heat in the suicide study being much lower.

The authors of the suicide study[25] note that a different analytic treatment for "displacement" – or the concept that in some cases heat alters the timing of but not the suicide outcome itself – could increase estimates by 17 percent, and a different treatment of the impact of precipitation (increased occurrence of days with precipitation tends to reduce suicide impacts) could increase estimates by an additional 7 percent.

[24] Basu, R., Gavin, L., Pearson, D., Ebisu, K. and Malig, B., 2018. Examining the association between apparent temperature and mental health-related emergency room visits in California. American journal of epidemiology, 187(4), pp.726-735.
[25] Belova et al. (2022), see previous footnote for full citation.

These estimates also do not consider recent trends in health and societal attention to the problem of mental health, which may reduce baseline suicide rates over time as well as suicides attributed to climatic factors. The estimates also assume current levels of adaptation to extreme heat, such as the prevalence of air conditioning, remain constant over time.

Related Impacts

Table A4 lists the impacts in other sectors that have a connection to this impact.

Table A4. Additional Impacts related to Health Effects of Mental Health

Sector	Impact	Connection
Economy	Reduced Ability to Work	Individuals miss work as a result of mental health morbidity, although this assessment does not quantify changes in mental health morbidity incidence.
Governance	Increase in Demand for State and Municipal Government Services	Increase in pressure for health care costs (e.g., MassHealth) to treat adverse mental health effects.
Natural Environment	All ecosystem degradation impacts	Access to open space and natural environments has shown to improve mental health. Loss or degradation of these places could worsen mental health outcomes.

Human Sector: Urgent Impact #6 (tie)

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.

Impact Summary

Climate change has been shown to extend pollen season length and intensity for many species, including those responsible for the most prevalent types of allergic pollen (e.g., trees, grasses, and some weeds). Rising CO_2 concentrations and climate-induced temperature and precipitation changes have been modeled to impact the following:[26]

- Pollen season timing and length
- Total amount of pollen produced throughout the season
- Allergen content of pollen grains
- Spatial distribution of species producing allergenic pollen

Increased pollen production and exposure leads to increases in respiratory problems, in particular emergency department (ED) visits for asthma attacks. Currently, about 1 in 11 people in Massachusetts suffer from asthma.[27]

Historically, the effect of more frequent floods on the production of mold, airborne mold spores, and mold fragments has been linked with increased risk of respiratory disease, including upper respiratory tract symptoms, wheezing, and asthma in sensitized people.[28] However, changes in respiratory illnesses associated with mold exposure with climate change have not been projected into the future.

[26] USEPA. 2017. Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. U.S. Environmental Protection Agency, EPA 430-R-17-001.

[27] https://www.mass.gov/service-details/statistics-about-asthma

[28] Institute of Medicine. 2011. *Climate Change, the Indoor Environment, and Health*. Washington, DC: The National Academies Press. https://doi.org/10.17226/13115.

Urgency Ranking Results

This impact is ranked as a **medium priority** because the impacts, while widespread, are overall moderate compared to other impacts in this sector, and there is limited to no disproportionate impact.

The allergen component of this work is evaluated using USEPA-sponsored literature that modeled the impact of climate on pollen season length for oak, birch, and grass pollens; the impact of changes in season length on pollen exposure; and the impact of pollen exposure on the rate of asthma ED visits.[29] The epidemiology relates outdoor pollen estimates with incidence rates, so implicitly considers both indoor and outdoor exposures, to the extent possible. Asthma-related ED visits are valued at $530 per visit in direct medical costs.

Health effects associated with mold exposure are discussed qualitatively but consistent with current DPH Indoor Air Quality Program guidance on potentially increased risk of mold formation in buildings during periods of high humidity.[30]

> *"I am very concerned about mold growth in low-income households in Central Mass that are unable to use air conditioning to manage internal heat and humidity."*
>
> *"Allergies have continued to get worse every year."*
>
> - Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The consequences of increased aeroallergen exposure are projected to be **moderate** due to widespread but moderate increases in aeroallergen-related health effects. Currently, about 42,000 individuals visit the ED for asthma per year in Massachusetts.[31] Over 500 additional aeroallergen-related asthma ED visits per year are estimated in the Commonwealth as a result of climate change by the end of the century, more than half of which occur among children. Rates of ED use as a result of pollen exposure are projected to increase from 2 in 100,000 in 2030 to 7 in 100,000 in 2090 statewide. For children in particular, rates increase from 6 in 100,000 in 2030 to 17 in 100,000 in 2090.

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[29] Neumann, J.E., Anenberg, S.C., Weinberger, K.R., Amend, M., Gulati, S., Crimmins, A., Roman, H., Fann, N., and Kinney, P.L. 2019. Estimates of Present and Future Asthma Emergency Department Visits Associated with Exposure to Oak, Birch, and Grass Pollen in the United States. Geohealth, 3(1), 11-27.

[30] See https://www.mass.gov/mold-moisture-and-mildew

[31] Baseline asthma ED visits for all causes, not specific to those exacerbated by pollen exposure, from U.S. EPA's BenMAP tool.

Table A5. Health Effects of Increased Aeroallergen Exposure

Emergency department visits due to asthma for individuals of all ages attributable to climate change. Statewide economic costs (in millions of dollars) are based on cost per emergency room visit for asthma. 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.

	Asthma Emergency Department Visits			
Region	**2030**	**2050**	**2070**	**2090**
Berkshires & Hilltowns	5	7	12	16
Greater Connecticut River Valley	21	30	44	53
Central	23	34	51	64
Eastern Inland	52	83	131	172
Boston Harbor	40	65	102	135
North & South Shores	18	29	46	61
Cape, Islands, & South Coast	13	21	32	42
Statewide	**172**	**270**	**419**	**542**
Economic Costs ($millions)	**$0.09**	**$0.14**	**$0.22**	**$0.29**

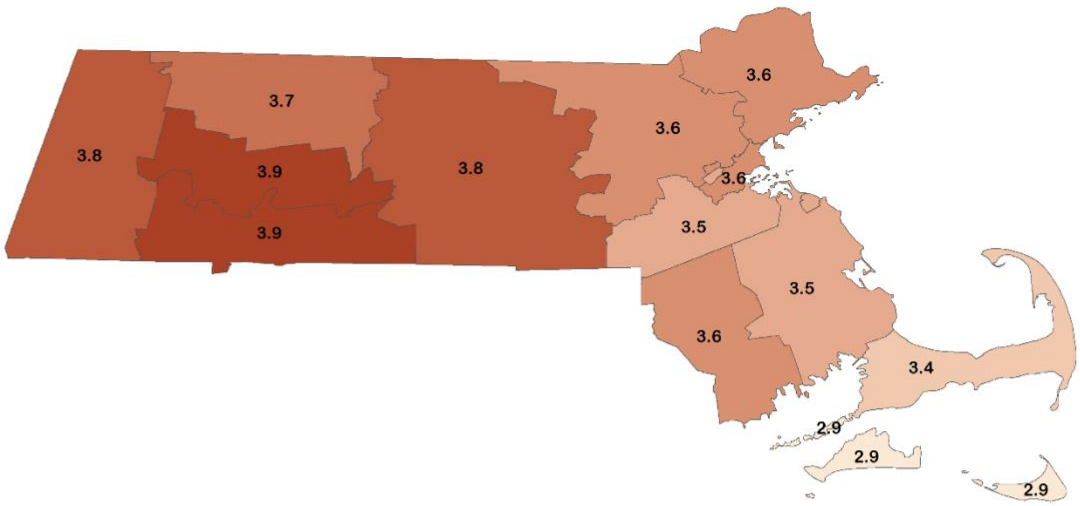
Source: Author's analysis based on Neumann et al. 2019

ED visits are one of the more severe complications of exposure to pollen – more commonly individuals experience more mild effects such as upper respiratory symptoms, headache, and fatigue, but these can nonetheless lead to significant (as large as 35 percent) loss of work productivity through lost work days or reduced performance while working.[32] Direct medical cost of allergic rhinitis could be as large at $3.4 billion in the U.S. – prescription medications are the largest component of these costs, and recent work suggests that the estimates of economic cost currently available may substantially under-estimate the full cost of climate-related changes in pollen on allergy sufferers.

The majority of impacts fall in the more populous Eastern Inland and Boston Harbor regions. However, the highest rates are in the Greater Connecticut River Valley and Berkshires and Hilltowns regions (10 and 8 percent higher than state average in 2090, respectively). In the underlying study, higher rates correspond to areas where baseline pollen counts are higher owing to a higher concentration of forested area – meaning they have current climate exposure to higher pollen concentrations. In Massachusetts, these western areas are also expected to see slightly higher rates of the specific climatic combinations of temperature and precipitation that exacerbate pollen, including for example the early spring wetness and late spring/early summer dryness that can elevate oak pollen concentrations. Figure A4 shows pollen-related asthma ED visit rates in 2050 by county.

[32] Vandenplas, O. et al. (2018), Impact of Rhinitis on Work Productivity: A Systematic Review. *Journal of Allergy and Clinical Immunology: In Practice*, 6(4) 1274 – 1286; Saha, S., A. Vaidyanathan, F. Lo, C. Brown, J.J. Hess (2021). Short term physician visits and medication prescriptions for allergic disease associated with seasonal tree, grass, and weed pollen exposure across the United States. *Environ Health (2021) 20:85.* https://doi.org/10.1186/s12940-021-00766-3

Figure A4. Asthma ED Visits from pollen-related causes per 100,000 in 2050



Source: Author’s analysis based on Neumann et al. 2019

Mold formation may also increase with climate change, as result of more frequent episodes of high humidity. Current DPH guidance notes that mold forms when building materials and components are wet. When the temperature of the building material or component drops below dew point, condensation accumulates to form water droplets. If relative humidity exceeds 70 percent for two or more days, wetness from condensation may occur and form mold in the household.[33,34,35] Incidence of coastal or inland flooding of structures may also lead to mold formation, particularly if flood remediation actions are not pursued in a timely manner. Unfortunately, estimates of change in the frequency of mold-inducing events are not currently available for Massachusetts.[36]

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[33] ASHRAE. 1989. Ventilation for Acceptable Indoor Air Quality. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA. ANSI/ASHRAE 62-1989

[34] ACGIH. 1989. Guidelines for the Assessment of Bioaerosols in the Indoor Environment. American Conference of Governmental Industrial Hygienists, Cincinnati, OH

[35] USEPA. 2001. Mold Remediation in Schools and Commercial Buildings. US Environmental Protection Agency, Office of Air and Radiation, Indoor Environments Division, Washington, D.C. EPA 402-K-01-001. March 2001. www.epa.gov/mold/mold-remediation-schools-and-commercial-buildings-guide-chapter-1

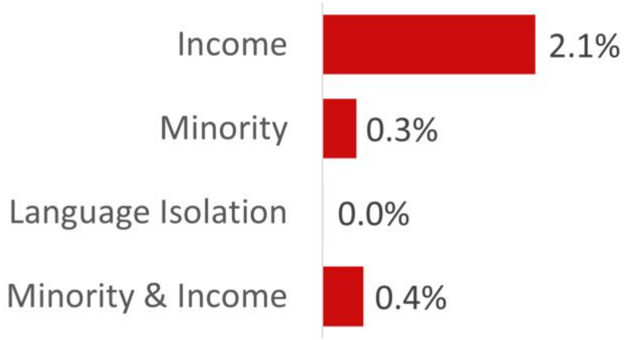
[36] Ideally, this analysis could present the number of consecutive days with relative humidity greater than 70 percent as an indicator for the likelihood of changes in mold prevalence in the future. The MACA climate modeling tools provide downscaled vapor pressure deficit (VPD), which can be transformed into relative humidity with air temperature using the Arrhenius equation, but current climate baseline variables for MACA are from a third-party source and currently unavailable in the same format.

Disproportionality

This impact shows **potential** for disproportionate exposure for socially vulnerable groups defined by the state EJ criteria.[37] For aeroallergens, exposure is nearly exactly proportionate to the distribution of EJ populations around the state, as shown below. Populations living in EJ block groups defined on the basis of low-income populations have two percent higher rates of asthma emergency department visits than the rest of the Commonwealth. The quantitative basis for assessing disproportionality is limited to the effects of pollen on ED visits. Qualitative evidence, however, suggests that the prevalence of the health effects of mold exposure fall disproportionately on minority and low-income households, particularly associated with substandard housing, lower rates of air conditioning penetration (and hence humidity control), and location in areas with more frequent risk of flooding.[38]

Figure A5. Disproportionality of Health Effects of Increased Aeroallergen Exposure

Comparison of asthma ED visits 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 of the main report for further description of the EJ block group definitions.



Adaptation

There is a **moderate** adaptation gap for the climate-related health effects caused by aeroallergens and mold. The climate action plans reviewed contain few actions that directly address this impact, though some plans consider aeroallergens in the context of other actions. For example, a few statewide and Boston-area plans encourage the use of hypoallergenic species in green infrastructure projects. While climate plans tend to overlook this impact, some actions are being taken or planned for within the public health sphere, including public

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[37] Although this analysis does not find a quantitative correlation between the locations of exposure to this impact and EJ block groups, it is important to note that not all populations will have the same experience with the effects of climate change and this impact because of pre-existing social vulnerabilities that are difficult to measure or comprehensively quantify across the Commonwealth.

[38] See Reponen T., Levin L., Zheng S., Ryan P., Grinshpun S.A., LeMasters G. Family and home characteristics correlate with mold in homes. Environ. Res. 2013;124:67–70. doi: 10.1016/j.envres.2013.04.003, also see https://insight.livestories.com/s/health-impacts-of-climate-change-mold-and-respiratory-illness/567b2bb962b12600174b9e02/

information campaigns on mold exposure and trainings for public health officials on climate stressors.

Example Adaptation Plan with Actions Addressing this Impact

- Metro Boston Regional Climate Change Adaptation Strategy Report includes actions such as exploring the use of hypoallergenic species in green infrastructure projects and funding programs for water damage and mold abatement on private properties

Sensitivities and Uncertainty

Estimates for allergen exposure reflect only the more readily quantifiable impacts of pollen on the rate of emergency department visits for asthma, and only for oak, birch, and grass pollens. Other health effects and the increased use of over-the-counter medicines may have a larger economic impact than the more readily quantifiable effects. Further, there is little epidemiological literature available on which to base a projection of mold-related morbidity incidence associated with climate change. Currently illustrative results for this category of effects are the best available estimate.

Related Impacts

Table A6 lists the impacts in other sectors that have a connection to this impact.

Table A6. Additional Impacts related to Health Effects of Aeroallergen and Mold Exposure

Sector	Impact	Connection
Economy	Reduced Ability to Work	Individuals miss work while sick or caring for others who are sick. Children may miss school, leading to learning losses.
Governance	Increased Demand for State and Municipal Government Services	Increase in demand for health care costs (e.g., MassHealth) to treat adverse health effects.
Infrastructure	Damage to Inland Buildings and Damage to Coastal Buildings and Ports	Increases in mold prevalence in residences are tied to inland and coastal flooding and structure damage and may also be connected to incidence of extreme heat and lack of air conditioning.
Human	Health and Cognitive Effects from Extreme Heat	Increases in mold prevalence in residences may also be connected to incidence of extreme heat, potentially correlated with high humidity, and lack of air conditioning.

Human Sector: Urgent Impact #6 (tie)

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.

Impact Summary

Flood and storm events could reasonably be anticipated to increase the risk of injuries and disease both during and after the event. Injuries or acute morbidity may be associated with flooding itself, actions taken to evacuate, individual responses to the loss of shelter, and loss of utilities such as electric power. Some of these injuries or acute medical conditions may be severe enough to require emergency department visits, hospital admissions, and/or emergency responses from trained medical personnel. A range of climatic events, including high heat episodes, could directly or indirectly lead to power outages, which have been linked to adverse health outcomes and mortalities, particularly based on outcomes of power outages in New York City after the August 2003 and Hurricane Sandy blackouts. The quantitative component of this impact evaluation focuses available information on potential changes in frequency of emergency responses due to increased flooding and storms, and the cost to provide increased emergency responses relative to periods where no storm or flooding has occurred. Qualitative evaluation addresses health effects specifically associated with the risk of power outages.

Urgency Ranking Results

This impact is ranked as a **medium priority** because of relatively lower quantified health impacts, a potential for disproportionate impacts, and a moderate adaptation gap.

Studies have found elevated rates of emergency room visits for gastrointestinal illness in Massachusetts in the two-week period following flooding and sewer overflows,[39,40,41] but research on a broader range of storm- and flood-related health impacts in the state is lacking. A more inclusive range of health effects associated with storm and flood events has been a subject of study in Florida since 2015, however.[42,43] The results presented here are based on a study comparing daily counts of selected health outcomes for specific "impact periods" including the day(s) of the event and a total of 14 follow-up days, as compared to control periods before and after the impact periods.[44] Two types of extreme events were assessed in that work: named hurricanes and severe flood, wind, or other storm events. For hurricanes, the projected change in frequency of tropical cyclones, by county, is based on analysis of storm frequency for the Massachusetts coast.[45] For other severe storm events, the change in annual frequency of 24-hour 2-inch rainfall events is drawn from downscaled GCM data.

To measure the incremental number of health effects and associated emergency response calls, the average baseline incidence is estimated over a two-week control period for the two health impacts with the most robust, statistically significant epidemiological results from the available literature: unintentional injuries and carbon monoxide (CO) poisonings. From this available literature the relative risk estimates are applied to generate excess risks during storm and hurricane events.

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[39] Wade TJ, Lin CJ, Jagai JS, and Hilborn ED. 2014. Flooding and Emergency Room Visits for Gastrointestinal Illness in Massachusetts: A Case-Crossover Study. PLoS ONE 9(10): e110474. doi:10.1371/journal.pone.0110474

[40] Jagai JS, deFlorio-Barker S, Lin CJ, Hilborn ED, and Wade TJ. 2017. Sanitary Sewer Overflows and Emergency Room Visits for Gastrointestinal Illness: Analysis of Massachusetts Data, 2006–2007. Environmental Health Perspectives. https://doi.org/10.1289/EHP2048

[41] Jagai JS, Li Q, Wang S, Messier KP, Wade TJ, Hilborn ED. 2015. Extreme Precipitation and Emergency Room Visits for Gastrointestinal Illness in Areas with and without Combined Sewer Systems: An Analysis of Massachusetts Data, 2003–2007. Environmental Health Perspectives. https://doi.org/10.1289/ehp.1408971

[42] Jagger MA, Kintziger KW, Dumas JS, Watkins S. March 2015. Health Effects of Tropical Storms and Hurricanes in Florida. Tallahassee, FL, Florida Department of Health. Available at http://www.floridahealth.gov/environmental-health/climate-and-health/_documents/tc-profile.pdf

[43] Kintziger, K.W., Jagger, M.A., Conlon, K.C., Bush, K.F., Haggerty, B., Morano, L.H., Lane, K., Roach, M., Thie, L. and Uejio, C.K., 2017. Technical documentation on exposure-response functions for climate-sensitive health outcomes. Available at https://www.cdc.gov/climateandhealth/docs/ExposureResponseFunctions_508.pdf

[44] Available in the form of a conference presentation: Kintziger, K.W., Odoi, E.W., Jagger, M.A. 2019. Impacts of Climate Change & Extreme Weather on Injury: A Primer for Investigation Focusing on Hurricane-Related Impacts. Presented at the January 8, 2019 annual meeting of the American Meteorological Association, as part of Themed Joint Session 15 – Hurricanes and Health: When Will We Stop "Learning Lessons" and Start Building Smarter? Abstract and recorded presentation available at: https://ams.confex.com/ams/2019Annual/webprogram/Paper354540.html; presentation text obtained from the authors.

[45] Marsooli, R., Lin, N., Emanuel, K., and Feng, K., 2019. Climate change exacerbates hurricane flood hazards along US Atlantic and Gulf Coasts in spatially varying patterns. Nature Communications. 10:3785, DOI:10.1038/s41467-019-11755-z

"I am additionally concerned about the intersection of these impacts during an extreme event -- a scenario where we have a heat wave and power is lost due to grid overload or a storm and folks can't cool their homes. "

"I also have elderly parents who depend on electricity to maintain a comfortable living environment. When the power goes out, they are at risk of getting hurt and even being impacted by the inability to regulate temperature."

"We recently installed an all house back up generator because we are privileged and have the means to do so. What about those who cannot afford such a thing?"

- Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The consequences of storms and power outages are projected to be **moderate**. The quantifiable effects are increasing frequency of CO poisoning and unintentional injury associated with extreme rainfall events and coastal hurricane; gaps in knowledge and data at this time prevent development of a comprehensive assessment. More than 400 additional annual storm-related medical incidents are estimated in Massachusetts as a result of climate change by the end of the century—a 52 percent increase from the estimated current climate incidence of 780 per year.[46] Costs of illness are not included in this estimate, but literature suggests potentially significant direct (morbidity and mortality) and indirect (lost productivity) costs associated with unintentional CO poisonings (more than $13 thousand per case[47]) and other injuries (more than $136 thousand per case for treatment and rehabilitation of major injuries[48]). Units costs of this magnitude, particularly for injuries, could mean incremental impacts of climate change of roughly $4 million by 2030, $28 million by 2050, and $50 million by 2070, but there is a high degree of variability in specific injury costs, which could be much lower for minor injuries, and a high degree of uncertainty on the specific types of injury associated with extreme events.

[46] Current estimates are based on statistical modeling of storm frequency under current climate, rather than health surveillance data

[47] Hampson, N.B. 2016. Cost of accidental carbon monoxide poisoning: A preventable expense. *Preventive Medicine Reports*, https://doi.org/10.1016/j.pmedr.2015.11.010

[48] Peterson, C., Miller, G.F., Barnett, S.B.L. and Florence, C., 2021. Economic cost of injury—United States, 2019. Morbidity and Mortality Weekly Report, 70(48), p.1655. https://www.cdc.gov/mmwr/volumes/70/wr/mm7048a1.htm

Table A7. Health Effects of Extreme Storms and Power Outages

Cases of carbon monoxide poisoning and unintentional injury attributable to climate-driven increases in the frequency of extreme rainfall events and coastal hurricanes. 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 add due to rounding.

	Additional Incidence of CO Poisoning				Additional Incidence of Unintentional Injury			
Region	**Baseline**	**2030**	**2050**	**2070**	**Baseline**	**2030**	**2050**	**2070**
Berkshires & Hilltowns	<1	<1	<1	<1	8	-1	1	2
Greater Connecticut River Valley	4	-<1	<1	1	47	-5	5	10
Central	5	-1	1	1	62	-4	9	18
Eastern Inland	16	1	6	10	250	18	84	140
Boston Harbor	14	-<1	4	7	220	2	58	110
North & South Shores	6	1	2	4	92	11	36	62
Cape, Islands, & South Coast	4	<1	1	2	61	6	20	33
Statewide	**49**	**<1**	**14**	**26**	**730**	**28**	**210**	**380**

Source: Author's analysis based on Kintziger et al. 2017 and 2019

The main climate driver of these additional incidents is extreme rainfall event frequency, which is expected to increase across the Commonwealth. Eastern regions are projected to see an additional, smaller bump in incidence due to increasing frequency of tropical cyclones. Higher populations in eastern regions coupled with this additional coastal cyclone risk account for the observed spatial distribution, with the highest increases in incidence expected in eastern regions for both sub-impacts. This distribution generally aligns with the relative rankings provided by stakeholders through the survey.

Carbon monoxide poisonings and unintentional injuries are indicators that can readily quantified using available methods, but the literature provides qualitative links for a number of additional health effects stemming from storms and power outages. A few studies in Massachusetts have measured emergency room visits for gastrointestinal illness following flooding and sewer overflow events, both of which can lead to increased exposure to contaminated water. One such study found an eight percent increase in the rate of emergency room visits for gastrointestinal illness in the four days following flood events.[49] A similarly constructed study focused instead on sanitary sewer overflows found a nine percent uptick in the rate of emergency room visits for gastrointestinal illness 10-14 days following events.[50]

Several other studies document adverse health outcomes and mortalities linked to medical technology failure and food spoilage. Much of this research in the United States examines the effects of power outages in New York City, particularly after the August 2003 and Hurricane

[49] Wade TJ, Lin CJ, Jagai JS, and Hilborn ED. 2014. Flooding and Emergency Room Visits for Gastrointestinal Illness in Massachusetts: A Case-Crossover Study. PLoS ONE 9(10): e110474. doi:10.1371/journal.pone.0110474

[50] Jagai JS, deFlorio-Barker S, Lin CJ, Hilborn ED, and Wade TJ. 2017. Sanitary Sewer Overflows and Emergency Room Visits for Gastrointestinal Illness: Analysis of Massachusetts Data, 2006–2007. Environmental Health Perspectives. https://doi.org/10.1289/EHP2048

Sandy blackouts. During power outage periods in New York State over the course of a decade, one study reported an increase of 3 to 39 percent for hospitalizations from chronic obstructive pulmonary disease (COPD), an average $4,670 increase in hospital costs per case, and a 38 percent increase in comorbidities per case.[51] Increased frequency of power outages due to extreme weather threatens the reliability of oxygen-supplying devices relied on by many people suffering from COPD, which is already the state's fourth leading cause of death, claiming nearly 3,000 lives in Massachusetts in 2017.[52] Climate impacts on populations that rely on electricity-dependent medical equipment is an area of ongoing research, with at least one study focused on Massachusetts,[53] though data limitations stemming from medical privacy have restricted the scope of such research to date.

A handful of additional studies in New York report on other health effects linked to storms and power outages. A study of the effects of Hurricane Sandy relates disruptions in dialysis services before, during, and following the storm to increased New York City emergency department visits, hospitalizations, and mortalities among patients with end-stage renal disease, when compared with hurricane-unaffected renal disease populations.[54] A more general assessment of outages in New York City found similar results, reporting higher incidence of respiratory disease hospitalizations and renal disease hospitalizations, as well as mortality.[55] A mortality-focused study reported increases in accidental (122 percent) and non-accidental (25 percent) deaths in New York City following the widespread August 2003 black-out, with elevated mortality risk persisting for most of the following month.[56] Another study reported a 16.6 percent increase in emergency department (ED) visits pertaining to pregnancy complications, a 26.7 percent increase in threatened and/or early delivery, and a 111.8 percent increase in gestational diabetes mellitus associated with power outages.[57]

Power outages can also indirectly affect health through food spoilage and/or refrigeration failure – these effects are categorized as part of the Food Safety and Security impact category. One research team reported immediate and statistically significant increases in the ratio of

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[51] Zhang, W., Sheridan, S. C., Birkhead, G. S., Croft, D. P., Brotzge, J. A., Justino, J. G., Stuart, N. A., Du, Z., Romeiko, X. X., Ye, B., Dong, G., Hao, Y., & Lin, S. (2020). Power Outage: An Ignored Risk Factor for COPD Exacerbations. Chest, 158(6), 2346–2357.

[52] Source: Centers for Disease Control data, available at: https://www.cdc.gov/nchs/pressroom/states/massachusetts/massachusetts.htm

[53] See, for example, Webb E, Balaji L, Nathanson LA, Balsari S, and Dresser C. 2021. Who's at Risk in a Changing Climate? Mapping Electricity-Dependent Patient Populations in a Coastal City. Rhode Island Medical Journal. http://www.rimed.org/rimedicaljournal/2021/11/2021-11-14-climate-webb.pdf

[54] Kelman, J., Finne, K., Bogdanov, A., Worrall, C., Margolis, G., Rising, K., MaCurdy, T. E., & Lurie, N. (2015). Dialysis care and death following Hurricane Sandy. *American journal of kidney diseases : the official journal of the National Kidney Foundation*, *65*(1), 109–115.

[55] Dominianni, C., Lane, K., Johnson, S., Ito, K., & Matte, T. (2018). Health Impacts of Citywide and Localized Power Outages in New York City. *Environmental health perspectives*, *126*(6), 067003.

[56] Anderson, G. B., & Bell, M. L. (2012). Lights out: impact of the August 2003 power outage on mortality in New York, NY. *Epidemiology (Cambridge, Mass.)*, *23*(2), 189–193.

[57] Xiao, J., Zhang, W., Huang, M., Lu, Y., Lawrence, W. R., Lin, Z., Primeau, M., Dong, G., Liu, T., Tan, W., Ma, W., Meng, X., & Lin, S. (2021). Increased risk of multiple pregnancy complications following large-scale power outages during Hurricane Sandy in New York State. *The Science of the total environment*, *770*, 145359.

diarrhea-associated ED visits compared to "other-cause" visits, sales of antidiarrheal medications, and gastrointestinal-illness-associated employee absences.[58]

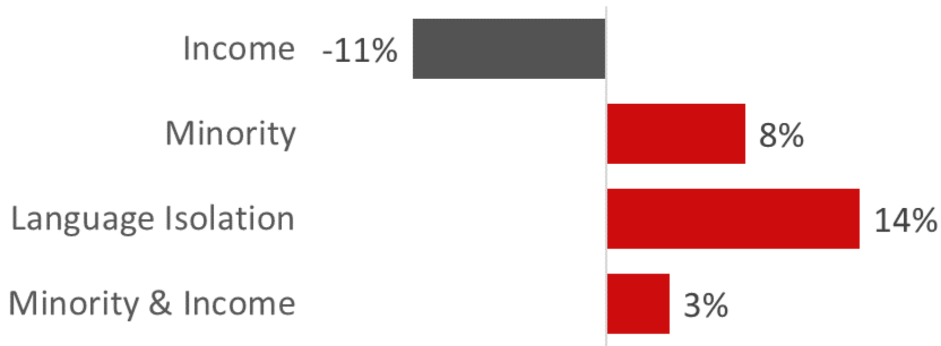
Disproportionality

This impact has **potential** for disproportionate exposure. Populations living in EJ block groups defined on the basis of:

- minority population have 8 percent higher rates of health effects from extreme events than the rest of the Commonwealth
- language isolated populations have 14 percent higher rates of health effects from extreme events than the rest of the Commonwealth

Figure A6. Disproportionality of Health Effects of Extreme Events

Comparison of the incidences of quantified health effects of extreme events 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 of the main report for further description of the EJ block group definitions.



The study referenced above linking pregnancy complications to the Hurricane-Sandy-associated power outages also noted that young adults, Black, Hispanic, and uninsured populations were at much greater risk for these pregnancy complications during that outage. Stakeholder consultations also highlighted potentially acute risks to individuals with pre-existing medical conditions, particularly those who may rely on medical devices requiring a consistent electric power source.[59]

Adaptation

There is a **moderate** adaptation gap for health effects from extreme storms and power outages. Municipalities across the state are exploring options for improving grid reliability and

[58] Marx, M. A., Rodriguez, C. V., Greenko, J., Das, D., Heffernan, R., Karpati, A. M., Mostashari, F., Balter, S., Layton, M., & Weiss, D. (2006). Diarrheal illness detected through syndromic surveillance after a massive power outage: New York City, August 2003. *American journal of public health*, *96*(3), 547–553.

[59] Data is available on Medicare beneficiaries reliant on electricity-dependent medical devices (https://empowerprogram.hhs.gov/empowermap), by zip code. A screening level analysis of these data suggests that about 3 percent of all Medicare beneficiaries in the Commonwealth are classified as electricity-dependent. The locations of these individuals do not appear to correlate with areas hardest hit by extreme storm outages.

preventing service disruptions through microgrid implementation, diversified energy production, and increased grid storage. Few plans specifically address the need to maintain power supply to emergency response infrastructure, which is particularly important for preventing adverse health impacts from extreme storms. Additional policy and funding support for residential adaptation is another effective approach that has yet to be widely implemented. Municipal programs can encourage further penetration of backup generators and provide public education about their use, both of which are key for mitigating the health risks included in this impact. While these smaller-scale approaches can be implemented relatively quickly, larger grid transformations and coordinated emergency planning require long lead times.

Example Adaptation Plans with Actions Addressing this Impact

- Climate Action and Resilience Plan – Weston: See backup energy and storage system for key infrastructure
- Hazard Mitigation Plan – Worcester: See emergency generator installation at evacuation shelter

Sensitivities and Uncertainty

Data on the future frequency of power outages that might be associated specifically with climate change impacts in Massachusetts were not available for this assessment. Research and analysis are underway to more specifically link climatic stressors to potential causes of outages, including high electricity demand, impaired electricity supply, and damages to electricity transmission and distribution infrastructure.

Estimates for changes in carbon monoxide poisonings and injuries are obtained from an unpublished study. While the results follow an established, published method, they have not undergone peer review. The method applied is well documented, however, and is straightforward to apply to estimate the health effect-specific results for demand for emergency services. Effects on food- and water-borne diseases reported in the study were excluded based on insufficient statistical support. Nonetheless, the lack of peer review may have some uncertain effect on results presented here.

Baseline incidence rates for carbon monoxide poisoning and injuries, and by extension for the emergency response outcomes estimated, are based on national data scaled to Massachusetts. The actual baseline incidence for the Commonwealth may be higher or lower than national data indicate.

The incomplete coverage of a broad range of accidental and non-accidental health outcomes potentially associated with both extreme storms and power outages within best available evidence likely leads to our underestimating health effects for this category, but better data and methods to support more on comprehensive assessments of all possibly linked health effects are not currently available.

Related Impacts

Table A8 lists the impacts in other sectors that have a connection to this impact.

Table A8. Additional Impacts related to Health Effects of Extreme Storms and Power Outages

Sector	Impact	Connection
Infrastructure	Damage to Electric Transmission and Utility Distribution Infrastructure	Extreme event damage to electric and communications service distribution infrastructure could lead to power outages, which could lead to adverse health effects.
Infrastructure	Loss of Energy Production and Resources	Power outages could be caused by extreme electricity demand events (such as in heat waves) or by damage to energy supply facilities (such as flood risks), which in turn could lead to adverse health effects.
Infrastructure	Reduction in Clean Water Supply	Energy outages can shut down water treatment and/or delivery services, potentially leading to further health impacts.
Human	Emergency Service Response Delays and Evacuation Disruptions	Potentially impassable roads due to episodic flooding may increase the time for emergency response, which in turn increases the severity of health impacts caused by extreme events.
Human	Reduction in Food Safety and Security	Power outages can lead to food spoilage through refrigeration failure.
Economy	Reduced Ability to Work	Individuals miss work while injured or sick or while caring for others who are injured or sick.
Governance	Increase in Demand for State and Municipal Government Services	Increase in demand for health care costs (e.g., MassHealth) to treat adverse health effects.

Human Sector: Urgent Impact #6 (tie)

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 and power outages) will mitigate some general risk, however more attention may be needed to target protection of cultural resources, including increasing the baseline inventory of at-risk resources.

Impact Summary

Cultural resources can be broadly defined to include historical buildings and artifacts, archeological sites, natural and built assets with links to tradition, and all other connections people have to living in Massachusetts. Some cultural resources are at risk of direct climate damage (e.g., flooding, erosion, and wind damage to historical buildings and archeological sites, and humidity levels and artifact preservation). Additionally, many of the direct effects of climate change discussed in other sectors also have a cultural component. For example, a decline in marine fisheries can impact the availability of local seafood, a key component in regional cuisine, and degradation of forests or freshwater ecosystems can decrease the value people hold for the environment around them. Evaluation of this impact draws heavily on conversations with stakeholders, where they were asked to identify cultural resources important to them that may be at risk due to climate change. It is important to acknowledge, however, that the scope of cultural resources is extremely broad, and so the Climate Assessment focuses on climate-related threats to a set of readily identified cultural heritage sites as indicators of the potential risks to cultural resources – some sites or resources of high cultural importance therefore may have been omitted.

Urgency Ranking Results

This impact is ranked as a **medium priority** because of lack of certainty around potential damages and changes in cultural resources, signaling a need for further research to characterize this risk.

To evaluate this impact, first the threats of climate change on resources, traditions, and characteristics that make up the sense of place in Massachusetts are qualitatively discussed. This discussion is supported by a summary of stakeholder input on cultural resources, and in many cases, more detailed analyses of direct damage presented in other sectors.

Next, flood risk profiles for inland and coastal flooding from the relevant Infrastructure sector analyses for this report are used to assess flood risks to Cultural Heritage Sites and Libraries, and sites listed on the Massachusetts Historical Commission inventory.

> *"I worry that cultural resources along the water aren't protected and [these] spaces, which are often free, will disappear."*
>
> - Stakeholder Survey Respondents (See Appendix C for details)
>
> *The rocks are living, the water has life, trees talk. When those things are removed from the environment or are in jeopardy, it has a real impact on us, including on our mental health and spiritual connection – it's like a death in the family.*
>
> - Tribal Member Interviewee (See Appendix C for details)

Magnitude of Consequence

This impact is found to have a **moderate** level of consequence due to the combination of measurable damages to cultural and historical sites from flooding, erosion, extreme weather, and humidity, as well as the intangible losses of some of the defining characteristics of Massachusetts. Many of the impacts discussed in other parts of the Climate Assessment also have primary consequences for cultural resources; Table A9 provides examples of these connections.[60] These connections highlight examples of the sense of place, which are often intangible but important to residents of the Commonwealth, and to Indigenous communities in particular. In general, the loss of distinct seasons emblematic of New England, as winters become milder is a potentially major impact.

Table A9. Cultural Resources at Risk Related to Other Assessed Impacts

This table provides examples of the types of cultural resources and values at risk due to climate change by primary sector and impact.

Sector	Impacts	Example Cultural Resources at Risk
Natural Environment	All assessed impacts	• Scenic landscapes and vistas • Existence values for native flora and fauna (particularly those held by Indigenous peoples) • Leaf peeping trips • Wildlife viewing (e.g., birds and butterflies)
Economy	Decrease in Agricultural Productivity; Decrease in Marine Fisheries Productivity; Damage to Tourist Attractions and Recreation Amenities	• Cultural and family traditions of agriculture and fishing as a way of life and a way of preserving food autonomy • Ability to know where food comes from • Harvest traditions (e.g., maple sugaring, apple picking, lobstering)

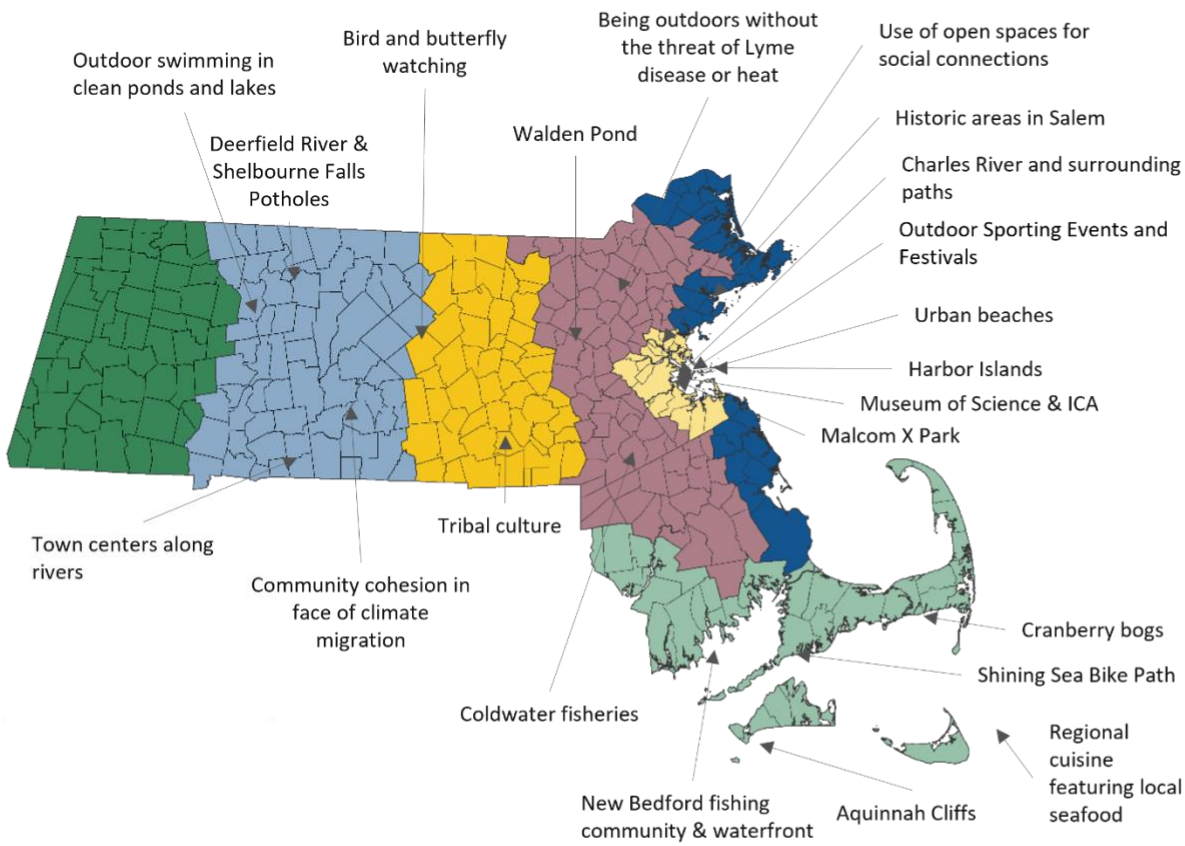
[60] Because the connections to other impacts are a primary component of this magnitude rating, the table of related impacts is presented in this section, rather than at the end of the section (as it is done for other impacts).

Sector	Impacts	Example Cultural Resources at Risk
		• Local ingredients for regional cuisine • Culturally important tourist attractions, including heritage tourism, and recreation amenities
Human	Increase in Vector Borne Diseases Incidence and Bacterial Infections and Health and Cognitive Effects from Extreme Heat	• Enjoyment of public outdoor gathering spaces during the day (particularly paved/turf/unshaded areas) and related community building • Enjoyment of public outdoor gatherings spaces during the evening (particularly grassy and semi-wooded areas) and related community building
Infrastructure	Damage to Inland Buildings; Damage to Coastal Buildings and Ports; and Damage to Electric Transmission and Utility Distribution Infrastructure	• Structures, burial grounds, and other culturally or historically important sites in floodplains • Artifacts and collections that require controlled climate (e.g., low humidity) for protection)

Stakeholder input is an important piece of this impact evaluation. In a series of virtual public meetings, as well as via targeted interviews, stakeholders were asked to identify cultural resources (e.g., places, traditions, resources, activities) that could potentially be at risk from climate change. Figure A7 presents a sample of the locations discussed, which include natural features (e.g., Deerfield River, Cape Cod National Seashore), built recreation infrastructure (e.g., Shining Sea Bike Path, Charles River paths, Malcom X Park), and historic sites and museums (e.g., Historic Salem, Museum of Science, Institute of Contemporary Art). Statewide, stakeholders voiced concerns over the loss of agriculture as a way of life, specifically the value of knowing where food comes from, being able to grow one's own food, and traditions around harvests (e.g., apple picking and maple sugaring), winter recreation culture (including the potential loss of reliable snowfall during December holidays), and threats to outdoor events which are critical to community (e.g., high heat threatening day events and mosquito borne illness threatening evening events). Tribal members particularly noted how a changing climate threatens their spiritual and traditional connection to aspects of the natural environment, which they consider a "peer" or part of their own family. Participants further highlighted natural features and open space for their importance regarding mental health. Respondents cited the demand for open space during the Covid-19 pandemic as an example of the criticality of these resources for maintaining mental health, particularly in times of crisis.

Figure A7. Stakeholder Identified Cultural Resources of Concern

Specific locations identified by public stakeholders during a virtual meeting focused on cultural resources at risk from climate change.

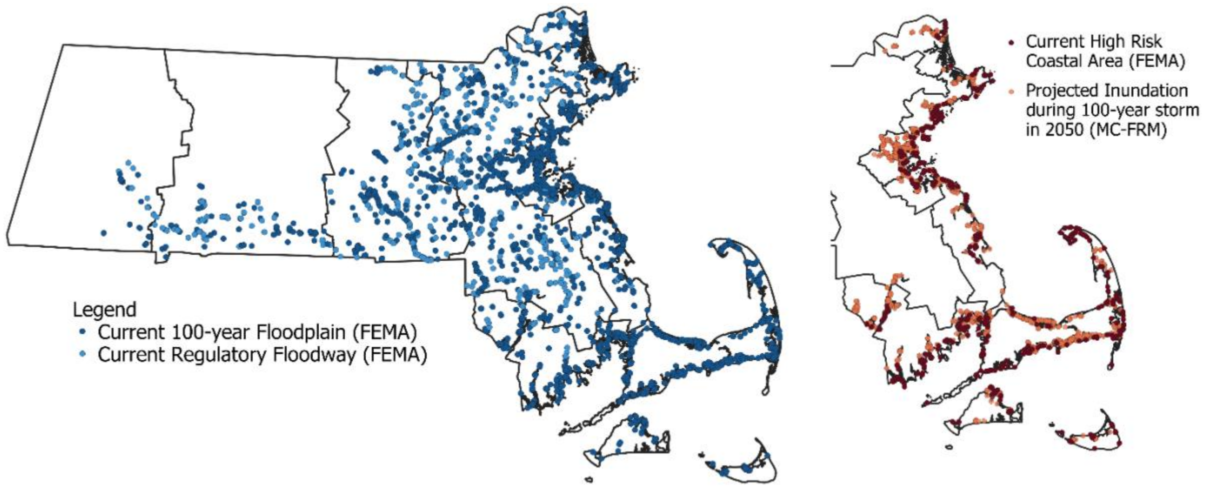


Using spatial data on cultural heritage sites, historical places, and other sites with cultural importance and/or archives and inland and coastal flooding data identifies specific locations that may be at risk of flooding. The Massachusetts Historical Commission maintains the Massachusetts Cultural Resource Information System (MACRIS), an inventory of over 200,000 cultural resources and historical sites in the Commonwealth Figure A8 below shows the sites in this list that fall within FEMA's current 100-year inland flood zone (left panel) and are at risk for coastal flooding (right panel). Approximately 8,000 sites and resources are within a currently designated FEMA floodplain and over 6,000 sites and resources could be at risk of inundation during a 100-year flood by 2050.[61]

[61] Note that MACRIS includes water-based resources and sites such as footbridges and fish runs. Not all of these resources will be vulnerable to flooding.

Figure A8. Massachusetts Cultural Resource Information System (MACRIS) Sites and Resources Vulnerable to Flooding

The left panel shows sites and resources that fall within FEMA's current 100-year floodplain or regulatory floodway. The right panel shows coastal sites located within areas either currently identified by FEMA as very high-risk coastal areas or projected to be inundated by a 100-year storm in 2050.



Source: MACRIS sites and FEMA floodplains from MassGIS, Coastal Flooding layer from MC-FRM

Figure A9 shows the cultural heritage sites and libraries with projected flooding for a 100-year storm event in the current period, both inland and coastal, as an example of some specific and relatively well-known sites that could be at risk of flooding.

Figure A9. Cultural Heritage Sites and Public Libraries within the current 100-year Flood Zone

Map shows cultural heritage sites and public libraries within the current 100-year flood zone based on FEMA hazard maps. As sea levels rise and precipitation becomes more intense, additional sites could become at risk.

Source: Site locations from MassGIS

Historical buildings are faced with challenges adapting to climate change as options for retrofitting historical structures may be more limited than typical structures, though strategies exist (see for example the Elevating History project in Newport, RI). Museums and historic sites face additional threats beyond direct structural damage. Electricity disruptions may limit the ability to control indoor climate conditions necessary to protect sensitive artifacts. Additionally, transportation disruptions and extreme weather could reduce visitation to these sites, resulting in a loss of revenue.

Disproportionality

This impact is characterized as having a **potential** for disproportionate impact based on a qualitative assessment. Values for cultural resources are specific to the lived experiences of those holding the value, and therefore, not all people in the Commonwealth hold value for the same resources. Historically marginalized groups may have less access to resources to protect the resources most important to them, which could lead to disproportionate losses. It is also likely that smaller institutions, with limited budgets, will have less capacity to prepare for and recover from potentially damaging events.

Adaptation

There is a **moderate** adaptation gap for protecting cultural resources from climate threats. Flooding is the main hazard considered here for physical assets, and many of the flood mitigation actions in the infrastructure sector will have carryover effects in reducing flood risk at cultural sites. However, protecting cultural and historical sites carries unique challenges. Relocating out of floodplains or other climate-threatened areas (e.g., areas vulnerable to erosion) may be difficult because the location of the site might be culturally significant or the site may not be movable (e.g., an archaeological site).[62] The need to maintain the historical character of buildings may complicate or rule out some retrofitting approaches. Additional adaptation is also needed to prepare for other stressors such as humidity control and withstanding power outages.

The large range of cultural resources in the state also means that no one set of actions will be applicable in all cases. Effective planning and coordination between federal, state, local, and Tribal agencies and communities is particularly important given these complications. Some communities have worked to inventory cultural resources (for example, the 2021 Introduction to Indigenous Cultural Sites in Shutesbury and archaeological reconnaissance surveys in Middleborough and North Attleborough) and assess their vulnerability to climate hazards, and the Coordinated Statewide Emergency Preparedness (COSTEP) framework provides a good model for regional coordination and emergency management for these resources. The Massachusetts State Historic Preservation Plan 2018-2022 outlines the state's plans for protecting historic resources, and specifically refers to the risk of coastal erosion to coastal archaeological sites. Further expanding these inventories and coordination efforts will be vital to protecting the state's cultural resources. Bolstering targeted state and local funding

[62] See the National Park Service Guidelines on Flood Adaptation for Rehabilitating Historic Buildings: https://www.nps.gov/orgs/1739/upload/flood-adaptation-guidelines-2021.pdf

programs aimed at capital improvements for cultural resources can help to ensure that the unique adaptation needs of these sites can be met.

Example Adaptation Plans with Actions Addressing this Impact

- Metro Boston Regional Climate Change Adaptation Strategy Report: See Protection of Cultural and Historic Assets and Records section
- Hazard Mitigation Plan, 2015 Update—Cambridge: See Historic, Cultural, and Natural Resource Areas section
- Resilient Nantucket: Flooding Adaptation & Building Elevation Design Guidelines provides suggested practices for historic Nantucket buildings at risk of flooding and sea level rise

Sensitivities and Uncertainty

The magnitude of consequence for many of the components discussed in this section are immeasurable due to their intangible nature, and also depend on individuals' preferences, heritage, and experience. Not all residents will experience loss from the same set of cultural resources but all residents will have resources of value at risk. It is unclear how residents' values, traditions, and behaviors surrounding the broad cultural resources and identify defining characteristics of the Commonwealth described in this chapter may change as climate effects these resources. For example, as winters become milder, some may find new traditions or value in extended warm seasons while others may experience acute loss of cold-weather activities.

This assessment is also unable to quantitatively assess damages beyond direct flooding, such as heat and precipitation stress on building exteriors or mold damage to archives. As described in the Aeroallergens and Mold impact (Human sector) estimates of change in the frequency of mold-inducing events are not currently available for Massachusetts.[63]

Related Impacts

This impact is defined based on strong connections to other impacts in this Climate Assessment. See Table A9 for a detailed list of the cultural resources at risk, as related to the impacts in other sectors.

[63] Ideally, this assessment could include changes in the number of consecutive days with relative humidity greater than 70 percent as an indicator for the likelihood of changes in mold prevalence in the future. The MACA climate modeling tools provide downscaled vapor pressure deficit (VPD), which can be transformed into relative humidity with air temperature using the Arrhenius equation, but current climate baseline variables for MACA are from a third-party source and currently unavailable in the same format.

Human Sector: Urgent Impact #9

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.

Impact Summary

Climate change has the potential to increase the incidence of certain vector borne diseases and bacterial infections, such as Lyme disease (tick-borne), West Nile Virus (mosquito-borne), and vibriosis (a marine waterborne bacterium), and their associated fatal and nonfatal outcomes, as a result of changes in temperature and extended seasons for vectors or more direct impacts on bacterial loads.

Urgency Ranking Results

This impact is ranked as a **medium priority** because major potential impacts but low risk of disproportionate impacts and a minimal adaptation gap.

The Lyme disease analysis is based on Couper et al. (2020) which provides functions for projecting Lyme disease incidence in six regions of the US in response to climate change.[64] The model estimates future incidence as a function of average spring temperature, number of hot/dry days, cumulative temperature, total annual precipitation, and temperature variability. Impacts are valued using a direct and indirect cost-of-illness estimate of $12,280 per incidence.[65]

The West Nile Virus (WNV) analysis is based on USEPA-sponsored literature that models the association between WNV neuroinvasive disease incidence with temperature in historical data,

[64] 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.
[65] 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.

and then projects ambient temperature to 2050 and 2090 using five GCMs.[66] Impacts are valued using medical cost-of-illness to treat the disease (an average cost of $45,000) and individual values for avoiding the risk of premature death.[67]

The vibriosis analysis is based on USEPA-sponsored literature that constructed logistic regression models using historic vibriosis and sea surface temperature data at the county level.[68] Cases were valued using a weighted cost-per-case value that included direct medical costs, indirect productivity losses, and willingness to pay to avoid the risk of premature death.

"*We farmed for 20 years without finding a tick on ourselves but now it is a common occurrence.*"

"I worry that as insect-borne diseases increase, people will want to use toxic pesticides more."

- Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The consequences of increased vector-borne disease incidence and bacterial infections are projected to be **major** due to widespread and substantial increases in Lyme Disease, and moderate increases in WNV and vibriosis, and the severity of the effects. Currently, approximately 3,000 cases of Lyme Disease are reported annually across the state.[69] One thousand three hundred additional annual cases of Lyme disease are projected to occur statewide in the near term (2030), with over 10,000 additional cases attributable to climate change by 2090. Lyme disease rates are estimated to increase from 19 in 100,000 in 2030 to 131 in 100,000 by 2090.

Currently, there are less than three cases of WNV infections annually, on average, across the state. Approximately 32 new cases of WNV are estimated in the Commonwealth as a result of climate change by the end of the century. Rates will increase from 0.04 in 100,000 currently to 0.4 in 100,000 by 2090.

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[66] Belova, A., Mills, D., Hall, R., Juliana, A.S., Crimmins, A., Barker, C. and Jones, R. (2017) Impacts of Increasing Temperature on the Future Incidence of West Nile Neuroinvasive Disease in the United States. *American Journal of Climate Change*, 6, 166-216.

[67] Approximately 6.5 percent of cases in the historical period resulted in death, which is assumed to remain constant throughout the century. Additional cases are valued using a weighted average of costs for fatal and nonfatal outcomes of WNV.

[68] Sheahan, M., Gould, C., Neumann, J., Kinney, P., Hoffmann, S., Fant, C., Wang, X., and Kolian, M. 2022. The Influence of Climate Change on Vibriosis in the United States: Projected Health and Economic Impacts for the 21st Century. Environmental Health Perspectives. [accepted, in print]

[69] Massachusetts Department of Public Health. 2014, Lyme Disease Surveillance in Massachusetts. Available at https://www.mass.gov/lists/tick-borne-disease-surveillance-summaries-and-data#lyme-disease-surveillance-data-Data averaged for 2010 to 2014.

Currently, there are approximately 8,900 annual cases of vibriosis in Massachusetts.[70] Sheahan et al. (2022) project that in the near term (2030), an additional 3,300 cases attributable to climate are projected to occur, with approximately 14,500 additional cases by 2090. Rates will increase from 46 in 100,000 in 2030 to 182 in 100,000 by 2090. While the vast majority of vibriosis cases are mild, and involve gastrointestinal distress for less than one week, some infections, particularly those contracted through a dermal route of exposure from exposure to *vibrio vulnificus*, are serious and can cause loss of limb or death. These more severe infections, usually contracted among swimmers with open wounds and/or immunocompromised conditions, are projected to account for a growing proportion of the incidence and economic impact over time, accounting for 15 percent of the current economic impact but projected to account for 28 percent by 2090.

Table A10. Additional Cases of Vector-Borne Disease and Bacterial Infections

Additional cases of Lyme Disease, West Nile Virus (WNV), and vibriosis attributable to climate change. Statewide economic costs are presented in millions of dollars. 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 Lyme Cases		Additional WNV Cases		Additional Vibriosis Cases	
Region	**2050**	**2090**	**2050**	**2090**	**2050**	**2090**
Berkshires & Hilltowns	120	650	<1	<1	0	0
Greater Connecticut River Valley	200	470	1	2	0	0
Central	440	1,100	1	4	140	310
Eastern Inland	1,400	3,800	3	11	1,800	4,000
Boston Harbor	570	1,600	3	10	1,300	3,000
North & South Shores	460	1,300	1	2	740	1,700
Cape, Islands, & South Coast	510	1,500	1	2	2,400	5,400
Statewide	**3,700**	**10,000**	**9**	**32**	**6,400**	**14,500**
Economic Costs ($millions)	**$45**	**$130**	**$8.2**	**$35**	**$54**	**$140**

Source: Author's analysis based on Couper et al. 2020; Belova et al. 2017; and Sheahan et al. 2022

The majority of impacts fall in the more populous Eastern Inland and Boston Harbor regions, with substantial vibriosis incidence originating in the Cape, Islands, and South Coast region as well. Rates of Lyme disease are highest in the Berkshires & Hilltowns region, as well as the Cape, Islands, and South Coast (120 and 78 percent higher than the state average, respectively). Rates of WNV are highest in the Boston Harbor Region (29 percent higher than the state average). Rates of vibriosis are highest in the Cape, Islands, and South Coast region (370 percent higher than the state average in 2090). County-level rates of Lyme Disease are presented in Figure A10.

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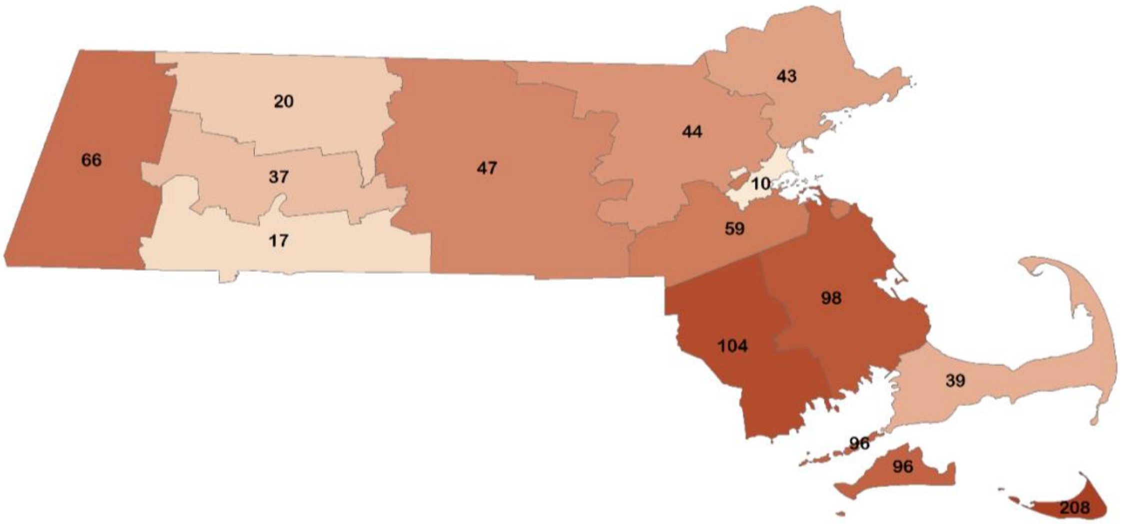
[70] Project team analysis of data supporting Sheahan et al. (2022). Estimate includes severe confirmed cases which are reported annually to CDC and characterized in CDC's COVIS database, as well as less severe cases estimated based on CDC's methodologies, found here: https://www.cdc.gov/vibrio/index.html.

Figure A10. Rates of Lyme Disease per 100,000 by County; 2050

Rates of Lyme Disease per 100,000 based on an analysis of functions from Couper et al. 2020. The highest rates are seen in the Cape, Islands, and South Coast region.



Source: Author's analysis based on Couper et al. 2020

Disproportionality

Of the three diseases assessed, West Nile Virus incidence is the only disease showing disproportionate exposure in the Commonwealth. Populations living in EJ block groups defined on the basis of:

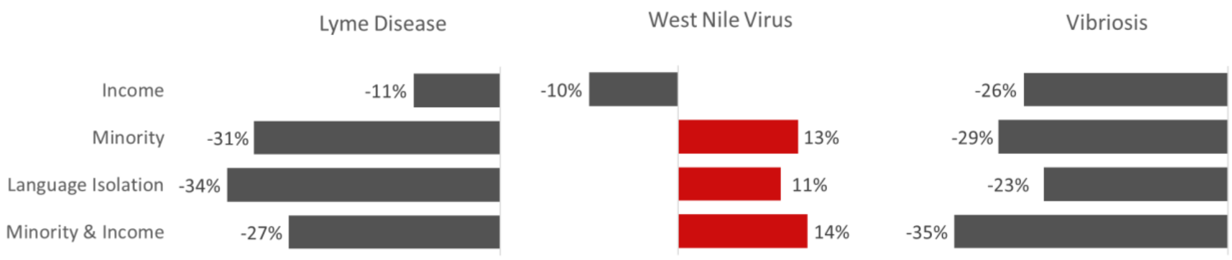
- minority population have 13 percent higher rates of WNV cases than the rest of the Commonwealth
- language isolated populations have 11 percent higher rates of WNV cases than the rest of the Commonwealth

Lyme and vibrio are expected to grow in incidence and account for a much greater share of incidence in this category than WNV, therefore, this impact is classified as **limited** disproportionate exposure.[71] Vulnerable populations are 11 to 35 percent less likely to be exposed to Lyme disease and vibriosis than the state population as a whole – that is, climate-induced incidence is projected to be much higher in non-EJ block groups than in EJ block groups.

[71] Although this analysis does not find a quantitative correlation between the locations of exposure to this impact and EJ block groups, it is important to note that not all populations will have the same experience with the effects of climate change and this impact because of pre-existing social vulnerabilities that are difficult to measure or comprehensively quantify across the Commonwealth.

Figure A11. Disproportionality of Vector-Borne Disease Incidence

Comparison of the additional cases of vector-borne diseases and bacterial infections 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 of the main report for further description of the EJ block group definitions.



Adaptation

There is a **moderate** adaptation gap for vector-borne disease incidence and bacterial infections. Available adaptation approaches are limited and vary across the set of illnesses included in this impact. Some municipalities are implementing public education campaigns about climate effects on these risks and expanding monitoring and reporting efforts for vector-borne diseases and other infections. The Massachusetts Department of Public Health provides information and incidence statistics to the public on ways to avoid Lyme disease and West Nile Virus infections (see the Recommendations of the Mosquito Control for the Twenty-First Century Task Force), and the Division of Marine Fisheries has an updated 2022 Vibrio Control Plan which is designed to limit vibrio infections, focusing on safe handling of oysters for human consumption to minimize risk. These plans have been effective in preventing many cases, but climate change is expected to enhance the environments for growth and activity of the disease vectors addressed in this summary, meaning that existing plans may require updating, additional public outreach activity, and other actions to limit the spread of these diseases.

Many adaptation actions have added benefits in the form of pest prevention—green stormwater infrastructure and landscaping practices improve drainage and reduce standing water, discouraging mosquito breeding, and making tick encounters less likely. Stronger food safety standards and local sustainable food systems can limit the incidence of bacterial infections like vibriosis. Still, incidence is projected to increase through the end of the century, and funding for expanded research and development of chemical and biological control methods for controlling vector-borne illnesses is warranted.

Example Adaptation Plans with Actions Addressing this Impact

- Division of Marine Fisheries 2022 Vibrio Control Plan
- Department of Public Health Lyme Disease Fact Sheet
- Integrated Vector-borne Disease Control Program – Uxbridge

Sensitivities and Uncertainty

In general, estimation of the incidence of vector-borne diseases is difficult to project because of the complex chain of events associated with the outcome. Climatic factors mostly influence the vector of the relevant disease, its abundance in the environment, and sometimes its ability to survive from season to season (e.g., for ticks, mild winters increase survival rates and peak season environments). The incidence is also dependent on human behavior which may lead to the exposure – for example, Lyme disease and West Nile Virus are contracted outdoors, sometimes in recreational settings, and vibriosis is a consequence of either consuming raw seafood or swimming with an open wound. Modeling all aspects of these chains of events is challenging, so the studies used in this section rely on correlations in the historical record between climatic variables relevant to the vector and historical incidence rates. This can add to the uncertainty in reliably identifying a causal relationship. The studies used In this section are published in peer-reviewed journals of epidemiology or climate science, and reflect best practices for climate impact assessment, but the existing literature would benefit from a broader base of corroborating studies to provide further support for this assessment.

Related Impacts

Table A11 lists the impacts in other sectors that have a connection to this impact.

Table A11. Additional Impacts related to Health Effects of Vector-borne Diseases

Sector	Impact	Connection
Economy	Reduced Ability to Work	Individuals miss work while sick or caring for others who are sick.
Human	Damage to Tourist Attractions and Recreation Amenities	People may be hesitant to spend time outdoors recreating as tick and mosquito-borne disease become more common.
Governance	Increase in Demand for State and Municipal Government Services	Increase in demand for health care costs (e.g., MassHealth) to treat adverse health effects.

Infrastructure Sector

The Infrastructure sector includes impacts to buildings and transportation systems, and how we get our electricity and water. Flooding (coastal and inland) is a major threat to infrastructure, but drought, freeze-thaw cycles, high heat, and wind are also of concern. Because of infrastructure lifespans and planning horizons, adaptation action is often needed near term.

Table A12. Infrastructure Sector Impacts Ranked by Urgency Score

IMPACT	MAGNITUDE	DISPROPORTIONATE EXPOSURE	ADAPTATION GAP	URGENCY SCORE
Damage to Inland Buildings (MOST URGENT)	Major	Disproportionate	Moderate	80
Damage to Electric Transmission and Utility Distribution Infrastructure (MOST URGENT)	Major	Potential	Extreme	75
Damage to Rails and Loss of Rail/Transit Service (MOST URGENT)	Moderate	Disproportionate	Moderate	72
Loss of Urban Tree Cover	Moderate	Disproportionate	Minimal	61
Damage to Coastal Buildings and Ports	Extreme	Limited	Moderate	55
Reduction in Clean Water Supply	Major	Potential	Minimal	53
Damage to Roads and Loss of Road Service	Major	Limited	Moderate	47
Loss of Energy Production and Resources	Moderate	Limited	Minimal	28
Increased Risk of Dam Overtopping or Failure	Minimal	Limited	Moderate	19

Infrastructure Sector: Urgent Impact #4

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, air pollution removal, stormwater filtration, and aesthetic values.

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.

Impact Summary

Climate change, in the short term, may promote tree growth in urban areas, but will ultimately lead to stresses and death of some existing species and plantings, the way they are currently planted and managed. Increased carbon dioxide (CO_2) and warmer temperatures will promote growth however a lack of nutrient availability and water quality from dense urban areas will amplify climate impacts.[72] Examples of the ways climate change stresses urban trees include:

- Increased climate extremes will increase the chances of extreme climate events such as ice storms leading to winter kill;
- Increasing extreme storms and high winds will lead to increased pressure on municipalities, utilities, and transportation departments to manage vegetation, which in some cases could result in tree removal or extensive pruning;
- Increased ambient winter temperature will allow for higher pest and pathogen levels; and
- Disturbance to the water cycle will lead to soil degradation, uprooting of trees, more frequent drought stress, and poorer water quality.[73]

Benefits from urban tree coverage has an estimated yearly value of $720.3 million in Massachusetts.[74] These benefits include carbon sequestration, air pollution removal, avoided energy cost, and avoided emissions. With some important exceptions, urban trees are planted

[72] Pretzsch, H., Biber, P., Uhl, E. *et al.* Climate change accelerates growth of urban trees in metropolises worldwide. *Sci Rep* **7**, 15403 (2017). https://doi.org/10.1038/s41598-017-14831-w

[73] Safford, H.; Larry, E.; McPherson, E.G.; Nowak, D.J.; Westphal, L.M. (August 2013). Urban Forests and Climate Change. U.S. Department of Agriculture, Forest Service, Climate Change Resource Center. www.fs.usda.gov/ccrc/topics/urban-forests

[74] Nowak, D.J. and Greenfield, E.J., 2018. US urban forest statistics, values, and projections. Journal of Forestry, 116(2), pp.164-177. https://doi.org/10.1093/jofore/fvx004

and maintained as part of the system of urban infrastructure and are valued for the service flows provided primarily to local urban residents. In this way, urban trees are similar to other forms of urban infrastructure. For that reason, urban tree cover is considered within the Infrastructure sector.

While it is clear certain conditions such as heat and drought will impact urban trees, the magnitude of the impact is recognized as uncertain in the literature.[75, 76]

Urgency Ranking Results

This impact is ranked as a **medium priority** because of its moderate but highly disproportionate effects. Baseline urban tree canopy coverage in all towns in Massachusetts is identified by USDA Forest Service data.[77] Available projections of urban tree coverage do not distinguish between development pressures and climate stressors, therefore in addition to evaluating the projected decline in canopy coverage from all causes, areas where urban trees may be at higher risk of mortality due to extreme heat are also using the Metropolitan Area Planning Council Land Surface Temperature Index. These "hot spots", also represent areas where the cooling services of urban tree coverage could be most beneficial.

> *"I feel that there is often not a lot of shade for pedestrians--this hurts people who do not own cars."*
>
> \- Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The consequences of climate change on the loss of urban trees in most areas are projected to be **moderate** because the impacts of climate change on urban tree coverage are outweighed by other factors such as development patterns and tree stewardship. However, stewardship behaviors are also influenced by climate change. Public works departments may need to remove and prune more trees as risks of limbs impacting power lines increase with increasing frequency and severity of storms.

The developed regions of Massachusetts, which are broader than what is typically considered 'urban areas', currently have 56 percent tree coverage, with the Boston Harbor region having a noticeably lower area of coverage than the statewide average. Growing urban development and climate change are two of the most significant pressures on urban tree coverage. More frequent extreme temperature affects nutrient cycling and lowers the ability for urban trees to survive.

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[75] Esperon-Rodriguez, M., Rymer, P.D., Power, S.A., Barton, D.N., Cariñanos, P., Dobbs, C., Eleuterio, A.A., Escobedo, F.J., Hauer, R., Hermy, M. and Jahani, A., 2022. Assessing climate risk to support urban forests in a changing climate. Plants, People, Planet, 4(3), pp.201-213.

[76] Khan, T. and Conway, T.M., 2020. Vulnerability of common urban forest species to projected climate change and practitioners perceptions and responses. Environmental management, 65(4), pp.534-547.

[77] USDA Urban Forest Data - https://www.nrs.fs.fed.us/data/urban/

Table A13. Current Urban Tree Coverage

This table reflects the percentage of Urban area (as designated by the Census) in each region that is covered by tree canopies. Note that the Census "urban areas" designation encompasses more area than may more generally be considered urban areas.

Region	Baseline Canopy of Developed Area Percentage
Berkshires & Hilltowns	73%
Greater Connecticut River Valley	64%
Central	57%
Eastern Inland	50%
Boston Harbor	18%
North & South Shores	43%
Cape, Islands, & South Coast	45%
Statewide	**56%**

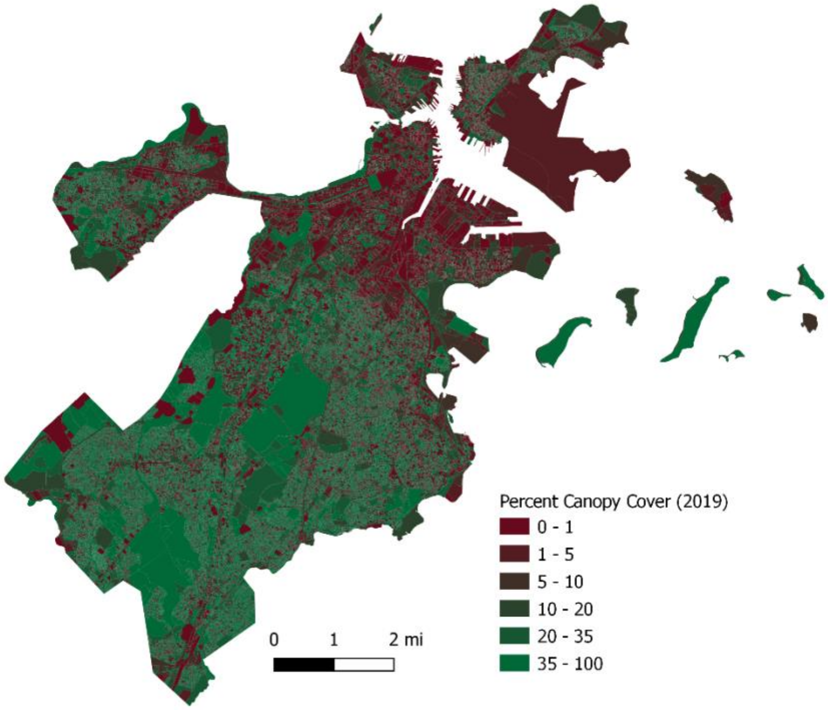
Source: USDA Urban Forest Data

Within a region, and even within a city or town, tree coverage can vary spatially. For example, the Boston Harbor region has 18 percent canopy coverage over developed land (cited above), the City of Boston has 26 percent canopy coverage due to large greenspaces such as Franklin Park, and less than half of parcels in the city have canopy coverage greater than one percent, seen in Figure A12.[78] Trees in large greenspaces may face some of the same challenges as other urban trees, such as those used to line city streets, however they are often managed for different purposes and provide different benefits. When thinking about how to adapt to the challenges climate change poses to urban trees, adaptation plans will need to identify which types of trees and in which specific locations will be the focus.

[78] Calculated based on City of Boston data available at: https://data.boston.gov/dataset/parcels-tree-canopy-metrics

Figure A12. Canopy Cover in the City of Boston

Percent canopy cover by parcel in the City of Boston, as of 2019. Less than half of parcels have greater than one percent canopy cover.



Source: Author's analysis using data from Boston Maps[79]

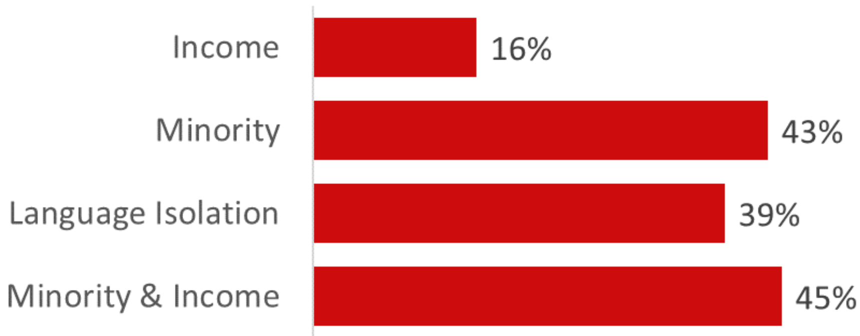
Disproportionality

This impact category is determined to have **disproportionate** exposure, as existing tree coverage is disproportionately lacking in EJ population areas, as summarized in Figure A13. EJ block groups defined on the basis of minority population, language isolation, and minority population in conjunction with low-income status have 39 to 45 percent less tree canopy coverage than other block groups in the Commonwealth. EJ block groups also have disproportionate exposure to temperature hot spots, which could threaten the relatively few trees in the areas.

[79] https://data.boston.gov/dataset/parcels-tree-canopy-metrics

Figure A13. Disproportionality of Impacts from Urban Tree Loss

Comparison of urban tree coverage 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.



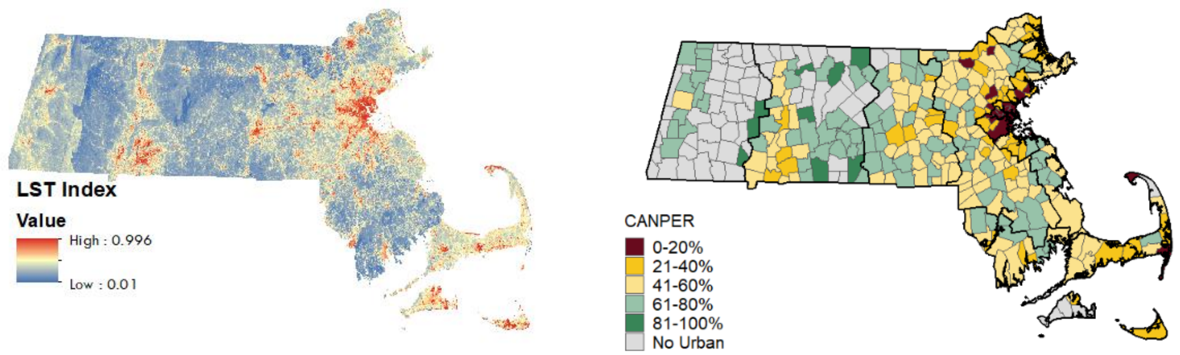
A recent study found urban areas between Washington D.C. and Boston had the greatest difference in tree cover between low and high-income blocks in the country.[80] Protecting and increasing urban tree coverage is also an important adaptation action to address other impacts of climate change, including health effects of extreme heat. Figure A14 maps the percentage of canopy coverage of towns in Massachusetts and locations that have experienced the hottest Land Surface Temperatures (LST) over a two-year period (2018-2020).[81] A comparison of the two maps reveals strong correlation between low canopy cover and high temperatures. For example, the Boston Harbor region, the Chicopee and Springfield area in the Greater Connecticut River Valley region, and Worcester in the Central region have the lowest tree coverage and also experience the highest land surface temperatures. The correlation can have compounding effects: places with fewer trees tend to be warmer in absence of the shade and cooling services of canopy cover and trees may have a more difficult time surviving the conditions in “hot spots” without adequate stewardship.

[80] McDonald, R.I., Biswas, T., Sachar, C., Housman, I., Boucher, T.M., Balk, D., Nowak, D., Spotswood, E., Stanley, C.K. and Leyk, S., 2021. The tree cover and temperature disparity in US urbanized areas: Quantifying the association with income across 5,723 communities. PloS one, 16(4), p.e0249715.

[81] Metropolitan Area Planning Council Land Surface Temperature Index

Figure A14. Percentage of Canopy Cover in Massachusetts Towns

LST Index takes land surface temperature estimates from multiple dates and combines them into a composite index which reflects heat effects across space.[82] CANPER represents the percentage of tree canopy land area coverage in each town of Massachusetts.



Data Source: Landsat and MAPC[83]   Data Source: USDA Forest Service

Adaptation

A significant portion of developed areas contain urban trees. The lowest percentage area, Boston Harbor, will most likely require the greatest assistance to combat the negative effects of climate change.

There is a **minimal** adaptation gap for loss of urban tree cover. Increasing green space and tree cover in urban areas has broad co-benefits across impacts and sectors, so actions that include tree coverage objectives are common in plans across the Commonwealth. However, implementing broad collective action across all urban areas will be difficult and require funding, coordination, and substantial labor. The Greening the Gateway Cities Program has planted over 30,000 trees in over 20 cities in the past 8 years, starting in Chelsea, Fall River, and Holyoke. Estimates of the benefits from the program start at $0.77 per household in 2018 and rise to $13.60 by 2050.[84] The cities of Boston and Somerville, among others, have developed Urban Forest Plans to invest in a long-term health and resilience of urban canopy coverage.[85,86]

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82 See Climate Data section

83 Dataset is created based on Landsat 8 Collection 1 Analysis-Ready Data (ARD) available from the United States Geological Survey (USGS) Earth Explorer tool (https://earthexplorer.usgs.gov/). Historical air temperature data is from National Oceanographic and Atmospheric Administration (NOAA) Global Historical Climatology Network Daily (GHCND) meteorological stations, with a single station assigned to each of the 13 RPAs.

84 Moody, R., Geron, N., Healy, M., Rogan, J., & Martin, D. (2021). Modeling the spatial distribution of the current and future ecosystem services of Urban Tree Planting in Chicopee and Fall River, Massachusetts. Urban Forestry & Urban Greening, 66, 127403. https://doi.org/10.1016/j.ufug.2021.127403.

85 https://www.boston.gov/departments/parks-and-recreation/urban-forest-plan

86 https://www.somervillema.gov/news/somerville-publishes-city%E2%80%99s-first-urban-forest-management-plan

Additional actions undertaken across the Commonwealth to improve urban tree coverage include:

- Community organizing and education on tree selection, maintenance, and care, particularly when considering the challenges of climate change.
- Targeted planting and investment in state-designated EJ areas to maximize the benefits of urban tree coverage and improve community buy-in and support, and protect areas experiencing some of the highest local temperatures.
- Development of data collection and sharing protocols to track urban tree coverage and monitor the impacts of climate change.
- Support for municipalities adopting tree retention bylaws/ordinances and funds where contributions to unavoidable losses can be used for planting elsewhere.

Given the time required for newly planted trees to reach maturity and the value of urban greening across sectors, further expanding these tree planting and stewardship efforts in the near term will be important.

Example Adaptation Plans with Actions Addressing this Impact

- Greening the Gateways Program
- Urban Forest Climate Resiliency Master Plan – Brookline
- Urban Forest Equity Plan – Holyoke

Sensitivities and Uncertainty

Sensitivity and uncertainties in this impact include:

- Uncertain inconsistent measurements of canopy coverage across the state. The data used in this analysis rely on Census definitions of urban areas and satellite data on canopy coverage that may overestimate the number of trees in areas. These urban areas encompass a range of densities in population and development with the fate of trees in more developed areas relying heavily on the stewardship of local governments and communities.
- Limited quantitative evidence of the relationship between urban tree health and specific climate stressors. Densely developed urban areas have more impervious surfaces, and therefore experience much hotter ambient temperatures leading to increased precipitation intensity, runoff, and runoff which would require more place specific data to properly incorporate into the analysis.
- Uncertainties around development trends and potential for tree removal in newly developed areas.
- Availability of continued funding and maintenance after planting. The implementation of maintenance and stewardship plans will require more staff capacity, therefore require more funding

Related Impacts

Table A14 lists the impacts in other sectors that have a connection to this impact.

Table A14. Additional Impacts related to Loss of Urban Tree Cover

Sector	Impact	Connection
Natural Environment	Distribution of Native and Invasive Species	Tree species common to the region may face increased pressure from pests, invasive plants, and diseases new to the area.
Natural Environment	Forest Health Degradation	There is some spatial overlap between overall Forest Health and the scope of the Urban Tree Cover impact, as some urban areas encompass arboretums and other forested areas, and distinctions between urban, suburban, exurban, and rural areas can be blurred.
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 Sector: Urgent Impact #5

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.

Impact Summary

Coastal regions of the U.S. are particularly susceptible to the risks of sea level rise and storm surge. As the climate warms, sea levels rise due to the combination of thermal expansion of water volume, melting of glaciers and other ice sheets, and other factors. Higher seas inundate land and structures, erode beaches, and degrade coastal ecosystems. Higher sea levels also lead to more damaging storm surges, which can cause devastating episodic flooding. Storm surge and coastal windstorm frequency and intensity are also affected by increases in sea-surface temperature, with elevated temperatures further increasing risks of damaging flood and windstorm episodes.

This impact category focuses on the effect of changes in sea level and storm surge and the direct impacts on flood damage to buildings in the Massachusetts coastal zone, and also considers impacts of changes in windstorm frequency and intensity, as well as direct impacts to port infrastructure. These direct infrastructure damage and economic impacts are considered here, but indirect impacts on the Massachusetts economy are considered separately, in the Economy sector, recognizing that coastal regions of Massachusetts that are vulnerable to these climate hazards are also critical to the local and statewide economy.

Urgency Ranking Results

This impact is ranked as a **medium priority** because, although impacts are expected to be large, the moderate adaptation gap and limited disproportionality scoring result in a modest urgency score.

Current and future flood depths were derived from the Massachusetts Coast Flood Risk Model (MC-FRM) covering the entire coast of Massachusetts at a 2-meter grid resolution for six extreme flooding events: 20-year, 50-year, 100-year, 200-year, 500-year, and 1,000-year. Flood damage to buildings from these events was estimated using differentiated depth-damage functions by residential, industrial, and commercial categories; estimated property values from readily available sources; and relevant building characteristics for residential, industrial, and commercial structures.

The projections of sea level rise used in the modeling of coastal flood risks are consistent with the approach used in the US Global Change Research Program's 2017 National Climate Assessment and the Global and Regional Sea Level Rise Scenarios developed for use in climate impact assessment (USGCRP 2017, 2018). Under this approach, the USGCRP developed projections of sea level rise for each of four representative scenario groups—Intermediate, Intermediate-High, High, and Extreme. The Commonwealth of Massachusetts has selected the High scenario as the preferred scenario for assessment of vulnerability and flood risk, consistent with an "Unlikely to exceed" (83 percent) probability for a higher greenhouse gas emission scenario when accounting for possible ice sheet instabilities. For the higher emissions alone (without consideration of ice sheet instabilities), the High scenario is consistent with an "extremely unlikely to exceed" (95 percent) probability. The relative sea level rise which Massachusetts residents may see in the future, and which was used as input for the Massachusetts Coast Flood Risk model (MC-FRM), 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 15 inches (39 cm) between 2008 and 2030; 30 inches (76 cm) between 2008 and 2050, and 51 inches (131 cm) between 2008 and 2070. Corresponding estimates for the southern part of Massachusetts are slightly higher – 16 inches (42 cm) by 2030, 32 inches (81 cm) by 2050, and 54 inches (136 cm) by 2070.[87]

Economic vulnerability is assessed using a customized variant of the National Coastal Property model, described in Neumann et al. (2021).[88] The model incorporates site- and property class specific U.S. Army Corps of Engineers and FEMA compiled depth-damage functions, and an inventory of structure value from a database of assessed value. The model incorporates structure value at a 150 m by 150 m grid resolution, which is updated with recent Zillow adjustments at zip code level. The full version of the model considers both episodic flooding from the combined effects of storm surge, tides, and sea level rise; and the possibility of property inundation as a result of gradual sea level rise. To better match the format of the MC-FRM outputs, only the former component of the model was applied here. Additional details are in the cited studies.

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[87] The derivation of these estimates relative to 2008 levels and relative to the NAVD88 datum is presented in Appendix B.

[88] Neumann, J. E., Chinowsky, P., Helman, J., Black, M., Fant, C., Strzepek, K., & Martinich, J. 2021. Climate effects on US infrastructure: the economics of adaptation for rail, roads, and coastal development. Climatic Change. https://doi.org/10.1007/s10584-021-03179-w. The National Coastal Property Model described there was run in "no additional adaptation" mode to characterize vulnerability. The model also incorporates reactive and proactive adaptation modes which use benefit-cost "rules" to identify potentially cost-effective adaptation options. See also 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 for additional model documentation.

> *"Not all people living near the coast can afford to move or invest in adaptation strategies."*
>
> *"Along the coast, development continues to occur in areas at high risk, when instead more effort should be placed on preserving remaining undeveloped coastline and planning for retreat where necessary."*
>
> - Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The consequences of coastal property damage from increased coastal flooding are projected to be **extreme** due to widespread and substantial potential for damage to coastal structures. Table A15 summarizes the detailed analysis of flood risks to coastal properties, using the MC-FRM and the Commonwealth's chosen projections for sea level rise (the "High" scenario referred to in the above text). The "Current" estimates shown below are for 2008 sea level. The results indicate that current statewide annual average expected damages to coastal structures is about $185 million – some years could be more or less than this average. Damages are projected to almost double by 2030 as a result of changes in sea level and storm surge activity, and almost double again, to over $600 million per year, by 2050. By 2070, statewide annual average damages could be more than $1 billion per year.[89] The estimates of current and projected future damages from coastal flooding largely reflect the value of vulnerable structures – for example, the total value of structures within the floodplain for current 100-year return period coastal storm is just less than $55 billion, of which about $40 billion is residential, $12 billion is industrial, and $2.5 billion is commercial.

These direct impacts are limited to the four coastal regions. The Boston Harbor region currently experiences about 55 percent of the average annual statewide impact, but projections show damages from coastal flooding could grow faster in the Boston Harbor region than in other areas of the state due to projected local sea level rise and the existing development footprint, and by 2050 structures in the Boston Harbor region would account for almost 2/3 of statewide damages.

[89] Results are based on a custom application of the National Coastal Property Model, described in the text above and consistent with Neumann et al. (2021) and Lorie et al. (2020).

Table A15. Annual Expected Flood Damages to Coastal Properties

Annual expected flood damage to coastal properties in millions from sea level rise and changes in coastal storms. This includes impacts on residential, commercial, and industrial properties. 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); and 2070 (mid-late century, 2060-2079). Values may not sum due to rounding.

	Annual total expected damage ($millions)			
Region	**Current**	**2030**	**2050**	**2070**
Eastern Inland	$1	$2	$5	$9
Boston Harbor	$100	$210	$400	$780
North & South Shores	$25	$40	$60	$100
Cape, Islands, & South Coast	$60	$70	$140	$210
Statewide	**$185**	**$330**	**$610**	**$1,100**

Note: The MC-FRM does not currently provide estimates for 2090.Estimates based on flood risk from MC-FRM and loss estimation methods from Neumann et al. (2021), see text for details.

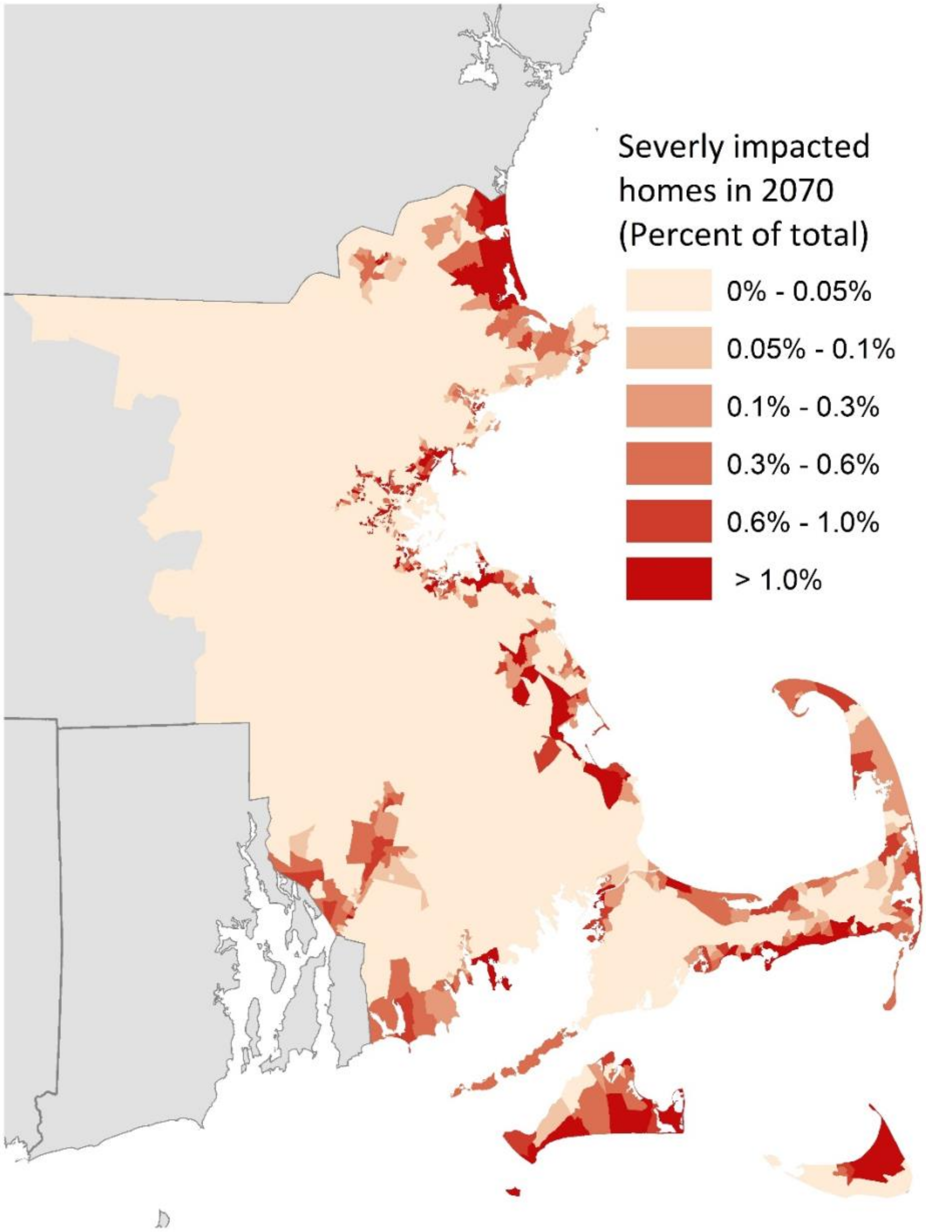
Note that all estimates in Table A15 use current property value data and reflect the joint effects of storm surge, tidal flooding, and sea level rise over time, with adjustments for future storm surge activity as climate change alters the expected frequency and severity of tropical storms.

Sea level rise and storm surge could also affect ports and marinas around the state. The direct damages to structures that are port and marina facilities are mostly included in the estimates shown in Table A15, but those estimates do not include indirect damages associated with disruption of supply chains or other associated business and recreational activity. These impacts are briefly discussed in the Economy sector. Impacts to road and rail are each discussed separately in their respective impact summaries.

The models also provide estimates of the number of buildings affected by flooding, and the average annual damage as a percent of total structure value. Figure A15 provides a map of severely impacted block groups, identified by the proportion of buildings in the Massachusetts coastal zone that could see severe impacts, of 5 percent or more of total property value, on an annual basis, by 2070 (note that annualized estimates are the product of both the severity of an event, which might be 50 to 100 percent loss for particular properties in some cases, and the annual probability of occurrence, which for severe events might be 1 to 5 percent per year in any given location). The deep red areas of the map could see more than 1 percent of all properties in the block group with these types of severe annual damages, if additional adaptation action is not taken.

Figure A15. Percent of Buildings Impacted by Coastal Flooding by 2070

The proportion of buildings in a block group with 5 percent (of total value) or higher expected annual damage by 2070 as a result of the combined effect of sea level rise, tides, and episodic storm surge combined. Building scope includes residential structures, spatial scope includes the full area of all NOAA-designated coastal counties. Note that the estimated Annual Economic Damage (AED) threshold of 5 percent also averages a range of severe and less severe events and their probabilities, and individual events could have much larger impacts.



Source: Project Team analysis of MC-FRM results using methods from Neumann et al. (2021), see text for details.

Another source of risk to coastal structures is wind damage, typically associated with the same coastal storms that result in extreme storm surge. Compared to estimates for flood damage, future wind damage estimates are more uncertain and more difficult to attribute at fine scale. Based on results from recent published papers, however, current annual damages from coastal wind storms to structures and public infrastructure could approach $500 million, but with very large variations from year to year.[90] By the end of the century, as a result of changes in storm activity attributed to climate change, wind damages could increase by up to fourfold. Wind damages also extend beyond the coastal zone – with the highest expected damages in Middlesex County, followed by Suffolk County.

Disproportionality

The Fourth National Climate Assessment (2018) found that the risks of coastal flooding and erosion can exacerbate pre-existing social inequities in low-lying areas of the coastal zone.[91] Concerns for socially vulnerable populations in the coastal zone stem from two related circumstances: 1) in some areas of the coast, disadvantaged communities are disproportionately located in areas that are most vulnerable to damaging flooding; and 2) although adaptation to coastal risks has been shown to be cost-effective in many instances, the need for financing of adaptive measures and the use of benefit-cost tests for larger adaptation projects implies that properties with lower market value are less likely to be prioritized for protection.

This analysis considers the first factor, that is, the potential for socially vulnerable populations to be disproportionately located in areas with high coastal flood risk. In Massachusetts, most properties that are particularly vulnerable to coastal flooding, and the most severe impacts, tend to be in areas that do not overlap with the Commonwealth-designated EJ Block Groups. As a result, in aggregate, coastal flooding does not disproportionately impact socially vulnerable communities state-wide. Overall, then, this impact is considered to be of **limited** disproportionality.[92] There may, however, be areas where high coastal risk does overlap with EJ populations areas– for example in Figure A16, coastal flood risk in the upper reaches of the Taunton River in the Eastern Inland region shows a high level of disproportionate risk for EJ block groups in the Minority category. That finding for the Eastern Inland region is taken directly into consideration in the regional urgency rankings. As shown in Table A15, however, the Eastern Inland region accounts for small portion of overall state magnitude of consequence,

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[90] The recently published papers are Dinan, T., (2017). Projected increases in hurricane damage in the United States: the role of climate change and coastal development. Ecol. Econ. 138: 186–198. https://doi.org/10.1016/j.ecolecon.2017.03.03; and Marsooli, R. Lin, N., Emanuel, K., Feng, K. (2019). Climate change exacerbates hurricane flood hazards along US Atlantic and Gulf Coasts in spatially varying patterns. Nature Communications. https://doi.org/10.1038/s41467-019-11755-z. The full method is described in Appendix B of EPA. 2021, Technical Documentation on the Framework for Evaluating Damages and Impacts (FrEDI). U.S. Environmental Protection Agency, EPA 430-R-21-004.EPA 2021 available at www.epa.gov/CIRA/FrEDI. Dinan applies the results of the Risk Management Solutions model for wind damage, but the vintage of the runs for Dinan (2017) may not take into account recent local or property scale adaptation to wind loads, or any recent updates to wind load building code requirements.

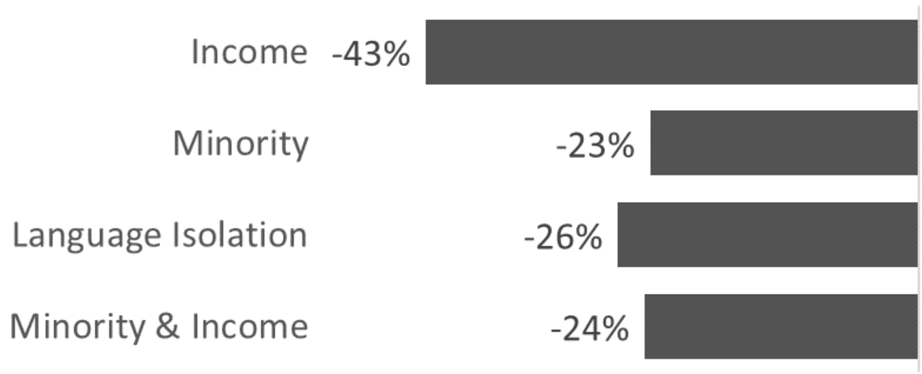
[91] Fleming E, Payne J, Sweet W, Craghan M, Haines J, Hart JF, Stiller H, and Sutton-Grier A. 2018. Coastal Effects. In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller DR, Avery CW, Easterling DR, Kunkel KE, Lewis KLM, Maycock TK, and Stewart BC (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 322–352. doi: 10.7930/NCA4.2018.CH8

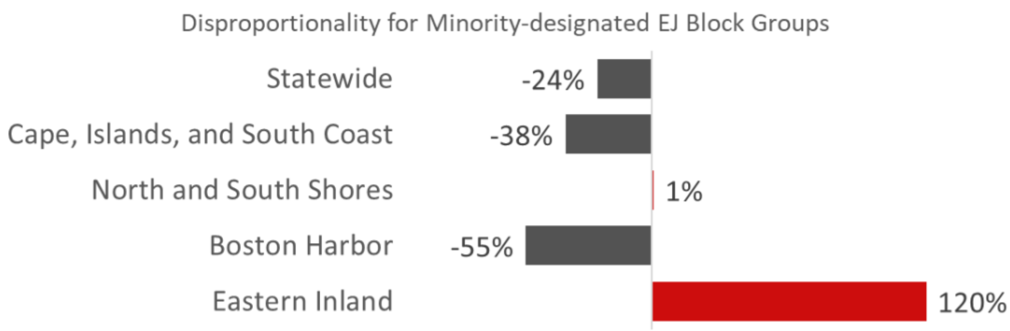
[92] Although this analysis does not find a quantitative correlation between the locations of exposure to this impact and EJ block groups, it is important to note that not all populations will have the same experience with the effects of climate change and this impact because of pre-existing social vulnerabilities that are difficult to measure or comprehensively quantify across the Commonwealth.

and so does not by itself alter the statewide finding of limited disproportionality. In addition, it is important to note that the EJ block groups are designated based on residence, not workplace. Effects on workers engaged in the marine economy or whose ability to work may be affected by impacts on coastal areas are considered in the Economy sector.

Figure A16. Disproportionality of Coastal Flooding on Coastal Properties

Comparison of the severely impacted buildings state-wide (top), and by region for the Minority status (bottom) 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 of the main report for further description of the EJ block group definitions. Severely impacted buildings are those with five percent or higher expected annual damage by the 2070s.





Adaptation

At a state level, there is a **moderate** adaptation gap to addressing the impact of Damage to Coastal Buildings and Ports. Though many actions are noted that could effectively address this impact, most are in the early stages of planning. While the worst impacts of sea level rise are not projected to affect the Massachusetts coast for several decades, storm surge events in recent years are notably more severe. Additionally, adapting to such hazards as sea level rise and storm surge intensification will require proactive rather than reactive action. Some adaptation steps that are already being taken along the coast including living shorelines, vertical storm wall construction, and zoning future construction to account for future sea level rise. In Marshfield and Scituate, coastal resiliency plans indicate funding may be allocated to private property owners to elevate those properties. One area not widely considered by coastal communities, and often controversial, is managed retreat of people and infrastructure away from vulnerable coastal areas.

Example Adaptation Plans with Actions Addressing this Impact

- CZM StormSmart Coasts Publications and CZM MORIS Data Viewer serve as clearing houses for resources, data, and plans regarding coastal flooding.
- Building a Resilient Scituate includes actions to conduct a more detailed vulnerability study, provide funding for elevating private homes, and redesign and reconstruct seawalls
- Coastal Resilience Feasibility Study for the Point of Pines and Riverside Area: a coastal resilience project in Revere that includes living shorelines among other proposed solutions

Sensitivities and Uncertainty

The results presented here are likely conservative estimates of future damage, as they reflect current property values – the current trend is for rapidly increasing structure values in the vulnerable coastal zone, although the rate of property value growth may change in the future in response to climate risks and/or the implementation of adaptation measures.

Increasing degrees of sea level rise and storm surge risks over time may also trigger changes in the demographics of the population at risk, which could alter the assessment of disproportionality in exposure to coastal flood impacts.

These results exclude the potential impact of changes to the frequency or severity of extra-tropical storms (one category of which is referred to as “Nor’easters” in New England) – consistent with advice to the Commonwealth of a peer review panel of climate science experts.

These results also exclude secondary and indirect effects of damage to structures associated with flood impacts, but those effects are considered elsewhere in the Economy sector, Business Interruptions impact write-up.

Related Impacts

Table A16 lists the impacts in other sectors that have a connection to this impact.

Table A16. Additional impacts related to Damage to Coastal Buildings and Ports

Sector	Impact	Connection
Economy	Economic Losses from Commercial Structure Damage and Business Interruptions	Coastal flood damage causes direct damage to business locations, in extreme cases total loss of commercial or industrial structures.
Economy	Reduced Ability to Work	Coastal flood damages to places of business may cause closures that affect people’s ability to work, resulting in lost wages—which further inhibit recovery efforts.

Sector	Impact	Connection
Economy	Damage to Tourist Attractions and Recreation Amenities	Sea level rise and storm surge can impact coastal tourist and recreation sites as well as tourist and recreational activity.
Economy	Decreases to Marine Fisheries and Aquaculture Productivity	Some coastal ports and marine commercial fishing establishments could be damaged or otherwise affected by sea level rise, storm surge, and wind damage.
Governance	Damage to Coastal State and Municipal Buildings and Land	Damages to structures presented here includes damage to state and municipally owned structures, which are separately characterized in the Governance sector.
Governance	Increase in Need for State and Municipal Policy Review and Adaptation Coordination	Adaptation to coastal risks often involves a high degree of government coordination at the municipal, regional, and/or state level to be most effective.
Natural Environment	Coastal Erosion; Coastal Wetland Degradation	Damage to ecological resources can result from sea level rise and storm surge, and the magnitude of impact can be affected by the presence of coastal structures
Human	Health Effects of Extreme Storms and Power Outages; Emergency Service Response Delays and Evacuation Disruptions	Coastal flooding can lead to injuries and death, delays in emergency response, and evacuation disruptions. Wind storms and coastal flooding can cause loss of power.
Human	Health Effects from Aeroallergens and Mold	More frequent coastal flooding can produce more mold growth, which has detrimental health effects.

Infrastructure Sector: Urgent Impact #6

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.

Impact Summary

Climate change threats to clean water supply include impacts on quantity, quality, and supply infrastructure. Specifically:

- Depletion of public and private water sources during periods of drought and less frequent precipitation;
- Contamination of surface water due to increased runoff and harmful algal blooms (HABs), which can also be brought on by stagnant water during droughts;
- Damage to water supply infrastructure including flooding of water treatment plants and power interruptions, an important consideration in Massachusetts where there are many older water distribution systems.; and
- Possible contamination of coastal groundwater supplies via saltwater intrusion.

Massachusetts has yet to experience the severe water shortages that more commonly occur in the western U.S. However, the combination of multiple threats to clean water supply, the lack of enough recharge because of high impervious cover, and the repercussions of potential service disruptions makes this a climate change impact of concern in the Commonwealth.

Urgency Ranking Results

This impact is ranked as a **medium priority** because of a moderate level of expected consequence, potential for disproportionality and minimal adaptation gap.

This impact is assessed quantitatively and qualitatively drawing on a number of sources of data to consider the various threats to clean water supply. Unmet municipal and industrial water demands in Massachusetts watersheds are cited from an analysis supporting EPA's Climate

Impact Risk Analysis (CIRA), as are increases in cyanobacteria concentrations.[93] Groundwater issues and water treatment and delivery infrastructure risks are addressed qualitatively.

> *"The reduction in clean water supply is a public health concern but also a major financial concern for small towns. This financial burden will disproportionately fall on low-income households who may be less able to afford a move if the local water company is with remediating water quality issues, a cost that it will likely pass on to its ratepayers."*
>
> *"Once the water supplies are compromised it becomes a much more challenging and expensive problem to solve."*
>
> - Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The consequences of reduction in clean water supply are projected to be **major** due to the variety of risks facing clean water supply and the uncertain, yet high magnitude, consequences that come along with lack of clean water. Although the projected damages from any one risk are relatively low, the combination of threats to clean water supply still result in moderate consequence rating. The potential stressors vary by region. The most at-risk water supplies are smaller wells which typically rely on precipitation-fed recharge, which could become more unreliable in the future. The Berkshires & Hilltowns, Greater Connecticut River Valley, Central, and Cape, Islands, and South Coast regions are most vulnerable to this risk. Water quality and delivery infrastructure issues could be felt across the Commonwealth, particularly in the context of other non-climate water supply issues (e.g., PFAS contamination). The Boston Harbor and much of the Eastern Inland regions are unlikely to experience clean water supply stress due to abundant water supply from Massachusetts Water Resources Authority (MWRA).. In the Cape, Islands, and South Coast, saltwater intrusion poses an additional potential risk given the proximity of many water supply sources to the coast, however the hydrology of the aquifers in this region make it unlikely significant intrusion will occur.

Water users served by MWRA are unlikely to experience water shortages due to the drought conditions thanks to the reliable water supplies of the Quabbin and Wachusett reservoirs, as well as supplemental and emergency supplies. MWRA provides water to 3.1 million people (nearly half of Commonwealth residents), including most of the Boston Harbor region (see Figure A17). MWRA water is sourced from the Quabbin Reservoir (412 billion gallon capacity) and the Wachusett Reservoir (65 billion gallon capacity).[94] The Quabbin and Wachusett reservoirs have a safe yield of 300 million gallons per day, which is sufficient to cover average daily demand (191.8 million gallons per day in 2021).[95] Demand reductions since the eighties are a result of leak detection and repairs, in-home plumbing retrofits and code requirements, Water Management Program and public information campaigns, and meter improvements.

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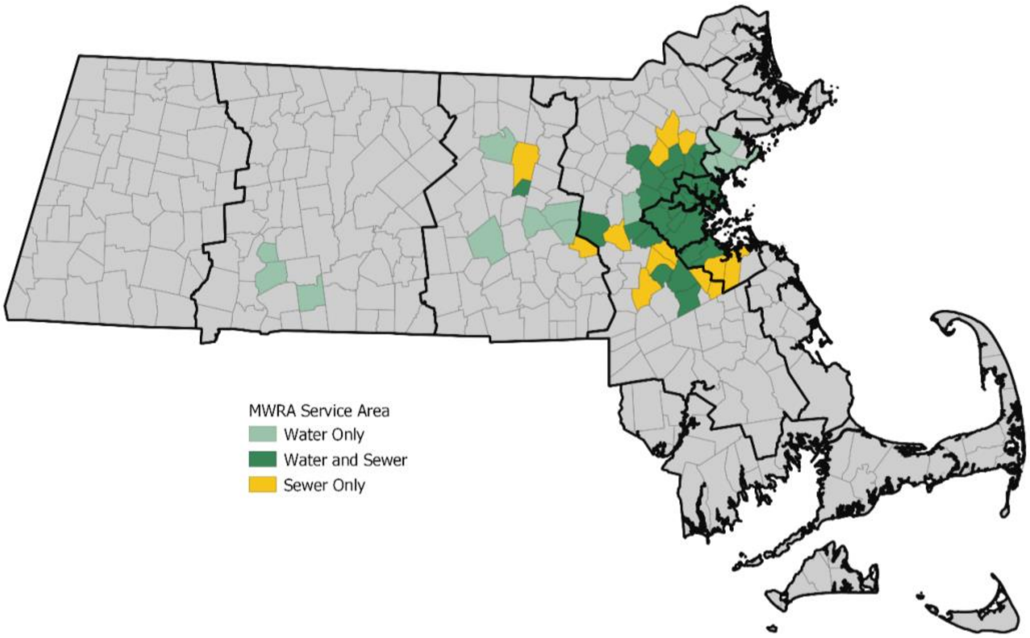
[93] USEPA. 2017. Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. U.S. Environmental Protection Agency, EPA 430-R-17-001.

[94] Mwra.com

[95] https://www.mwra.com/04water/html/wsupdate.htm

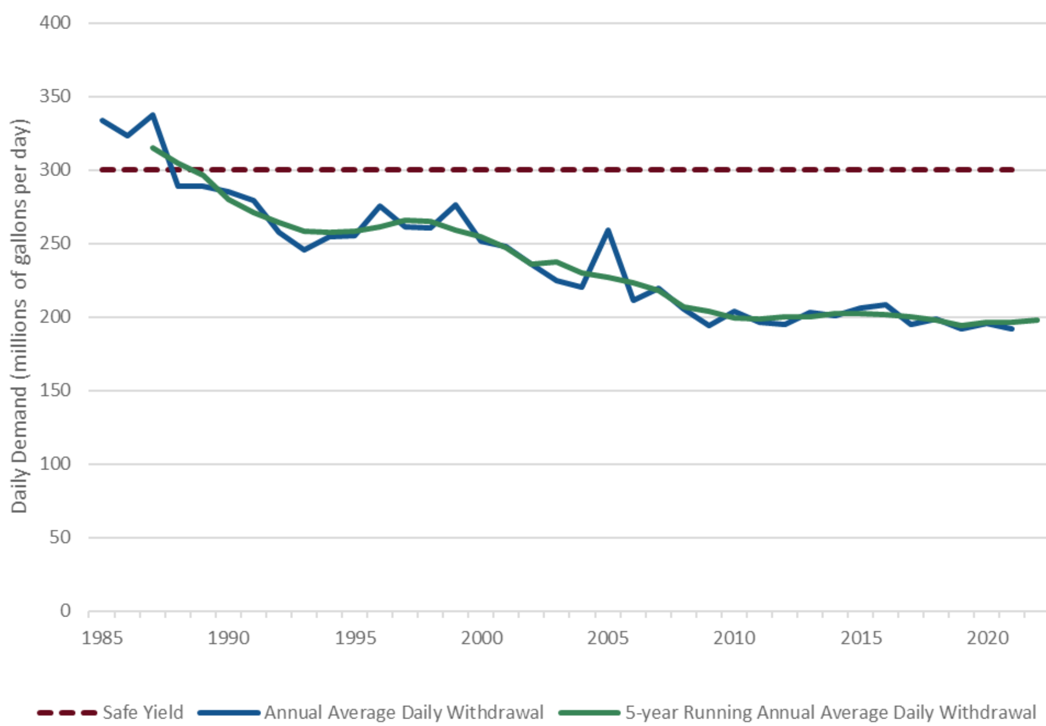
Figure A17. MWRA Service Area (2022)



Source: MassGIS

Figure A18. MWRA Average Daily Water Demand 1985-2022

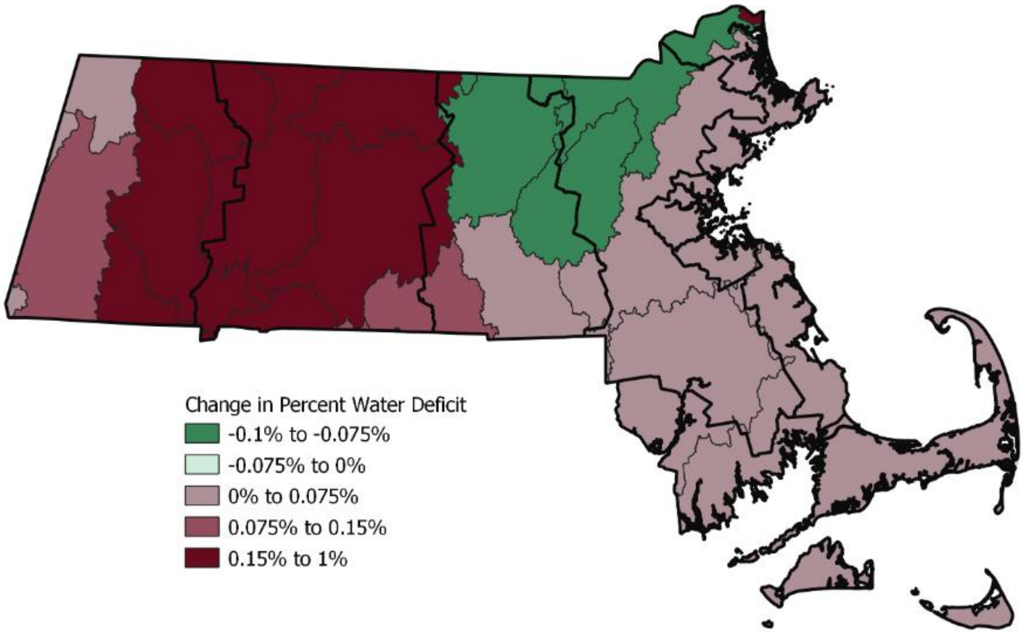
Average daily demand in millions of gallons per day by year (blue) and 5-month running average (green) by MWRA water users. Demand has been below the safe yield level (red) of 300 million gallons per day since demand reduction campaigns in the late eighties.



Source: Adapted from data provided on mwra.com

This finding is supported by the literature as well. A previous national analysis (EPA 2017) examined projected unmet water demand by accounting for changing demand and supply of municipal and industrial water for three categories of water use: municipal indoor, municipal landscape, and industrial. Unmet demands are distributed among the three categories of demand based on a prioritization scheme where shortages are first expected to be absorbed by outdoor use (municipal landscape). If unmet demand is greater than landscape demand, the remaining shortage is absorbed by industry. Finally, any remaining unmet demand after both outdoor and industry uses have been exhausted is taken from indoor municipal demand. In Massachusetts, all changes in unmet demand compared to the baseline are projected to be absorbed by municipal landscape usage and are concentrated in central and western parts of the Commonwealth (see Figure A19). Changes in unmet demands are minimal, with the largest expected changes in deficits by hydrologic unit to be about 0.5 percent of demand by 2070. In the eastern part of the Commonwealth, deficits are projected to decline slightly compared to baseline unmet demands because increased precipitation outweighs increases in demand.

Figure A19. Change in Percent Water Deficit for Municipal Landscape Uses in 2070



Source: U.S. EPA data at www.epa.gov/CIRA and project team analysis

This change in unmet demand can be valued using the consumer welfare values, or willingness-to-pay to avoid shortages for municipal landscape usage. Annual economic impacts for the three westernmost regions total only about $300,000 by 2070 and $650,000 by 2090.

Table A17. Annual Economic Impact of Unmet Water Demand 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.

	Total annual economic impact of unmet water demand due to climate change (millions $)			
Region	**2030**	**2050**	**2070**	**2090**
Berkshires & Hilltowns	$0.06	$0.09	$0.20	$0.44
Greater Connecticut River Valley	$0.01	$0.02	$0.05	$0.10
Central	$0.02	$0.02	$0.05	$0.12
Statewide	**$0.09**	**$0.13**	**$0.30**	**$0.66**

Note: No losses projected for the Eastern Inland, Boston Harbor, North & South Shore, or Cape, Islands, & South Coast regions.

Source: Project Team analysis of data from USEPA (2017)

Surface water sources are also vulnerable to increasing levels of harmful algal blooms (HABs), or cyanobacteria. Microcystis is the most common type of cyanobacteria found in freshwater bodies, such as surface drinking water sources. It produces a liver toxin that, when ingested, can cause gastrointestinal illness and liver damage.[96] Although the exact conditions that lead to cyanobacteria blooms are unknown, blooms are associated with warmer waters. Water utilities in the Commonwealth currently monitor surface water sources for changes in cyanobacteria levels. Following the analysis of HABs in the Freshwater Ecosystem impact, within the Natural Environment sector, cyanobacteria concentrations are expected to increase over the century, particularly in the eastern and northern parts of the Commonwealth. Most municipal water treatment facilities can remove low levels of cyanobacteria. However, they face challenges during bloom events when the concentrations rise. Elevated cyanobacteria levels can lead to increased treatment costs and in some cases drinking water health advisories, particularly for children and vulnerable populations.

Although the majority of the eastern part of the Commonwealth, particularly areas that receive water through MWRA and other large surface waterbodies, is not expected to see water shortages, reduced groundwater recharge and saltwater intrusion of water sources is another potential concern for municipalities and individuals. Detailed modeling is required to identify patterns in groundwater recharge and to identify which groundwater sources are vulnerable to saltwater infiltration, as it is a function of site specific hydrological and geological characteristics. Although a number of public water supplies and wells are located close to the coast, particularly in the Cape, Islands, and South Coast region, a 2016 USGS study suggests that groundwater infiltration on the Cape is unlikely because of geological and hydrological features of the area (namely, the presence of surface water drainages that will dampen the response of

[96] National Institute of Environmental Health Services. Algal Blooms. https://www.niehs.nih.gov/health/topics/agents/algal-blooms/index.cfm

the water table to sea level rise and the thick vadose zone, or unsaturated earth between the surface and the flowing groundwater table).[97] Reduction in groundwater recharge is likely a more significant problem, particularly in the central and western parts of the Commonwealth. Climate change is projected to lead to reduced groundwater recharge through less infiltration (i.e., precipitation during high volume events cannot absorb in the ground as well as more frequent, lower volume events) and increased temperatures lead to more evaporation. This could lead to periods of stress in the aquifers, though it may also shift timing of aquifer recharge throughout the year rather than a true net decrease in recharge. An analysis of the Metropolitan Area Planning Council region by the Greater Boston Research Advisory Group projects shifts in seasonal recharge rates that result in modest declines in average annual recharge rates by 2030 and more significant reductions (18 percent or higher) by 2070.[98] Climate-driven reduction in recharge could be exacerbated by other factors over time, including increased development and land use conversion. Additional localized research, particularly in the western part of the state, is needed to understand the full extent of this issue.

Finally, water supply infrastructure is vulnerable to threats such as treatment facility flooding and power outages. Comprehensive data on the location of water treatment facilities are not available, therefore the risk of flooding is unknown. Because treatment facilities are often located near surface water sources, inland flooding threats are of most concern. Power outages can also disrupt treatment. However, generators can be used in most cases to continue operations during outages.

Disproportionality

There is a **potential** for disproportionality in exposure for this impact. Nearly half (49 percent) of block groups identified as EJ on any basis fall within the MWRA water service area, where water quantity concerns are minimal and robust infrastructure is in place to handle potential water quality concerns, compared to 23 percent of non-EJ block groups, suggesting there is not a disproportionate exposure. However, the relative exposure to other threats to clean water supply are not as clear. Smaller towns, particularly in the central and western parts of the Commonwealth with lower median incomes may not have the resources to adequately mitigate risks from cyanobacteria blooms or dig deeper wells if drought conditions intensify. Residents not connected to municipal water supplies could face similar challenges.

Adaptation

There is a **minimal** adaptation gap for this impact. In 2018, Massachusetts DEP implemented a Water Conservation Pilot program to encourage a reduction in lawn watering. The campaign distributed educational materials to a sample of households with high summer water usage, which resulted in a savings of 3,510 gallons per summer per household that received the

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[97] Walter, D.A., McCobb, T.D., Masterson, J.P., and Fienen, M.N., 2016, Potential effects of sea-level rise on the depth to saturated sediments of the Sagamore and Monomoy flow lenses on Cape Cod, Massachusetts (ver. 1.1, October 18, 2016): U.S. Geological Survey Scientific Investigations Report 2016–5058, 55 p., http://dx.doi.org/10.3133/sir20165058.

[98] Douglas, E. and Kirshen, P. 2022. Climate Change Impacts and Projections for the Greater Boston Area: Findings of the Greater Boston Research Advisory Group Report.

materials. Campaigns like this could be deployed more widely, and reductions in landscape water use would free up significant water capacity for critical uses. In 2021, EEA developed a Water Conservation Toolkit and branding under the *Conserve MA Water* umbrella to provide water conservation tools, tips, and resources as they relate to residents, municipalities, businesses and farmers. The U.S. EPA offers a number of resiliency strategies through their [Creating Resilient Water Utilities (CRWU)] program. Water source protection, including reducing nutrient loading in drinking water source watersheds is important to protect against cyanobacteria blooms. Implementing intermunicipal and regional water purchase agreements and emergency connections could reduce vulnerability to localized water shortages.

Example Adaptation Plans with Actions Addressing this Impact

- Pioneer Valley Climate Action and Clean Energy Plan includes actions such as planning an emergency intermunicipal water connection
- Watershed and Water Supply Vulnerability, Risk Assessment and Management Strategy – Gloucester

Sensitivities and Uncertainty

Significant uncertainties remain in the estimation of the potential magnitude of clean water supply reductions. Threats to groundwater, including reduction in recharge rates and saltwater infiltration, vary by site specific characteristics. This poses a challenge, particularly for individuals and smaller municipalities reliant on groundwater sources as water supply. Additionally, through large water sources such as those relied upon by MWRA currently reliably supply adequate water to users, the potential for increasing demand from an expanded service area, either forced by climate change stressors to smaller sources or other threats such as PFAS contamination, could strain the typically robust system.

Related Impacts

Table A18 lists the impacts in other sectors that have a connection to this impact.

Table A18. Additional Impacts related to Reduction in Clean Water Supply

Sector	Impact	Connection
Human	Health Effects of Extreme Storms and Power Outages	Power outages can disrupt water treatment facility processing, and therefore disruption in clean water supply. Outages can also affect private well residents; pumps that move water from the well to the house cannot function without a source of power.
Infrastructure	Damage to Inland Buildings; Damage to Coastal Buildings and Ports	Flooding (coastal and inland) of water treatment and distribution facilities can impact the availability of clean water supply.
Governance	Damage to Inland State and Municipal Buildings and Land;	Flooding (coastal and inland) of water treatment and distribution facilities can impact the availability of clean water supply.

Sector	Impact	Connection
	Damage to Coastal State and Municipal Buildings and Land	Many water treatment facilities are municipally owned.
Governance	Increase in Demand for State and Municipal Government Services	Municipalities may see an increased demand for water treatment to combat increased levels of cyanobacteria in drinking water sources.
Natural Environment	Freshwater Ecosystem Degradation	The same threats to water quality for drinking water are felt by freshwater ecosystems more generally.
Economy	Decrease in Agriculture Productivity	Reduction in water quantity reliability, particularly from smaller wells or surface water sources in the central and western parts of the Commonwealth could affect water availability for irrigation.

Infrastructure Sector: Urgent Impact #7

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.

Impact Summary

Roads are essential for transportation in the U.S. and road maintenance is already a substantial cost to state and local agencies. Climate impacts road surface conditions and structural integrity in various ways.

- As temperatures increase, binder material will age faster and rutting in asphalt surfaces will be more common, necessitating more frequent maintenance or immediate repair so as not to impede traffic flows.
- Increases in precipitation cause more cracking and erosion, which impacts the structural stability of roads, causing potholes and the need for reworking drainage systems.
- More frequent severe flooding events can cause roads to wash out or at least require reconstruction of asphalt or unpaved roads. Existing storm drainage infrastructure such as culverts are typically designed to historical standards and flood frequencies.

Due to constraints of governing bodies that maintain these roads, including budgets, there may be a decline in the level of service for roads that has a direct impact on the drivers. For example, road rutting is likely to both increase traffic by decreasing the comfortable driving speed and increase vehicle operating costs.

This impact is focused on the direct effects of climate on road maintenance, repair, and rehabilitation costs. In addition, roads can also serve as utility corridors which could be impacted and lead to direct costs. Indirect impacts of loss of road service to commuters, students, and business concerns, or during extreme weather events, is considered in other parts of this report, including health effects associated with road outages and delays in emergency response in the Human sector; reduced ability to work in the Economy sector; and increased demand for government services in the Governance sector.

Urgency Ranking Results

This impact is ranked as a **medium priority** because of its high increased costs, especially near the end of the century.

This impact is evaluated using the approach described in Neumann et al. (2021)[99] with more detail in Chinowsky et al. (2013)[100] and Neumann et al. (2014)[101]. Impacts are associated with high heat (which softens and reduces the life of asphalt binders), heavy precipitation (which mostly affects maintenance needs for unpaved roads following erosion events), and flood risk (which can overwhelm culverts). The approach estimates climate-related changes in road maintenance and construction costs such that the current level of service provided by both paved and unpaved roads is maintained over time, but it is highly 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 lane mile by road type on a quarter-degree (latitude/longitude) grid and distributed by lane mile using the latest road network data from MassDOT.

"Damage to roads from extreme precipitation and temperature changes will be a growing financial burden for many small towns. The costs of road maintenance and constant repair work will take funds away from every other municipal priority."

"If roads are damaged people cannot get to work and potholes are destroying people's cars and costing them more money."

- Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The consequences of increased road maintenance costs are projected to be **major** due to the increased costs, particularly after 2050. Following the approach described above, the results show costs are slightly lower than baseline in the 2030s when a slight reduction in inland flooding impacts lowers road repair costs below baseline but as heat waves and precipitation increase in 2050, incremental costs attributed to climate change rise to $45 million a year higher than current costs. Given that current climate-induced road maintenance costs are roughly $25 to $45 million a year, this would require significant changes to current budgets to avoid massive delays. Increases in costs over baseline rise to $140 million a year by 2090, tripling compared to the 2050s. As shown in Figure A20, road costs increase more significantly

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[99] 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

[100] 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

[101] 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.

in parts of western Massachusetts and in the Cape, Islands, and South Coast region than the mid- and north-eastern parts of the state.

Table A19. Impacts to Road Maintenance Costs

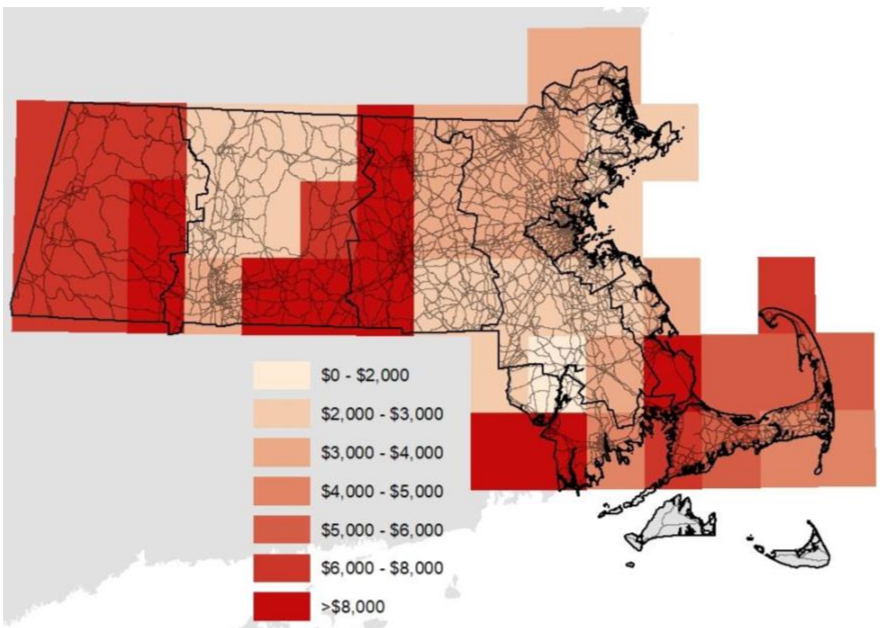
Change in road maintenance and repair costs compared to a 1986-2005 baseline. Future impacts presented for four time periods identified in the table by their central year: 2030 (near-term, 2020-2039); 2050 (mid-century, 2040-2059); 2070 (mid-late century, 2060-2079); and 2090 (end of century, 2080-2099).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

	Annual expected damage ($millions)			
Region	**2030**	**2050**	**2070**	**2090**
Berkshires & Hilltowns	$1.5	$5.1	$7.0	$14
Greater Connecticut River Valley	-$0.5	$5.2	$11	$21
Central	-$0.6	$11	$16	$23
Eastern Inland	-$4.0	$9.0	$17	$30
Boston Harbor	-$0.2	$4.1	$5.9	$10
North & South Shores	$0.4	$4.8	$8.8	$14
Cape, Islands, & S. Coast	-$1.5	$6.4	$21	$30
Statewide	**-$5.0**	**$45**	**$87**	**$140**

Source: Project Team analysis of data from Neumann et al. (2021)

Figure A20. Change in Road Maintenance Costs ($/lane mile) from Current to the 2090s

Total increase in the maintenance costs per lane mile ($/land mile) from current to the 2090s time period for each quarter degree grid.



Source: Project Team analysis of data from Neumann et al. (2021)

There are additional impacts to roads and repair that are not included in this assessment. For example, Knott et al. (2018)[102] demonstrate that coastal roads may be significantly damaged by increased groundwater levels caused by sea level rise in New Hampshire. Rising groundwater levels decrease the service life of pavements when the unbound layers are saturated. There is a high likelihood this may become problematic in the coastal regions of the state. More extreme coastal storms may also become problematic in the future, damaging roads and bridges.

Some estimates exist to characterize impacts of climate on the road 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 in the New England region may be vulnerable to this effect, however results specific to Massachusetts are not available. 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 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.[103]

In addition, some information exists on the vulnerability of the tunnel component of the road network. Existing work is focused on assessing the vulnerabilities of the Central Artery and Tip O'Neill roadway tunnels to the threat of increased coastal flooding attributed to the combined effect of sea level rise, tides, and episodic storm surge. The Massachusetts Department of Transportation has sponsored analyses of vulnerability using the Boston Harbor Flood Risk Model (BH-FRM), a model similar to the MC-FRM tool applied in this assessment, and which used the same sea level rise scenarios chosen for the Climate Assessment.[104] Boston's Central Artery/Tunnel System consists of more than 160 lane-miles, more than half of them in tunnels, six interchanges and 200 bridges. That analysis found an important lack of road network redundancy, making the system potentially extremely vulnerable to sea level rise threats. Both reports include specific recommendations for adaptation actions that could address identified vulnerabilities. The assessment indicates that the number and spatial extent of vulnerable structures increase over time as sea level rise and the intensity of storms increase, across this complex transportation system. The second report responds directly to flood damage associated with a severe event in January 2018. Both reports follow a standardized and largely complete vulnerability assessment and risk mitigation planning process, including assessing

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[102] Knott,J., Daniel, J.S., Jacobs, J.M., Kirshen, P. 2018. Adaptation Planning to Mitigate Coastal-Road Pavement Damage from Groundwater Rise Caused by Sea-Level Rise. Transportation Research Record: Journal of the Transportation Research Board, Vol 2672 issue 2 pgs 11-22. https://doi.org/10.1177/0361198118757441

[103] 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.

[104] See MassDOT-FHWA Pilot Project Report: Climate Change and Extreme Weather Vulnerability Assessments and Adaptation Options for the Central Artery (2015), available at: https://www.cakex.org/sites/default/files/documents/MassDOT_FHWA_Climate_Change_Vulnerability_1.pdf and MassDOT – FHWA Resiliency and Durability Pilot Project Report: Implementing Coastal Flood Resilience Solutions for the Tip O'Neill Tunnel Egress 434 and MBTA Blue Line Aquarium Station, (2021), available at: https://rosap.ntl.bts.gov/view/dot/58569

physical risks, designing effective adaptation responses, generating bid documents or cost assessments to implement those actions, and in the case of second report, outlining an emergency response flood barrier deployment plan.

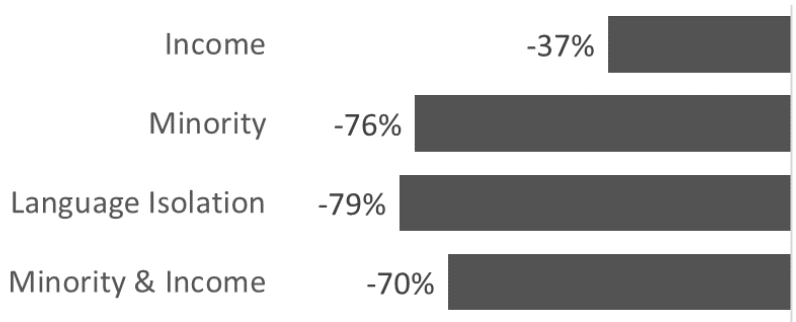
Disproportionality

These costs will impact communities across the state differently due to factors such as transportation department budgets, how budgets are distributed geographically, and how these agencies adapt to changing conditions. Local roads in communities with lower tax revenues may be impacted more severely as a result and in some cases, road surfaces may become increasingly difficult for drivers if maintenance is delayed. This analysis does not consider the budgets of the government agencies maintaining roads or other restrictions they may face when dealing with these increasing costs. Note also that potentially disproportionate effects on evacuation routes are considered separately in the Human sector.

The analysis does consider, however, the difference in rising costs to maintain the level of service necessary to compensate for damage by climate change. Impacts shown in the map indicate increases in costs are higher in the western half of the state and lower in many of the areas with the most EJ census block groups, providing additional support that the climate-induced changes are considered to be of **limited** disproportionate exposure.[105]

Figure A21. Disproportionality of Impacts on Road Infrastructure

Comparison of the road impacts in EJ block groups defined by income, minority status, and English isolation, 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.



[105] Note that this impact, in the Infrastructure sector, focuses on repair costs for road damage. Although this analysis does not find a positive quantitative correlation between the locations of exposure to this impact and EJ block groups, it is important to note that not all populations will have the same experience with the effects of climate change and this impact because of pre-existing social vulnerabilities that are difficult to measure or comprehensively quantify across the Commonwealth. The effects of road damage in terms of delays and inability to get to work, are captured in the Human sector (Reduced Ability to Work impact). Disproportionality in the Human sector considers how some populations are more or less sensitive to changes in road conditions and potential for increased vehicle operating costs.

Adaptation

There is a **moderate** adaptation gap for this impact. Adaptation actions that target flooding across the infrastructure sector have co-benefits in reducing flooding damage to nearby roads both along the coast and further inland. Some road-specific flood mitigation actions are also being undertaken across the state, including redesigning culverts to accommodate increasing volumes and incorporating nature-based stormwater management strategies along roadways (e.g., bioswales, green medians, permeable pavements). More significant actions like elevating road surfaces to prevent inundation should be considered, particularly in vulnerable coastal areas. Non-flooding climate threats to roads include extreme heat and intensifying freeze/thaw cycles, but fewer adaptation options currently exist for addressing these impacts. Most of the adaptation focus has been on paved roads, but some effort has been made to assess the vulnerability of rural, unpaved roads, particularly in the western part of the state. Changes to building codes and development guidelines could accelerate rollout of adaptation strategies, but action is required soon given the advanced planning required for major infrastructure redesign.

Example Adaptation Plans with Actions Addressing this Impact

- MA DOT Flood Risk Assessment
- Rural Dirt Road Resilience Assessment and Recommendations Report – Sheffield, New Marlborough, & Sandisfield
- RT 181 Culvert Replacement & Culvert Infrastructure Assessment – Palmer
- Regional Low-Lying Road Assessment and Feasibility Study – covering all towns on Cape Cod

Sensitivities and Uncertainty

- There are likely additional costs beyond the temperature- and precipitation-induced stressors presented here that are more difficult to quantify, including changes in the freeze-thaw cycle. This analysis also 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 construction activities to maintain the roads and repair the damage. As labor and material costs change over time, these costs could also change.
- The response of governing agencies and other road maintainers is likely to vary, depending on budgets and other constraints those agencies may have. Here roads are assumed to be maintained so as to provide the current level of service to users.

- Flood damage to roads is complex and has been simplified to estimate the broad impact of increased extreme precipitation events on road maintenance costs as described in Chinowsky et al. (2013).[106]

Related Impacts

Table A20 lists the impacts in other sectors that have a connection to this impact.

Table A20. Additional impacts related to Damage to Roads and Loss of Road Service

Sector	Impact	Connection
Economy	Economic Losses from Commercial Structure Damage and Business Interruptions	Increased construction activity causes traffic delays, which impact passenger's time and the transportation of goods.
Economy	Reduced Ability to Work	People who commute to work may experience delays that result in lost wages.
Governance	Increase in Demand for State and Municipal Government Services	Roads that are maintained by state and municipal agencies will be more expensive to maintain, increasing demand for services from those agencies.
Natural Environment	Coastal Erosion and Soil Erosion	Erosion along roadways can threaten the integrity of roads and require protections and repairs.

[106] 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

Infrastructure Sector: Urgent Impact #8

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.

Impact Summary

Changes in temperature increase electricity demand and reduce production efficiency, requiring changes in the overall network cost of meeting those demands. Effects on natural gas (freeze events and extreme storms), wind (freeze or extreme wind events, as well as possible "doldrum" events when wind power generation is not possible), and solar (flooding of areas for solar production or snow coverage) can also directly reduce the availability of energy production facilities.[107]

Forced outages in energy production that are associated with weather events (such as during extreme heat/high electric demand events) can also result in damages, and these types of weather events are projected to be more frequent in the Commonwealth. Power outages have potentially large associated direct and indirect economic costs. Indirect damages, such as health effects and impacts on commercial and economic activity, are not included here. They are instead addressed as part of other impact categories under the Human (health effects of power outages) and Economy (business interruption) sectors.

Urgency Ranking Results

This impact is ranked as a **lower priority** because of its smaller anticipated magnitude of consequence, expected no or limited disproportionate exposure, and minimal adaptation gap.

Monetized damages for this sector are the total costs of supplying electricity to Commonwealth customers (residential, commercial, and industrial) based on a national-scale study of the impact of climate on national and regional electricity supply and demand. The costs are the sum of power system costs across technologies and cost categories (e.g., capital, fuel, variable operating and maintenance costs, and fixed operating and maintenance costs). The modeling

[107] It is important to note that as the Commonwealth shifts to additional reliance on offshore wind and Canadian hydropower imports, there is an interplay between risk of loss of generation and a loss of transmission infrastructure which is difficult to assign solely to either production or transmission.

compares incremental costs of future climate and weather conditions, relative to a "no climate change" reference scenario. The Massachusetts state-level estimates of power sector costs were estimated in McFarland et al. (2015) using the Global Change Analysis Model (GCAM).[108] This assessment also consider the results of studies of electric energy decarbonization efforts currently underway in the Commonwealth.[109]

> *"I am a senior and do not have family close by. No generator to take up the slack of losing power. No car to evacuate. Limited air conditioning during severe heat waves. I would be severely affected by power loss and loss of public transportation."*
>
> *"With our dependency on the internet for public services and commerce, electricity is more vital than ever."*
>
> - Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The consequences of climate change on the incremental costs of supplying electric energy to Commonwealth customers are projected to be **moderate** due to relatively small and potentially declining economic costs for electric energy supply over time. The assessment is also informed by the potential for risks to certain additional aspects of energy supply (e.g., solar installations subject to flood risks) not considered in the broader electric sector study. Finally, the assessment considers additional power supply uncertainties that may be associated with future electric demand and supply as the Commonwealth transitions to a decarbonized economy.

Changes in costs are based on projected changes in the demand for and supply of electricity across generation types. Effects on energy demand reflect the net impact of changes in demand for residential, commercial, and industrial space cooling during summer/warmer months, and decreased demand for space heating during winter/cooler months. Effects on supply reflect the decreased production capacity of thermal power plants, and transmission capacity of the transmission system, associated with higher temperatures. The complex interplay of supply and demand, coupled with forecasted changes in fuel and energy production technology availability and prices, are modeled using the Global Change Assessment Model (GCAM-USA), a detailed service-based building energy model with a 50-state domain.

Costs presented here are in comparison to a reference case run, in which climate is held constant to current climate while socioeconomic variables are dynamic, and a projection run in

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[108] McFarland, J., Zhou, Y., Clarke, L., Sullivan, P., Colman, J., Jaglom, W.S., Colley, M., Patel, P., Eom, J., Kim, S.H., Kyle, G.P., Schultz, P., Venkatesh, B., Haydel, J., Mack, C., and Creason, J. 2015. Impacts of rising air temperatures and emissions mitigation on electricity demand and supply in the United States: a multi-model comparison. *Climatic Change*, 131, 111-125. Doi:10.1007/s10584-015-1380-8.

[109] 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

which both climate and socioeconomic variables are changing. Costs are expected to increase in the near term but decrease and drop below baseline costs by 2050 through end of century.

Table A21. Annual Economic Impact of Climate Change on Costs of Electric Supply

Change in electric transmission and distribution infrastructure impacts ($millions/year) 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).

	Baseline	Annual economic impact of climate change on costs of supplying electric energy ($millions)			
	2010	**2030**	**2050**	**2070**	**2090**
Statewide	$4,900	$2.3	-$21	-$51	-$68

Source: Based on McFarland et al. 2015

These costs were estimated only at the state-level in the underlying study. The interconnectedness of energy supply in the Commonwealth and the ability of both the larger investor-owned and local municipally owned electric utilities to purchase electric supply from a wide range of sources implies that there is a measure of resilience at the state level in electric supply through the broad accessibility of the market for electric power. The results of the underlying study consider factors related to climate change on overall demand (including additional deployment of space cooling) and on “climate penalties” on supply and transmission (such as reduced thermal plant and transmission efficiency associated with extreme heat) but do not consider recently adopted Commonwealth policies that might substantially change the generation mix that makes up electric energy supply.

The Commonwealth has conducted analyses of actions required to meet GHG emissions reductions and decarbonization goals, and how they could affect electric energy supply in the 2030 and 2050 timeframes. The recently published Massachusetts Clean Energy and Climate Plan for 2025 and 2030 outlines specific actions to be taken in multiple sectors, including the electricity supply sector. Actions affecting electric energy supply include transitioning electric supply to cleaner sources, including new deployment of solar and wind capacity; electrifying portions of the space heating and transportation sectors that currently rely on direct use of fossil fuels; and expanding energy efficiency measures. The Plan adopts a “Phased” scenario as the least-cost and lowest risk option, which is expected to have an increased net energy supply cost compared to the reference scenario of roughly 10 percent in 2030 and less than 10 percent in 2050.[110] A separate national scale-study led by Princeton University researchers found similar results for analysis of several variants of a net-zero emissions strategy through 2050. The study found that with a large nationwide effort the United States could reach net-zero emissions of greenhouse gasses by 2050 using existing technology and at costs aligned with historical spending on energy. The marginal impact of the net-zero emissions scenario costs was estimated to be comparable to spending in recent history, but higher than for the reference

[110] MA EOEEA 2022, page 27, with details in Appendix A, in particularly Figure A.16.

scenario – by about 3 percent (or $300 billion) more for the decade through 2030, and about 20 to 30 percent more (NPV) through 2050.[111]

For the solar category of clean energy production, this assessment also examined the potential for inland and coastal flooding to temporarily or permanently reduce supply from that source. Flood risk profiles for inland and coastal flooding from the relevant Infrastructure sector analyses for this report are used, as well as the following data and GIS sources: the FEMA 100-year floodplain file; the MA DOER Production Tracking System (PTS) Solar Photovoltaic Report (as of February 2022); and a GIS file developed by Clark University professor John Rogan that documents the physical outlines of solar installations in the Commonwealth.[112] The results of this overlay analysis are shown in Table A22 and reveal that while 26 percent of current solar production is located in a FEMA 100-year floodplain, not all of that production is likely to experience flooding, according to available flood risk modeling. Using forecast flood risk modeling, the amount of currently deployed production actually at risk in future years could be as high as four percent of total current annual solar electricity production.

Table A22. Annual Solar Electric Production Potentially at Risk from Inland and Coastal Flooding Associated with Climate Change

Estimates of current solar electric production located in the 100-year return period inland and coastal floodplain, and total annual solar electric production that may be at elevated risk of flooding based on currently available flood modeling. 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.

	Production in 100-yr floodplain (GWhr)	Total annual solar electric production at risk of flooding from 100-year flood (inland and coastal flood risk combined) (GWhr)			
Region	**Current**	**2030**	**2050**	**2070**	**2090**
Berkshires & Hilltowns	15	15	0.3	0.3	14
Greater Connecticut River Valley	60	12	0.6	0.4	8
Central	240	15	2	5	3
Eastern Inland	430	60	1	2	65
Boston Harbor	33	16	0.2	0.3	31
North & South Shores	60	25	17	18	4
Cape, Islands, & South Coast	64	11	0.8	4	4
Statewide	**900**	**160**	**22**	**30**	**130**

[111] The "Net-Zero America" study by Princeton University researchers is described here: https://www.princeton.edu/news/2020/12/15/big-affordable-effort-needed-america-reach-net-zero-emissions-2050-princeton-study?source=email

[112] PTS data available here: https://www.masscec.com/production-tracking-system-pts. Solar installation outlines obtained via personal communication with Dr. John Rogan of Clark University, the dataset is described here: https://clarknow.clarku.edu/2021/04/21/geography-research-documents-solar-farms-negative-effects-on-landscape/

	Production in 100-yr floodplain (GWhr)	Total annual solar electric production at risk of flooding from 100-year flood (inland and coastal flood risk combined) (GWhr)			
Region	**Current**	**2030**	**2050**	**2070**	**2090**
Statewide as % of current production	**26%**	**4%**	**1%**	**1%**	**4%**

Source: Project Team analysis of data provided by Dr. John Rogan of Clark University

A separate consideration is whether climate change impacts on electric supply and demand might affect the likelihood of future power outages. The electric load analysis conducted to support the Commonwealth's Clean Energy and Climate Plan also shows that increased electrification should shift the peak electricity demand season from summer to winter, mainly as a result of electrification of space heating. One interpretation of this result is that warming associated with climate change could have a mitigating effect on forecast peak electric loads over time, but peak winter loads may also increase as a result of climate change.

Analyses of electric load-induced power outages are sometimes undertaken by the relevant Independent Systems Operator, or ISO – for Massachusetts this is ISO New England.[113] While ISO New England does not currently have a climate reliability study available for interpretation, the neighboring state New York ISO study on the impact of climate change on electric reliability concludes that climate disruption scenarios involving storms or the reduction of renewable resource output (e.g., due to wind lull) could lead to loss of load occurrences (when demand outstrips supply), with a risk of a longer duration of an outage in the winter than summer. Specifically, during the occurrence of severe wind storms in winter, lulls in wind resource output and icing events could all lead to loss of load in New York, as well as elevated reliance on distributed energy resources. While no such study is currently available for Massachusetts, and the frequency of the type of severe winter storm and icing event that leads to outages under changed climate has not been assessed for Massachusetts, the New York ISO study may provide a framework for future analyses to assess that risk.[114]

Disproportionality

This impact has **limited** disproportionate exposure.[115] Available estimates of statewide costs of supplying electric energy associated with climate change were not allocated by municipality or region so it is difficult to assess how EJ block groups might be differentially affected.

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[113] The Federal Electric Reliability Commission created independent system operators, or ISOs, to oversee restructuring of the utility system on a regional basis. These ISOs also were given responsibility for ensuring reliability (prevention of outages) and establishing and overseeing competitive wholesale electricity markets.

[114] Itron, Inc. New York ISO Climate Change Impact Study Phase 1: Long-Term Load Impact, December 2019; and Paul J. Hibbard et al. Climate Change Impact and Resilience Study – Phase 2: An Assessment of Climate Change Impacts on Power System Reliability in New York State, September 2020.

[115] Although this analysis does not find a quantitative correlation between the locations of exposure to this impact and EJ block groups, it is important to note that not all populations will have the same experience with the effects of climate change and this impact because of pre-existing social vulnerabilities that are difficult to measure or comprehensively quantify across the Commonwealth.

If climate change were to have an effect on electric rates, any increase may disproportionately fall on low-income groups that have a reduced ability to absorb any potential price increases. The 2022 CECP results forecast a slight increase in average electricity rates from 2020 to 2025 as result of the plan (from about 17.5 to about 18.5 cents per kWh) but a reduction in rates for 2030 (to about 16.5 cents per kWh) and continuing through 2050 (just over 14 cents per kWh).[116] As a result, this assessment concludes impacts on rates can be expected to be small in the immediate term and that a reduction in rates may be more likely in the short- to medium-term.

Adaptation

There is a **minimal** adaptation gap for energy production and resources. Diversity in energy production is already increasing due to a combination of market forces, policy, and funding initiatives bolstering the growth of renewables. Municipalities across the state are incentivizing the inclusion of small-scale renewable energy installations in new development projects and incorporating renewable and microgrid compatibility in zoning regulations. Some plans include load management strategies like smart meters, adjustable electricity rates, and increased storage capacity in the grid. Microgrids are commonly cited as a way to increase grid resilience. Statewide planning, for example the initiatives set forth in the 2025/2030 CECP, take critical steps towards adequate energy production.

Example Adaptation Plans with Actions Addressing this Impact

- Climate Action and Resilience Plan – Concord: See Energy section
- NB Resilient – New Bedford: See Climate & Energy section

Sensitivities and Uncertainty

A key uncertainty for this analysis is projecting demand and supply investments necessary to meet goals for electric energy decarbonization. As summarized above, best available information from the Massachusetts CECP indicates these costs to supply the projected demand for electricity will increase but the overall projected impact on rates will be small.

Climate stressors could increase the occurrence of power outages, but specific analyses are not currently available for Massachusetts – this finding is based solely on information currently available for an electric reliability study conducted for neighboring New York State, where both demand and supply conditions can be expected to differ from those in Massachusetts. Direct and indirect costs of damage for power outages are not estimated here but are considered in other impact categories (see list below).

The MacFarland et al. (2015) study which is the basis for estimating overall system costs through 2090 projects changes in heating degree days (HDD) and cooling degree days (CDD) based on a temperature set-point of 65°F, a common convention that may lead to a

[116] Massachusetts EOEEA 2022, see Figure A.20 in Appendix A. Note that impacts on rates involve both energy costs and transmission and distribution charges. See Infrastructure sector, Damage to Electric Transmission and Distribution Infrastructure impact write-up for analysis of impacts to transmission and distribution costs.

conservative energy demand estimate. In addition, the temporal aggregation of the underlying electricity supply model is too coarse to assess the impact of extreme temperature events that occur on only the very hottest days of the year. As a result, the underlying study focuses on a single aspect of climate change: average ambient air temperature, and therefore omits effects of extreme temperature effects on daily peak demands and the loads required to meet those changes. Effects from future changes in the frequency and magnitude of extreme temperatures may stress electric power systems, and these economic risks are not captured in this study.

Related Impacts

Table A23 lists the impacts in other sectors that have a connection to this impact.

Table A23. Additional Impacts related to Loss of Energy Production and Resources

Sector	Impact	Connection
Infrastructure	Damage to Electric Transmission and Utility Distribution Infrastructure	Electric supply is in part dependent on the continued reliable operation of transmission and distribution infrastructure, which may itself be affected by climate change.
Economy	Economic Losses from Commercial Structure Damage and Business Interruptions	Power outages related to disruptions in electric supply and demand have substantial impacts on businesses.
Human	Health Effects from Extreme Storms and Power Outages	Power outages in general 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.

Infrastructure Sector: Urgent Impact #9

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.

Impact Summary

Climate change is expected to increase the probability of extreme events and the severity of downstream impacts from dam failures:

- Increased flood events will lead to more breaching and overtopping events, potentially (see uncertainty section on limitations on analysis of flood events) leading in the most extreme cases to dam failure
- Increasing population density and population growth over time increases the exposure of critical infrastructure and people to flooding from dam failure

Exposure to dam failure impacts is also heavily influenced by capital expenditure and the ability of funding to be allocated toward risk mitigation. This can lead to a disproportionate burden of impacts to fall on communities with limited funding ability. For the purposes of this assessment, the scope of dams evaluated is limited to those specifically defined by the Massachusetts Department of Conservation & Recreation (DCR) as Significant and High Hazard Dams under dam safety program regulations.

Urgency Ranking Results

This impact is ranked as a **lower priority** because the magnitude of consequence is low relative to other impacts in this sector; is not expected to increase significantly until 2050; and the impacts have limited to no disproportionate exposure. The adaptation gap is currently low because of successful current efforts by DCR to administer a program for dam safety in Massachusetts to prevent dam failure.

Dams in the DCR program are classified in hazard categories from low to high based on their potential risk to life, health, and property should the dams fail. The categorization does not account for the condition of these dams, or the likelihood of failure to occur. Climate change could lead to more frequent overtopping of dams, causing flooding of downstream areas, even if dam safety protocols remain successful at avoiding complete dam failure. The impacts of dam failures are calculated by estimating baseline economic costs of repair and replacement of dams, and an estimate of the likelihood of a damaging dam failure, adjusted for the economic value of surrounding homes and infrastructure. Estimates of the probability of future flood events and damages from those events are used to calculate damages associated with climate change projected into the future, which are compared to the baseline economic costs.[117]

> "*If one [dam] breaks the cascading water flow will break the next dam in its path, and so on, and so on.*"
>
> *"We're concerned about the Amelia Earhart Dam overtopping and the effect on our region."*
>
> - Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

In Massachusetts there are 2,903 dams within the purview of the state dam safety program, of which 1,075 are classified as Significant or High Hazard dams.[118] Of those, 666 are publicly owned with a majority of them owned and operated by municipalities (469). The consequences of dam infrastructure failure are projected to be **minimal**.[119] The result is an estimated annual economic impact of damage due to dam failure events that is low compared to that from other infrastructure sectors. It may be important to note that other, generally smaller dams are present in the Commonwealth and are not within the dam safety program jurisdiction, which may also pose risks to property and people. Because data are not available for dams not within the dam safety program jurisdiction, it is not currently possible to assess potential risks from climate change associated with non-jurisdictional dams.

Table A24 shows the annual estimated future impacts of climate change (difference from the baseline) from overtopping and breaching events for the 738 significant hazard dams and 330 high hazard dams evaluated. For the purposes of this Climate Assessment, and based on existing incident reports, the cost of repairs and other damage from *overtopping* events are estimated to be just less than $200,000 per event. The economic impact of the potentially more serious and hazardous *breaching* events varies by location but average to slightly more than $2.9 million per event.

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[117] Further explanation of methods can be found in Appendix C.

[118] Number of dams represent registered jurisdictional dams, as defined by the Department of Conservation and Recreation (see here: https://www.mass.gov/office-of-dam-safety) and for which dam locations are recorded in the MassGIS database as of July 2022.

[119] Described more thoroughly in Appendix C, methods section: Databases with records of Dam incidents and consequences in Massachusetts show a majority of incidents happening before the year 2000, and even fewer in the last 10 years suggesting that rules in Massachusetts to require Emergency Action Plans for all Significant and High hazard Dams and requirements for inspections every two years may be impacting the reduction of Dam Incidents. River reach-specific flow projections for a range of return period events at relevant dams under future climate derived from data in Fant, C., R. Srinivasan, B. Boehlert, L. Rennels, S.C. Chapra, K.M. Strzepek, J. Corona, A. Allen, and J. Martinich (2017). Climate change impacts on US water quality using two models: HAWQS and US Basins. *Water*, 9, 118, doi:10.3390/w9020118. Available online at https://www.mdpi.com/2073-4441/9/2/118

Table A24. Annual Economic Impact of Overtopping and Breaching of Significant and High Hazard Dams due to Climate Change

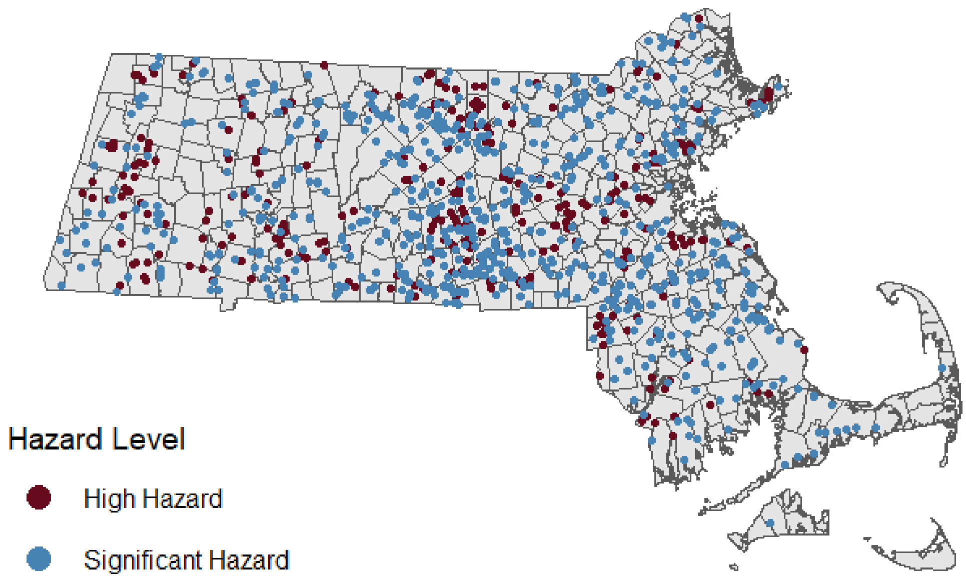
Economic impacts are defined as annual economic impact as compared to the baseline climate scenario (1986-2005). Future impacts presented for four time periods identified in the table by their central year: 2030 (near-term, 2020-2039); 2050 (mid-century, 2040-2059); 2070 (mid-late century, 2060-2079);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

		Annual economic impact of overtopping and breaching ($millions)			
Region	**Baseline**	**2030**	**2050**	**2070**	**2090**
Berkshires & Hilltowns	$0.2	-<$0.05	$2.3	$2.0	$2.1
Greater Connecticut River Valley	$0.3	$0.9	$4.3	$4.5	$4.7
Central	$0.4	$0.6	$4.1	$3.3	$3.4
Eastern Inland	$0.5	-$0.2	$1.1	$1.4	$1.4
Boston Harbor	$0.1	-<$0.05	$0.2	<$0.05	<$0.05
North & South Shores	$0.2	$0.3	$0.6	$2.6	$2.7
Cape, Islands, & South Coast	$0.1	$0.3	$0.3	$2.6	$2.7
Statewide	$1.7	$1.9	$13	$16	$17

Source: Project team analysis of MassGIS data and climate induced streamflow data from Fant et al. (2017)

Impacts are generally predicted to increase over time for Massachusetts. The spatial distribution of outcomes is skewed toward regions with a higher number of significant and high hazard dams (Greater Connecticut River Valley and Central. Across Massachusetts, annual expected baseline period damages are $1.65 million and expected to have an incremental increase of $11 to $16 million by the end of the century.

Figure A22. Location of Dams and their Hazard Significance Levels



Source: MassGIS

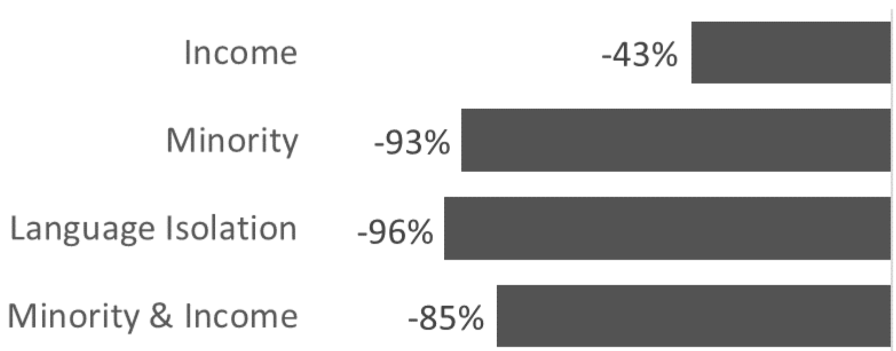
Note that the impacts summarized above exclude consideration of dams classified as low hazard, and also do not consider climate stresses to dams in coastal regions that result from sea level rise or coastal storm surge. Two examples of dams that are both classified as low hazard and potentially affected by coastal hazards are the Amelia Earhart dam spanning the Mystic River between Somerville and Everett; and the Charles River Dam in Boston. This analysis does examine the potential for freshwater side overtopping and breach risk for those dams, but does not examine the saltwater side, coastal storm surge and sea level rise risk. The MC-FRM analysis included in the Damage to Coastal Buildings and Ports sector, however, does include the risks of saltwater side overtopping to potentially vulnerable structures near these two dams.

Disproportionality

This impact category is classified as **limited** disproportionate exposure, as summarized in Figure A23.[120] The Commonwealth maintains a spatially precise and publicly available database on the location of these dams and their surrounding areas, and only a small number of the Significant or High Hazard dams statewide (108) are in block groups identified by the Commonwealth as EJ population areas. The Eastern Inland region has the most dams in EJ block groups with 29.

Figure A23. Disproportionality of Impacts from Dam Failure

Comparison of dam failures 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 a **minimal** adaptation gap to addressing the risk of dam overtopping or failure although few actions were found in the reviewed climate plans that address the risks of dam overtopping or failure. When dams are mentioned, dam removal is often considered a priority. Several plans outline specific dam removal feasibility studies and others are actively implementing those

[120] Although this analysis does not find a quantitative correlation between the locations of exposure to this impact and EJ block groups, it is important to note that not all populations will have the same experience with the effects of climate change and this impact because of pre-existing social vulnerabilities that are difficult to measure or comprehensively quantify across the Commonwealth.

plans. Other notable actions include dam restoration using green infrastructure (primarily restoration of natural floodplains, in particular including wetland restoration) and future stream flow modeling projections.

The low reported incidence of dam overtopping and breach events in Massachusetts in available national dam incidence reporting inventories supplies strong evidence that the existing dam safety program is well adapted to current climate and flow event occurrence. Estimates of future incidence of high flow events suggest that in aggregate, significant increases in risks from dam failures may not occur until mid-century.

While many of Massachusetts's dams are old, the existing inspection, monitoring, and emergency preparedness program appears to be effective in reducing incidence to a low level. There have also been recent pledges from state and federal government agencies to invest in dam repair and flood control projects.[121] The impact of these investments could reduce the projected impact of damage across the state.

Example Adaptation Plan with Actions Addressing this Impact

- Eagle Dam Removal Technical Feasibility Study

Sensitivities and Uncertainty

- The analysis assumes that dams in Massachusetts, which are regularly inspected and monitored, are built and maintained to their stated design standards – for Massachusetts, that means significant and high hazard dams are designed to the 1000-year flow event standard (0.1-percent annual likelihood event) for overtopping and 5000-year flow event (0.02-percent) for dam breaching. In some cases, the actual design standards and performance characteristics of these dams may differ from the required design standards.
- Costs per event are based on the available information from review of Massachusetts Emergency Action Plans and the available data from the National Performance of Dams Program and Association of State Dam Safety Officials Dam online[122] Incident Database (DID). Detailed, project-level estimations of flood damage that are unique to each dam would improve the estimate of cost but would require a significantly expanded level of effort.
- Data on the construction specifications and purpose of each dam were not available. Some are built for flood control or water supply, and some are built for aesthetics. The purpose of the dam and design specifications would give us better estimates of damages from a dam failure. For example, the Amelia Earhart Dam was designed for flood control and is located in close proximity to large urban development areas near

[121] See July 28, 2021 press release announcing Commonwealth plans for investment in dam and coastal infrastructure safety: https://www.mass.gov/news/baker-polito-administration-awards-over-17-million-in-funding-for-dams-and-coastal-infrastructure - and the related February 3, 2022 program regarding recent MVP grant program funding which includes funding for dam safety: https://www.mass.gov/news/baker-polito-administration-outlines-bipartisan-infrastructure-law-funding-plans-for-massachusetts

[122] See https://damsafety.org/incidents

the shore. The dam is therefore susceptible not only to fluvial flooding but also to ocean flooding such as storm surge worsened by rising sea levels, increasing the probability of overtopping and failure. The compounding effects of fluvial and ocean flooding, including sea level rise, are notably complex and were not considered in this analysis. If the dam were to fail, the damages would be much higher.

- Streamflow simulated at the project-scale with bootstrapping (artificially generated flows) would improve the estimation of event occurrence for both the historical period and the future period but would also require a significantly expanded level of effort. Estimating occurrence probabilities of 1000- to 5000-year events with 20 years of data, as done for this assessment, can result in less reliable solutions.
- The analysis conducted here focuses on potential downstream effects of dam failure and omits upstream effects. Following a dam breach upstream effects can include bank erosion and other impacts that compromise road crossings or other infrastructure. Unfortunately, existing information to characterize the frequency or severity of upstream effects is limited.

Related Impacts

Table A25 lists the impacts in other sectors that have a connection to this impact.

Table A25. Additional Impacts related to Increased Risk of Dam Overtopping or Failure

Sector	Impact	Connection
Natural Environment	Freshwater Ecosystem Degradation	Freshwater Ecosystems in front of and behind dams could be disrupted by overtopping or failure.
Infrastructure	Damage to Inland Buildings	Residential and commercial buildings behind dams could be vulnerable to overtopping and failure.
Infrastructure	Damage to Coastal Buildings and Ports	Dams located near the coast with the purpose of flood control will be vulnerable to overtopping and failure, leading to damages to coastal buildings
Governance	Damage to Inland State and Municipal Buildings and Land	Government buildings and land behind dams could be vulnerable to overtopping and failure.

Natural Environment Sector

The Natural Environment section includes impacts to ecosystems and natural resources, and how plants and animals can thrive here. A changing climate will permanently alter habitats in the Commonwealth, resulting in disruption of ecosystem services flow during habitat transition and loss of native ecosystems. Three key features of the Natural Environment Sector, described further in Section 4.3 of the main report, are:

1. **Impacts in the Natural Environment Sector often represent foundational changes that influence impacts in other sectors**.
2. **Distinct categories of impact are difficult to define in this sector.**
3. **All impacts are classified as Potential for Disproportionality of Exposure** due in part to the focus of this sector on natural environment, rather than direct impacts to humans, and in part due to the challenges in disentangling the flows of disrupted ecosystem services to specific groups of people**.**

Table A26. Natural Environment Sector Impacts Ranked by Urgency Score

IMPACT	MAGNITUDE	DISPROPORTIONATE EXPOSURE	ADAPTATION GAP	URGENCY SCORE
Freshwater Ecosystem Degradation (MOST URGENT)	Extreme	Potential	Extreme	83
Marine Ecosystem Degradation (MOST URGENT)	Extreme	Potential	Extreme	83
Coastal Wetland Degradation (MOST URGENT)	Extreme	Potential	Moderate	72
Forest Health Degradation (MOST URGENT)	Extreme	Potential	Moderate	72
Shifting Distribution of Native and Invasive Species	Major	Potential	Moderate	64
Coastal Erosion	Major	Potential	Moderate	64
Soil Erosion	Minimal	Potential	Moderate	47

Natural Environment Sector: Urgent Impact #5 (tie)

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.

Impact Summary

Climate change will alter existing biogeochemical cycles that support viable environments for native species to thrive and may consequently make it viable for invasive flora and fauna to thrive. This shift in suitable habitat will change the distribution of biodiversity of Massachusetts, potentially lead to the loss of some native species, and have cascading effects across the state and across all other sectors in the report. Examples of the ways climate change will change the distribution of native and invasive species include:

- Changes to temperature levels and their duration will shift growing seasons such that some invasive species and generalist species will gain a competitive advantage
- Changes to precipitation levels and their timing will impact the availability of nutrients as well as change waterways and their associated ecosystems
- Changes to the extremes of climate will make ecosystems more vulnerable to pests and disease, weakening the ability of native flora and fauna to adapt to a new climate[123]

Urgency Ranking Results

This impact is ranked as a **medium priority** because of its major level of consequence, potential for disproportionate effect, and moderate gap in adaptation action needs. The level of consequence is major because of the difficulty in projecting the severity and magnitude of shifting habits and the associated consequences. Disproportionality is also difficult to assess, but the effects will be felt across the state regardless of socioeconomic status. Efforts to preserve, manage, and study the shifting of habitats to mitigate the proliferation of invasive species has become a focus of MassWildlife and other organizations, but more can be done.

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[123] Massachusetts Division of Fisheries & Wildlife (November 2016). Massachusetts State Wildlife Action Plan. https://www.mass.gov/service-details/state-wildlife-action-plan-swap

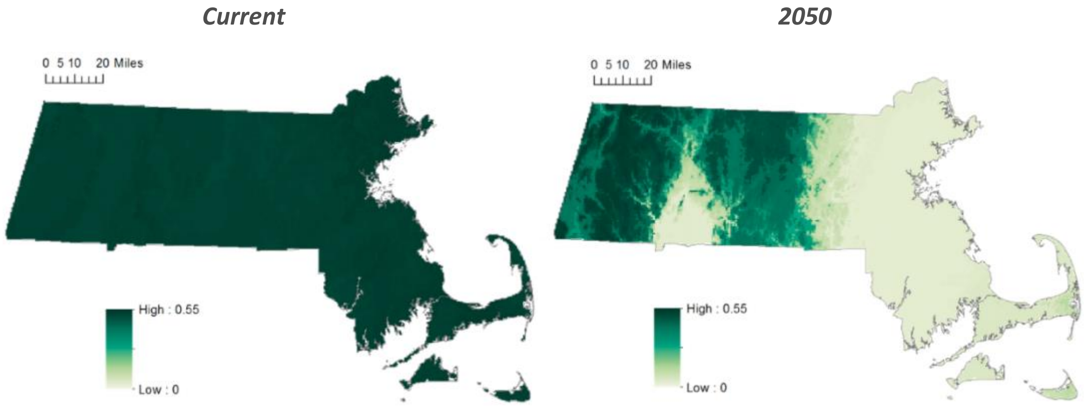
> *"The explosion of invasive species and loss of native plants threatens our ecosystem from the bottom up - the loss of biodiversity we are already experiencing is deeply concerning, and while a lot of good work is being done by conservation groups and individuals to address these problems, much more needs to be done."*
>
> \- Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The consequences of climate change on the distribution of species are projected to be **major** due to uncertainty on exact impacts and the underlying importance of a resilient biodiversity to the natural environment. The 2015 Massachusetts State Wildlife Action plan (SWAP) listed 172 vertebrates, 115 invertebrates, and 283 plants as species of greatest conservation need in Massachusetts.[124] Climate change will change the timing of life events such as migration and reproduction for these flora and fauna across the state. An example impact of a shifting climate is illustrated in Figure A24 for the state bird of Massachusetts: the Black-capped Chickadee. Mass Audubon listed the Chickadee as highly vulnerable to a change in climate. seethe figure illustrates that approximately half the state will no longer be suitable for the Chickadee.

Figure A24. Land Area Suitable for Black-capped Chickadee

Mass Audubon projected the area suitable for species based on overlaying historical temperature and precipitation to determine a range of values suitable for each studied species. They then use projected climate to determine the area of suitable climate in 2050 under a high emissions scenario. The legend represents the probability that the climate will be suitable for this species by 1km^2 blocks.



Data Source: Mass Audubon State of the Birds 2017[125]

Another example of such a change can be seen with the Roseate Tern (Sterna dougallii), a federally listed endangered species. The SWAP designates the Roseate Tern as a species of "very high" concern and the Mass Audubon Society designates a "Highly vulnerable" rating to

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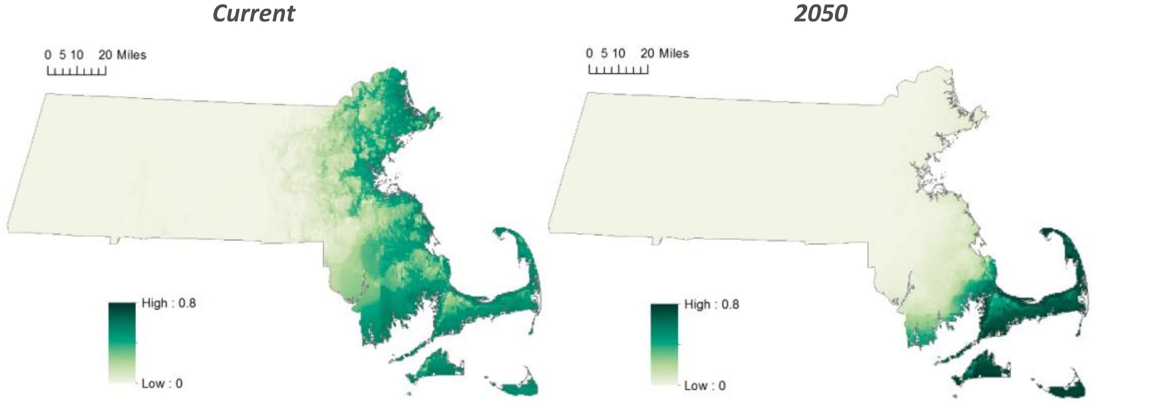
[124] Massachusetts Division of Fisheries & Wildlife (November 2016). Massachusetts State Wildlife Action Plan; Chapter 3. https://www.mass.gov/files/documents/2016/12/wh/ma-swap-public-draft-26june2015-chapter3.pdf

[125] Massachusetts Audubon Society. State of the birds 2017 Report https://www.massaudubon.org/content/download/21633/304821/file/mass-audubon_state-of-the-birds-2017-report.pdf

climate change vulnerability and a bird species in “Strong Decline” with regard to breeding viability in Massachusetts. Furthermore, as seen in Figure A25, an approximately 75 percent loss in viable land for breeding is projected by the year 2050.

Figure A25. Land Area Suitable for Roseate Tern

Mass Audubon projected the area suitable for species based on overlaying historical temperature and precipitation to determine a range of values suitable for each studied species. They then use projected climate to determine the area of suitable climate in 2050 under a high emissions scenario. The legend represents the probability that the climate will be suitable for this species by 1km² blocks.



Data Source: Mass Audubon State of the Birds 2017

Beyond the shift in viable area for the species to live, there will be simultaneous and cascading effects. For example, the Roseate Tern relies on sand lance, hake, and herring fish populations for food. Climate change will directly impact the life cycles of these fish species, shifting the timing of their maturity and the locations of their habitats. Consequently, food availability for the Roseate Tern will shift, altering the connections of species in the region and potentially driving the Roseate Tern to follow their food source.[126]

Non-native, invasive species are also a concern because of the impacts they can have on the viability of native species and ecosystems.[127] Rockwell-Postel et al. 2020 present results of a meta-analysis of potentially invasive species for southern New England and focus on the species with the largest potential ecological impacts, which include:

- **Competition** with native species for resources (e.g., food, water, space);
- **Physical impacts** causing changes in characteristics of ecosystem, including fire regimes, water cycles, or soil erosion;
- **Structural impacts** such as adding or removing canopy levels and altering structural resources (e.g., nesting habitat);
- **Poisoning/Toxicity** that is toxic or allergenic to wildlife, allelopathic to plants, or alters microbial communities; and

[126] Staudinger, M. D., Mills, K. E., Stamieszkin, K., Record, N. R., Hudak, C. A., Allyn, A., … Yakola, K. (2019). It’s about time: A synthesis of changing phenology in the Gulf of Maine ecosystem. Fisheries Oceanography, 28, 532–566.

[127] Non-native, invasive species can also impact agricultural productivity. Of the listed species in Table 1, all but Bur chervil present a threat to agriculture (see Decrease in Agricultural Productivity in the Economy sector).

- **Bio-fouling**, or growth on surfaces in water.[128]

The five species of most concern are listed in Table A27. Some of the identified species are already present in southern New England while others could become established under future climate conditions. These species do not necessarily present the largest current threat, rather they exemplify how climate change will bring new species to the area.

Table A27. Non-Native, Invasive Species and Pests of Future Concern in Southern New England

Five non-native, invasive species of highest concern based on findings from a meta-analysis performed by Rockwell-Postel et al. 2020 and two additional species of concern in Massachusetts

Species	Primary Ecological Concerns	Presence in southern New England
Bur chervil (*Anthriscus caucalis)*	Bio-fouling	Present in Southern New England
Giant reed (*Arundo donax)*	Competition, Physical Impact, Poisoning/Toxicity	Could establish in future conditions
Slender wild oat (*Avena barbata*)	Competition, Poisoning/Toxicity	Present in Southern New England
Water primrose (*Ludwigia grandiflora)*	Bio-fouling, Poisoning/Toxicity, Structural impact	Present in Southern New England
Elmleaf Blackberry (*Rubus ulmifolius)*	Competition	Could establish in current conditions
Lanternfly (*Lycorma delicatula*)	Poisoning/Toxicity	Present in New England
Emerald Ash borer (*Agrilus planipennis*)	Poisoning/Toxicity	Present in New England

Source: Rockwell-Postel et al. 2020

The Massachusetts Invasive Plant Advisory Group (MIPAG) developed a list of invasive and potentially invasive species in the Commonwealth. Last published in 2005, the list does not include the above listed species, suggesting changing climate conditions may shift which species require the most focus in the Commonwealth. Current species of concern include phragmites, wooly adelgid, and bittersweet.

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

[128] Rockwell-Postel, M., Laginhas, B.B. and Bradley, B.A., 2020. Supporting proactive management in the context of climate change: prioritizing range-shifting invasive plants based on impact. Biological Invasions, 22(7), pp.2371-2383.

assets and systems. Often the indirect impacts to humans resulting from changes to natural environment are captured in other sectors (see Table A28). 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 this impact. Habitat restoration and preservation efforts are underway across the Commonwealth and in many municipalities, many of which focus on reconnecting ecosystems and restoring natural channels for wildlife passage. Land use restrictions and zoning measures aimed at protecting existing unfragmented ecosystems provide additional options for accommodating range shifts of native species. For coastal zones, rolling easements allow for inland migration of marshes and wetlands and should be more widely implemented. Integrated management planning for invasive species is key, and while some municipalities have implemented plans, more regional coordination is needed for effective monitoring. As with other ecosystem-related impacts, effective restoration and resource management requires planning and significant time investment. For invasive species in particular, prevention and early detection are far less costly than management and removal once species are established, so proactive efforts are key.

Example Adaptation Plans with Actions Addressing this Impact

- Monatiquot River Restoration – Braintree: See channel restoration and bypass fishway
- Tree and Invasive Species Inventory and Management Plan – Westford
- Climate Action and Clean Energy Plan – Pioneer Valley: See wildlife corridor protection

Sensitivities and Uncertainty

Sensitivity and uncertainties in this impact include:

- Limited quantitative ability to predict shifts in the distribution of flora and fauna,
- Uncertainties around the consequential effects of shifts in the distribution of species,
- The impacts of actions taken to adapt to shifts are hard to determine.

The novel conditions that climate change will bring make it difficult to predict exactly how native and invasive species will persist across the state. The missing component from current research is a lack of understanding of the mechanistic underpinnings that drive population dynamics across all connected species.[129]

[129] Merow, C., Bois, S. T., Allen, J. M., Xie, Y., & Silander, J. A. (2017). Climate change both facilitates and inhibits invasive plant ranges in New England. Proceedings of the National Academy of Sciences, 114. doi:10.1073/pnas.1609633114

Related Impacts

Table A28 lists the impacts in other sectors that have a connection to this impact.

Table A28. Additional Impacts related to Distribution of Native and Invasive Species

Sector	Impact	Connection
Natural Environment	All impacts	This impact, focused on flora and fauna, is related to all other impacts in the Natural Environment which are focused on ecosystems. The native and invasive species discussed here are affected by the degradation of their habitats.
Human	Damage to Cultural Resources	Residents of the Commonwealth hold special value for certain species and highly functioning landscapes emblematic of the area. This cultural value may be lost as species distributions shift.
Economy	Decrease in Agricultural Productivity	Increasing invasive species presence create a hazard for agricultural productivity, particularly forestry. Similarly, loss of native pollinators can lead to a reduction in yields.
Economy	Decrease in Marine Fisheries and Aquaculture Productivity	Massachusetts fisheries currently target species native to the area. Fisheries revenues may be impacted as these species shift northwards.

Natural Environment Sector: Urgent Impact #5 (tie)

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.

Impact Summary

Rising sea levels coupled with coastal storms of increased frequency and intensity, land use changes, and shoreline development all contribute to increasing erosion along the coast. Shoreline change is defined as an area that is either eroding (disappearing at a rate >0.1 feet per year) or accreting (building at a rate >0.1 feet per year). Beach and dune systems provide critical habitat, open space for recreation, and a first line of defense against coastal storms. Tracking erosion and accretional areas along the Commonwealth's coastline identifies regions that will require adaptive management to preserve the value of these critical areas.

Urgency Ranking Results

This impact is ranked as a **medium priority** due to localized but potentially severe impacts. The Massachusetts Shoreline Change Mapping and Analysis Project analyzed the historical record shoreline positions extending back to 1845 for 1,121 miles of shoreline. Below are the CZM-USGS long-term rates of shoreline change for select regions of the Massachusetts Coast, and descriptions of the patterns in each region. Note, the focus regions below are areas experiencing high rates of shoreline change and tend to feature fine-grained sediments that are easily transported by waves and long-shore currents (sand, silt). These regions are focused north of Boston, south of Boston, and across Cape Cod and the Islands. Sample, representative imagery summarizing results in site-specific locations within each region is also presented.

> *"I fear that coastal erosion is slipping beyond the control of humans since we have failed to address it sooner."*
>
> *"Cape Cod will lose beaches which are the magnets for the economy."*
>
> \- Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The losses associated with coastal erosion are expected to be **major**, with particularly high impacts in certain regions of the state, including Cape Cod and the Islands where multiple feet of beach loss are occurring each year. High rates of erosion pose a risk to natural resources, including the loss of the beaches themselves, but also poses a significant threat to salt marsh habitat on barrier beaches, and residential areas located immediately landward of the shoreline. The highest long-term rates of change were observed on the Cape and Islands – specifically Outer Cape Cod, and on Nantucket, and Martha's Vineyard. The highest long-term erosion rate of (23.6 feet per year) was observed on Muskeget Island, Nantucket. The highest long-term accretion rate was observed on the leeward (west) side of Monomoy Island, Nantucket Sound (32.8 feet per year). The most acute short-term rates of change (both erosion and accretion) were observed on the North Shore, Outer Cape Cod, and Nantucket.

Table A29. Dry beach loss by region

Losses assume a constant shoreline erosion rate. 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). Totals may not sum due to rounding.

	Dry Beach Area Loss Due to Coastal Erosion (Acres)		
Region	**2030**	**2050**	**2070**
Boston Harbor	140	460	770
North & South Shores	690	2,220	3,750
Cape, Islands, & South Coast	4,800	15,470	26,140
Statewide Dry Beach Loss	**5,630**	**18,150**	**30,660**
Note: No coastal erosion threats expected for inland regions (Berkshires & Hilltowns, Greater Connecticut River Valley, Central, and Eastern Inland).			

Source: Analysis of data from CZM-USGS Massachusetts Shoreline Change Mapping and Analysis Program

Shoreline erosion leads to the loss of accessible, dry beach located below the Mean High Water (MHW) line. Using the average shoreline erosion rates for each region, the number of acres of high beach loss was estimated for each region relative to the 2030, 2050 and 2070 out-years.[130] Given the dynamic nature of the region, the highest acreage of dry beach loss is expected to occur across the Cape, Islands and South Coast of Massachusetts at 4,800; 15,470; and 26,140 acres of dry beach loss by the years 2030, 2050 and 2070, respectively. The historic rates of shoreline change in the Boston Harbor region are heavily influenced by the presence of coastal armoring. As such, the Boston Harbor region had the lowest estimated acreage of dry beach loss at 140 acres, 460 acres, and 770 acres by the years 2030, 2050 and 2070, respectively.

The following figures show how accretion and erosion rates vary by specific locations along the coast.

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[130] More detailed analysis of the impact of climate change on shoreline change at a more spatially refined scale requires highly localized data and analysis, and therefore is not possible for this Climate Assessment at a statewide scale.

Figure A26. Shoreline Erosion/Accretion in Winthrop-Revere

Areas experiencing acute erosion in Winthrop are concentrated along the Winthrop parkway, extending northward to the Cherry Island sand bar. A substantial portion of the Winthrop shoreline is accreting, in some places greater than 1 foot per year. These areas include Winthrop Beach, Yirrell Beach and Point Shirley Beach. Data is sourced from the Massachusetts Shoreline Change Project (USGS and CZM, 2021)

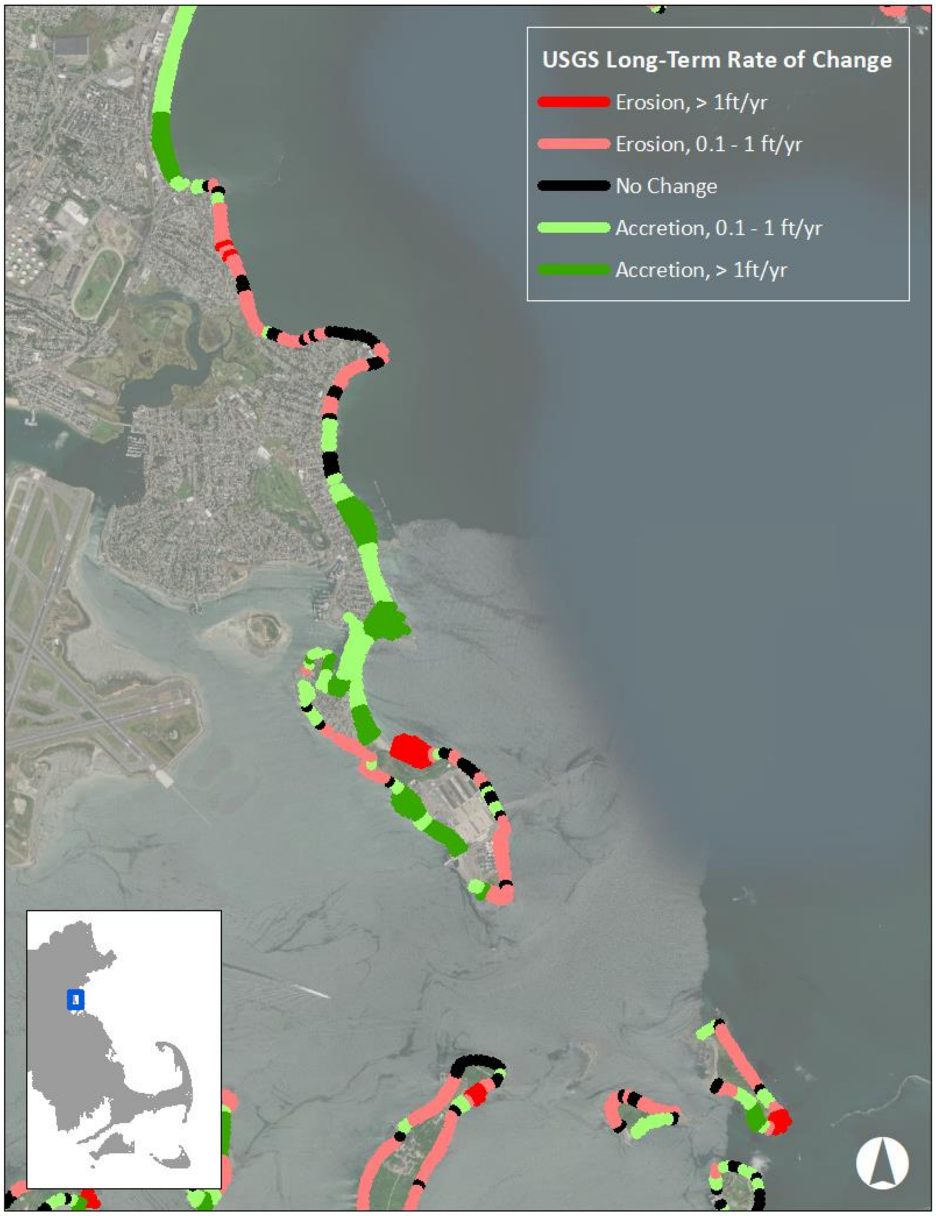


Figure A27. Shoreline Erosion/Accretion in Sandwich

Town Neck Beach in Sandwich, MA is experiencing high (> 1 foot per year) rates of erosion along the entire length of the beach. This highly dynamic shoreline is the main source of coastal storm protection for the communities that lie immediately landward of Sandwich Harbor. To the north-west of the Cape Cod Canal (Scussett Beach), accretion rates of > 1foot per year are observed, due to the presence of a shore-perpendicular jetty at the mouth of the Cape Cod Canal that retains sediment transported along the shore that would otherwise make its way to Town Neck Beach. Data is sourced from the Massachusetts Shoreline Change Project (USGS and CZM, 2021)

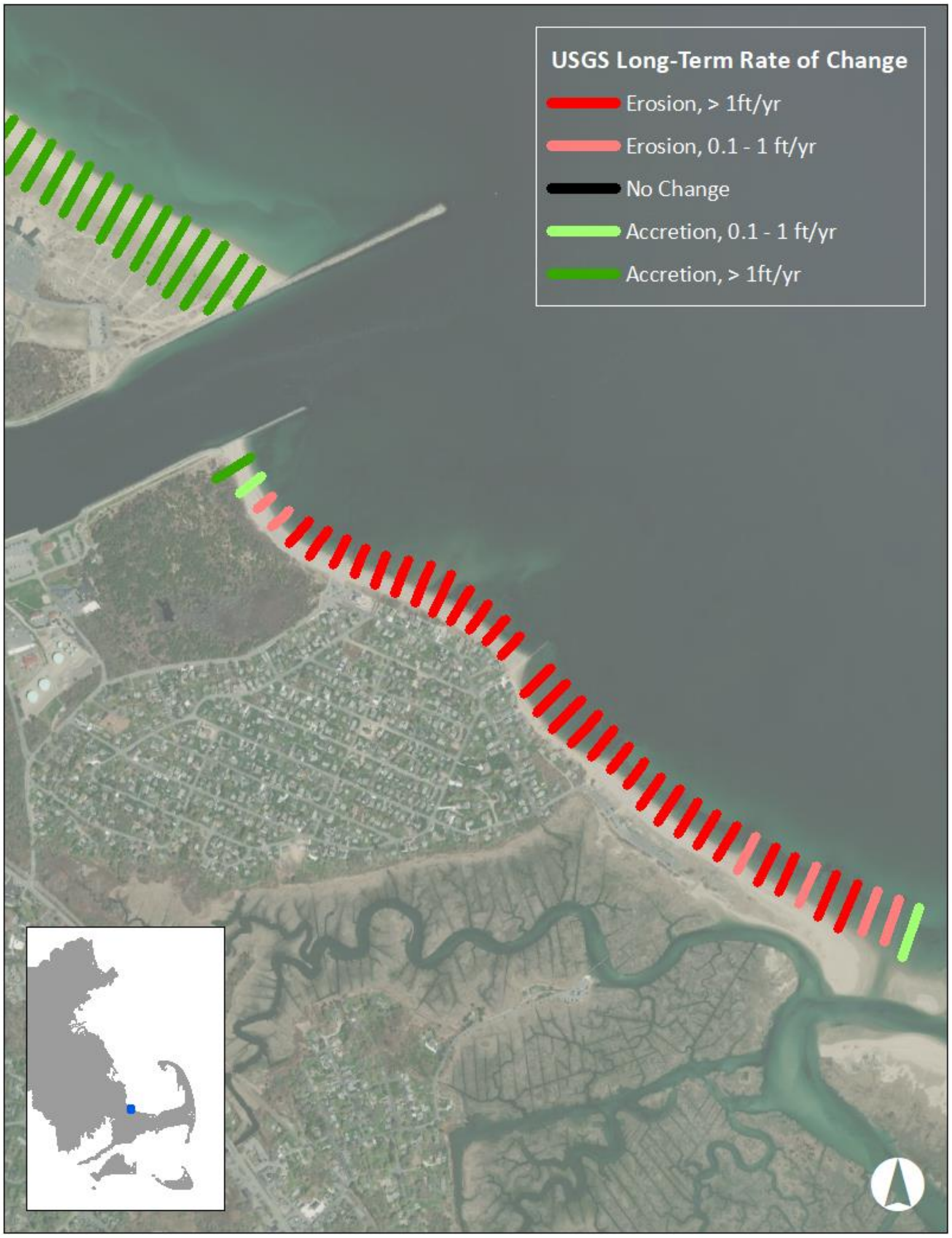
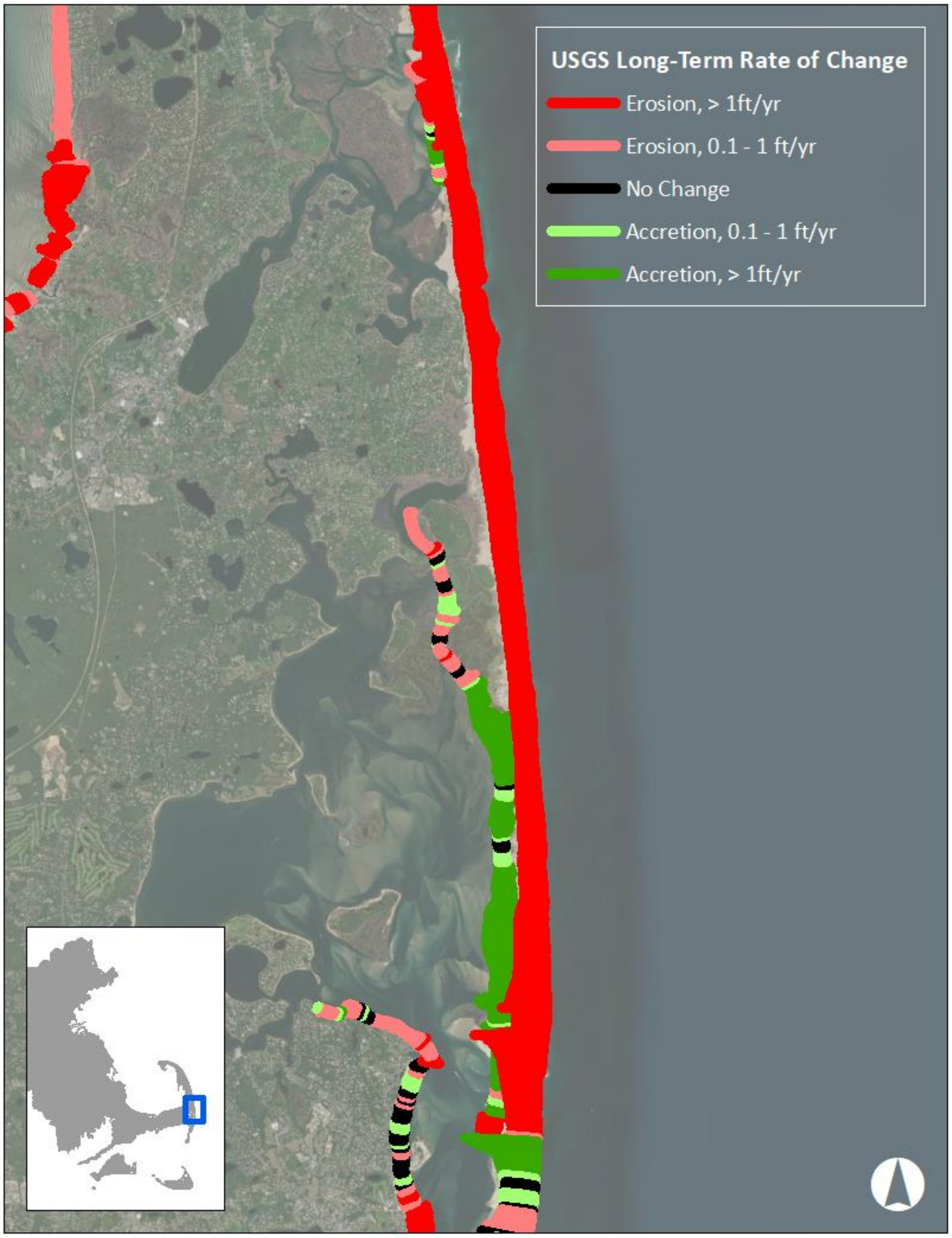


Figure A28. Shoreline Erosion/Accretion Outer Cape (South)

Long term rates of shoreline change indicate that the Outer Cape (southern extent) is experiencing high rates of erosion from Monomoy Island to the entrance of Pleasant Bay, as well as on the outer beaches of the Cape Cod National Seashore (Nauset Beach, Coast Guard Beach). Pockets of accretion exist at Harding Beach, the southern tip of Monomoy Island, estuarine beaches of Pleasant Bay, and areas near the inlet to Pleasant Bay at North beach. Data is sourced from the Massachusetts Shoreline Change Project (USGS and CZM, 2021)



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 A30). 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 erosion. Modeling and surveying work is being done in many areas to characterize sediment erosion and transport processes and assess coastal habitats. Many municipalities are implementing beach and dune nourishment projects, which replace lost sediment but do not discourage continued erosion. These projects provide a useful stopgap measure to address short term erosion threats, but longer-term strategies for erosion management are needed. Many such longer-term adaptation approaches in Massachusetts rely on vegetation and coastal habitats to provide natural erosion protection and coastal storm buffering. In that vein, some coastal communities have undertaken wetland restoration, shoreline revegetation, and coastal bioengineering projects. Effective strategies exist, but they often require significant planning, lead time, and investment of resources, so continuing to expand their use and operationalize the data collection and modeling work will be important in the near term as coastal hazards ramp up.

Additional available adaptation strategies can include, but are not limited to:

- Planting of native grasses and perennial species to stabilize coastal resource areas
- Beach nourishment and dune enhancement to replace sediment lost during erosive storm events
- Installation of coastal bioengineering structures, such as the construction living shorelines, that reduce rates of erosion and shoreline change while still allowing sediment to erode and convey to near shore areas during coastal storms.

Sensitivities and Uncertainty

There is tremendous variability in the long-term rates of erosion and shoreline change in coastal communities throughout the Commonwealth. Coastal beach, coastal bank, and coastal dune loss pose a danger to public and private coastal properties. Communities facing high rates of erosion may need to adapt more quickly, more decisively, and more regularly than those located further inland or those experiencing lower rates of erosion. These same communities may need to spend more on beach nourishment and dune enhancement to maintain the resource areas and buffer coastal storm impacts. Uncertain impacts from year-to-year make it difficult to plan on the level of action required from year-to-year, requiring plenty of foresight and advanced planning.

This analysis is based on historical shoreline change data sourced from the Massachusetts Shoreline Change Project, updated in 2021 (USGS and CZM, 2021). Due to the use of historic shoreline change data, key assumptions that were made to project historic rates of shoreline change to the 2030, 2050, and 2070 out-years include:

- Long-term, historical rates of shoreline change were assumed to remain constant from 2021-2070, not taking into account non-linearities or discontinuities caused by sea level rise, increased frequency and intensity coastal storms, and changes to beach, dune, and coastal bank geomorphology.
- This analysis assumed that historical rates of shoreline change would continue at a constant rate, including historical accretion related to beach nourishment.
- This analysis assumed that the composition of the shoreline would remain erodible over time, regardless of existing or future coastal armoring and/or hardened infrastructure.

Related Impacts

Table A30 lists the impacts in other sectors that have a connection to this impact.

Table A30. Additional impacts related to Coastal Erosion

Sector	Impact	Connection
Infrastructure	Damage to Coastal Buildings and Ports	Sand dunes and other shoreline habitats serve as a buffer for many structures potentially vulnerable to sea level rise and storm surge.
Infrastructure	Damage to Roads and Loss of Road Service	Erosion along roadways can threaten the integrity of roads and require protections and repairs.
Natural Environment	Coastal Wetland Degradation	Erosion can occur at faster rates in areas with degraded or lost wetlands. Beaches can also provide a buffer for high wetlands.
Economy	Damage to Tourist Attractions and Recreation Amenities	Coastal beaches are a draw for tourists and recreators but are vulnerable to erosion risk.
Governance	Reduction in State and Municipal Revenues	Coastal erosion could lead to property loss, and associated tax revenues, in coastal cities and towns.

Natural Environment Sector: Urgent Impact #7

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 Level of Consequence	Potential for Disproportionality	Moderate Adaptation Gap
• More frequent extreme precipitation events due to climate change could worsen erosion, but regions most vulnerable to erosion 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.

Impact Summary

Soils play a key role in ecosystems across the Commonwealth, sequestering carbon, supporting food production and other plant growth, absorbing water, and filtering pollutants. Changes in the seasonality and intensity of rainfall events due to climate change are expected to exacerbate soil erosion, threatening these ecosystem services. In addition, eroded soils from terrestrial ecosystems and agricultural lands can negatively impact aquatic ecosystems, contributing to eutrophication and reduced water quality, which can have knock-on effects on human health. Climate-driven increases in storm frequency and intensity directly increase erosivity and contribute to elevated stream flows and riverbank scour and erosion. While Massachusetts-specific projections of erosion risk are not available, studies at the regional level suggest that erosion risk in the Commonwealth will rise over time through late century.

Urgency Ranking Results

This impact is ranked as a **medium priority** because of its potential for disproportionate impacts and moderate adaptation gap.

No quantitative assessments of the impacts of climate-driven erosion on ecosystems are available for Massachusetts. However, spatial data are available for some quantifiable soil indicators. In particular, the Soil Survey Geographic (SSURGO) database[131] includes data on K factor, a measure of soil erodibility, and slope for the entire state. These data, coupled with climate projections of future extreme rainfall event frequency, provide some sense of the potential scale of this impact.

[131] https://www.mass.gov/info-details/massgis-data-soils-ssurgo-certified-nrcs

> *"We have, and are, experiencing significant erosion along the North Branch of the Hoosac River which is putting properties in peril."*
>
> *"Soil erosion is a concern as far as trying to sustain local food security and stability of natural areas."*
>
> - Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The consequences of soil erosion are projected to be **minimal**. The more mountainous regions in the central and western parts of the state are most susceptible to soil erosion, but these regions are projected to see only small increases in extreme rainfall event frequency due to climate change. Coastal regions are expected to face additional coastal erosion threats from sea level rise and extreme storms, but the soils in these regions are less prone to erosion (see Coastal Erosion impact for more details). Table A31 summarizes soil erosion vulnerability (measured as an index that considers K factor—a measure of soil erodibility—and slope) and change in frequency of extreme rainfall events by region.

Projected changes in the frequency of extreme rainfall events provide an indicator of climate-related increases in storm erosivity. Extreme rainfall events are expected to increase in frequency across all regions, with the most significant increases in coastal regions, where severe storms are already more frequent.

Table A31. Extreme Rainfall Event Frequency and Soil Erosion Vulnerability

Frequency of extreme rainfall events is measured as the annual number of events with two inches of rainfall over a 24-hour period. Erosion vulnerability is an indicator combining slope and K factor (a measure of soil erodibility) at the soil unit level from the SSURGO database. Future impacts presented for two time periods identified in the table by their central year: 2050 (mid-century, 2040-2059) and 2090 (end of century, 2080-2099). Values are expressed as a percentage of regional land area.

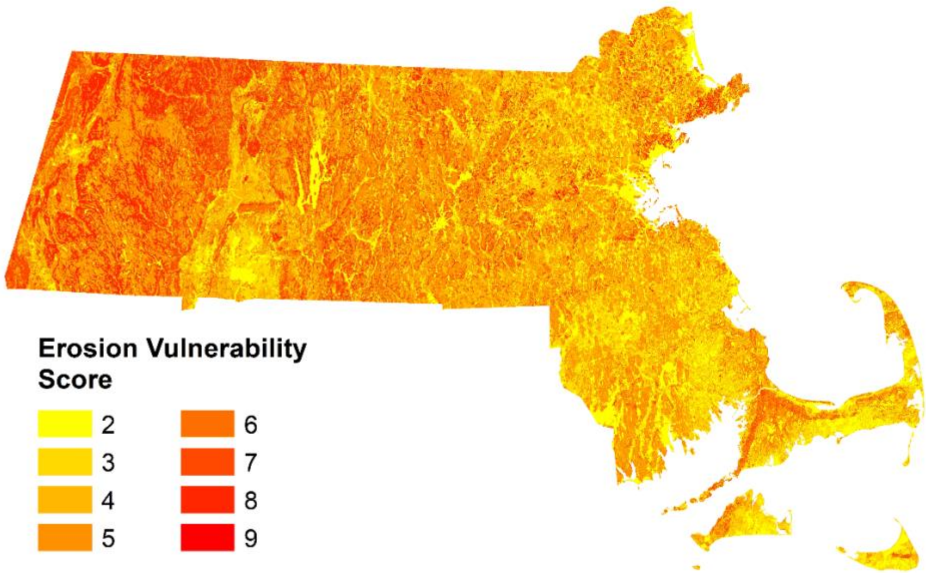
	Change in Frequency of Extreme Rainfall Events			Erosion Vulnerability as a Percentage of Land Area		
Region	**Baseline**	**2050**	**2090**	**Low**	**Medium**	**High**
Berkshires & Hilltowns	.5	0.1	0.2	21	52	26
Greater Connecticut River Valley	.4	<0.1	0.2	41	50	9
Central	.5	<0.1	0.2	43	50	7
Eastern Inland	.6	0.2	0.5	66	32	3
Boston Harbor	.8	0.3	0.6	85	13	1
North & South Shores	.7	0.2	0.5	86	12	2
Cape, Islands, & South Coast	.6	0.2	0.5	87	13	0
Statewide				**61**	**32**	**7**

Source: Analysis of data from LOCA (rainfall event projections, see Appendix B); SSURGO (K factors)

The erosion vulnerability indicator represents a combination of K factor[132] and slope. Using data from the SSURGO database, soil units were given a score (1-5) by quintile for each component, with higher scores representing higher K factors and higher slopes, such that a higher score represents a soil more vulnerable to erosion. Erosion vulnerability scores by soil map unit are shown in Figure A29.

Figure A29. Erosion Vulnerability Scores

Erosion vulnerability scores intend to provide a scale of relative risk of soil erosion based on soil and topographical features. Each area is given a score (1-5) by quintile for k factor and slope, and these two scores are summed together to create the erosion vulnerability score. Higher scores (in red) represent soils more vulnerable to erosion.



Source: Author's analysis of information from the SSURGO Database

While coastal regions are expected to experience more frequent and more erosive storms, most of the land area in those regions is less prone to the soil erosion included in this impact.[133] Conversely, the western and central regions of the state have significantly more soil area vulnerable to erosion but are projected to face less frequent severe rainfall events. While these indicators do not capture the full range of potential climate hazards and impacts to ecosystems, the spatial mismatch between these measurable threats and vulnerabilities indicates that the impacts of soil erosion are likely to be small in magnitude.

Note that while impervious surfaces are not particularly erodible (and have correspondingly low K factors), they do increase runoff volume and velocity and elevate flashiness of nearby streams and rivers. As such, ecosystems surrounding urban areas with high proportions of connected impervious cover are at an elevated risk of soil erosion, though these effects are not captured by the erosion vulnerability metric used here. As development continues and land use shifts across the state, this effect could become more significant.

[132] K factor is a measure of soil erodibility based on soil composition, texture, and hydraulic conductivity. See https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs144p2_025079.pdf

[133] Note that coastal erosion due to sea level rise, hurricanes, etc. is considered as a separate impact.

Literature describing climate interactions with erosion is limited. Segura et al. (2014) modeled erosivity and erosion vulnerability in the contiguous U.S. using spatially downscaled projections from three CMIP3 GCMs under low, medium, and high emissions scenarios.[134] The authors found strong increases in erosivity for the Northeast for all models and scenarios. The study also indicates that western regions of Massachusetts may be particularly vulnerable to mass wasting events[135] under future climate conditions. The 2018 State Hazard Mitigation and Climate Adaptation Plan also included discussion of landslide risk in the western part of the Commonwealth.[136]

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 A32). 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 to addressing soil erosion and degraded soil health. While there are a number of actions both planned and implemented that indirectly address soil erosion, fewer actions target erosion directly. Native tree planting and nature-based solutions to mitigate flooding are commonly cited actions in urban areas, and both have broad cross-sectoral benefits, including reducing runoff, slowing stormwater flow, and improving soil retention. A few municipalities have undertaken more direct actions like riverbank revegetation to prevent scour during high flow events and drafting new permitting and land use bylaws to control stormwater runoff and erosion. Other effective measures to reduce soil erosion include riparian corridor restoration, soil health evaluation and remediation planning, and bank stabilization using green infrastructure. Improved local wetland bylaws can also assist in reducing stormwater flow and use natural or created wetlands to mitigate velocity and volume of stormwater discharged into rivers and streams. Continued development across the Commonwealth is expected to reduce vegetative cover and soil health. This risk from land use change combined with climate-related stressors like more frequent and severe storms require proactive and robust adaptation approaches at both the local and regional level.

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[134] Segura, C., Sun, G., McNulty, S., and Zhang, Y. 2014. Potential impacts of climate change on soil erosion vulnerability across the conterminous United States. Journal of Soil and Water Conservation, 69(2), pp. 171-181.

[135] Mass wasting is a catch-all term for gravity-driven downhill movement of soil and rock, including landslides, debris flows, etc.

[136] Massachusetts EEA and OPSS. 2018. State Hazard Mitigation and Climate Adaptation Plan.

Example Adaptation Plans with Actions Addressing this Impact

- Building Resilience Across the Charles Watershed – See erosion bylaws and mitigation planning in Natick
- Massachusetts Healthy Soils Action Plan
- Massachusetts Clean Energy and Climate Plan for 2025 and 2030 – See Coordinated Soil Health Program

Sensitivities and Uncertainty

Detailed erosion risk modeling requires site-specific information that is not feasible for the scope of this Climate Assessment. However, the screening analysis performed here gives a sense of where the greatest issues may occur. This is especially true for riverbank erosion, which is not qualitatively addressed in this Climate Assessment.

Related Impacts

Table A32 lists the impacts in other sectors that have a connection to this impact.

Table A32. Additional Impacts related to Soil Erosion

Sector	Impact	Connection
Natural Environment	Forest Health Degradation; Freshwater Ecosystem Degradation; Shifting Distribution of Native and Invasive Species; Coastal Erosion	The ecosystems and natural assets in the Natural Environment Sector are connected through ecological processes. For example, forests need healthy soil to avoid degradation and loss of tree cover can lead to an increase in soil erosion rates.
Economy	Decrease in Agricultural Productivity	Healthy soil cover is critical for agricultural productivity.

Governance Sector

The Governance sector includes impacts to state and local government owned facilities, government finances, and demand on government services. State and local governments will face growing demand for the essential services they already provide as climate change increases need due to exacerbating stressors in all sectors. Small municipalities with limited tax bases may be disproportionately burdened.

Table A33. Governance Sector Impacts Ranked by Urgency Score

IMPACT	MAGNITUDE	DISPROPORTIONATE EXPOSURE	ADAPTATION GAP	URGENCY SCORE
Reduction in State and Municipal Revenues (MOST URGENT)	Major	Disproportionate	Moderate	80
Increase in Costs of Responding to Climate Migration (MOST URGENT)	Major	Potential	Extreme	75
Increase in Demand for State and Municipal Government Services (MOST URGENT)	Major	Potential	Moderate	64
Damage to Coastal State and Municipal Buildings and Land	Major	Limited	Moderate	47
Increase in Need for State and Municipal Policy Review and Adaptation Coordination	Minimal	Potential	Minimal	36
Damage to Inland State and Municipal Buildings and Land	Minimal	Limited	Minimal	19

Governance Sector: Urgent Impact #4

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 adaptations such as rezoning policies are less common.

Impact Summary

Coastal regions of the U.S. are particularly susceptible to the risks of sea level rise and storm surge. As the climate warms, sea levels rise due to the combination of thermal expansion of water volume, melting of glaciers and other ice sheets, and other factors. Higher sea levels also lead to more damaging storm surges, which can cause devastating episodic flooding. This impact category focuses on the effect of changes in sea level and storm surge and the direct impacts on flood damage to state-owned buildings in the Massachusetts coastal zone, as a subcategory of the impacts characterized in the Infrastructure sector analysis of risks to coastal property.

Urgency Ranking Results

This impact is ranked as a **medium priority** because of its large yet limitedly disproportionate impacts.

The analysis relies on an inventory of major buildings owned by the Commonwealth and maintained by the Division of Capital Asset Management and Maintenance (DCAMM), intersected spatially with results of Massachusetts Coastal Flood Risk Model (MC-FRM) results for coastal risks.[137] The key metric is the expected annual damage (EAD) attributable to coastal flooding at state-owned buildings in the Commonwealth. Details of the methodology applied to estimate economic damages at buildings are described in the Infrastructure sector, Damage to Coastal Buildings and Ports impact category.

[137] Note future revisions to this analysis will include municipal wastewater treatment plants, which are typically located nearshore in coastal areas. Economic flood damage estimates for state owned buildings derived using Neumann, J.E., P. Chinowsky, J. Helman, M. Black, C. Fant, K. Strzepek, and J. Martinich (2021). Climate effects on US infrastructure: The economics of adaptation for rail, roads, and coastal development. *Climatic Change*, 167(44), doi:10.1007/s10584-021-03179-w. Available online at https://link.springer.com/article/10.1007/s10584-021-03179-w

> *"Many of our municipal facilities are in harm's way, particularly from flooding. Even today, king tides have ocean water lapping at our building foundations."*
>
> *"Public buildings will become more important as shelters, cooling centers, and communal gathering centers - funding their continued maintenance and sustainable design is essential."*
>
> - Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

Annual expected coastal flood damage to state- and state-authority owned properties could be **major** due to increases in damages relative to current risks of about $9 million statewide in the 2030s ($17 million in 2030 less the current $8.2 million) but increasing to over $43 million by the 2070s. About two-thirds of the expected annual damages are expected at state-owned buildings, while about one-third are at state authority owned buildings. Most of the current and expected damages are expected in the Cape, Islands, and South Coast region, but damages grow faster over time in the Boston Harbor region because of the intersection of building locations and the increasing area of flood risk in that region.

Table A34. Annual Expected Flood Damages to State-owned Coastal Properties

Annual expected flood damage to coastal properties in millions from sea level rise and changes in coastal storms. This includes impacts only on state-owned properties. 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 total expected damage ($millions)			
Region	**Current**	**2030s**	**2050s**	**2070s**
Eastern Inland	$0	$0	$0	$0
Boston Harbor	$2.4	$3.2	$9.3	$21
North & South Shores	$0.3	$1.0	$7.0	$8.7
Cape, Islands, & South Coast	$5.5	$13	$20	$23
Statewide	**$8.2**	**$17**	**$36**	**$52**

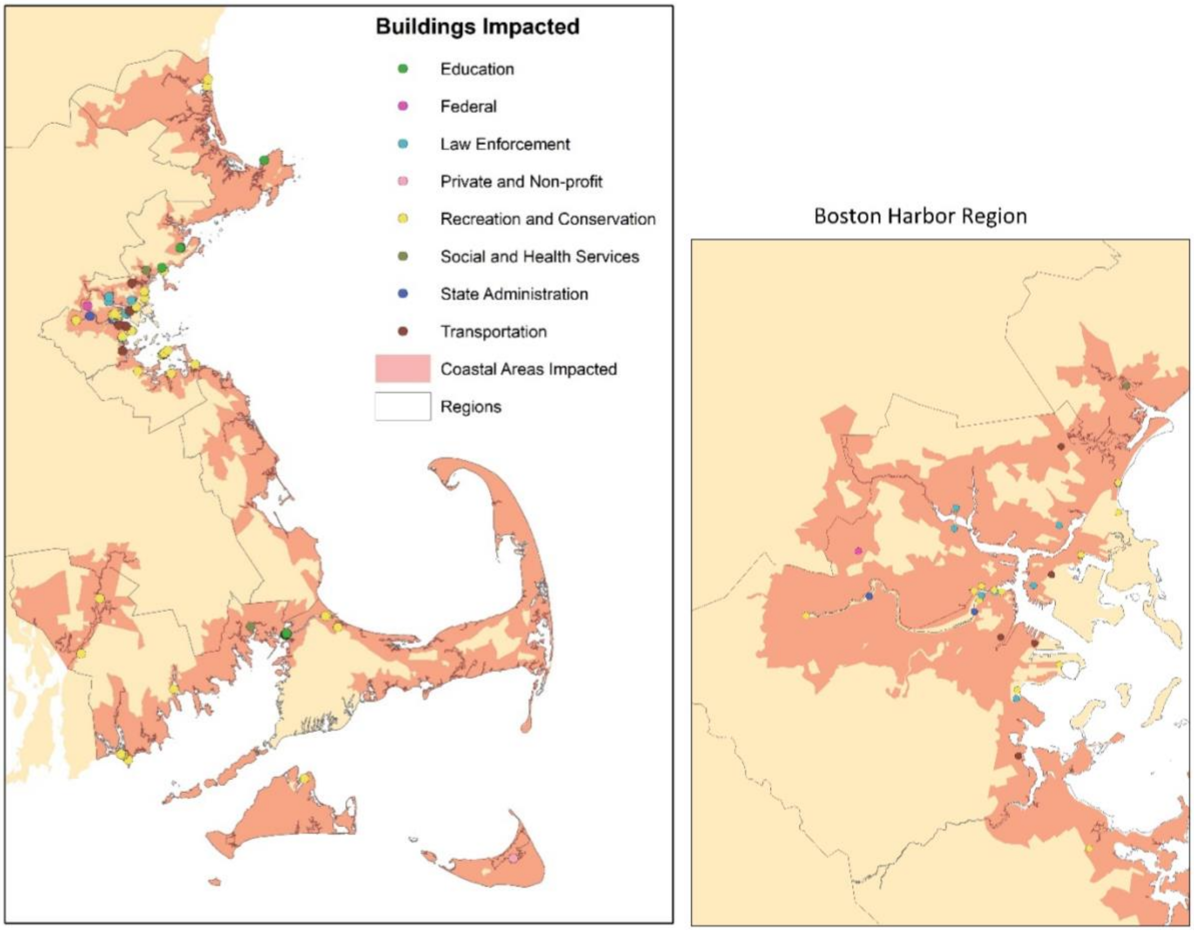
Note: There are no losses in the Berkshire & Hilltowns, Greater Connecticut River Valley, Central, or Eastern Inland regions. There are four block groups in the Eastern Inland region which are considered potentially influenced by coastal floods, but no state-owned buildings are present in those block groups.

Source: Analysis of MC-FRM flood risk, Neumann et al.2021 damage estimation, and DCCAM state asset database

Figure A30 below shows the state ownership, in groupings by function, of buildings at risk of at least the 100-year return period coastal flood (or more frequent flooding) in the 2070s, which reflects expansion of the 100-year flood zone in the current period as a result of sea level rise and storm surge attributable to climate change.

Figure A30. State- and Authority-owned Buildings Within the 2070 100-year Return Period Flood Zone, by Agency/Authority Function Class

Locations of buildings are shown with dots, colors indicate the Agency or Authority ownership function class. Inset shows Boston Harbor region.



Source: Analysis of MC-FRM flood risk, Neumann et al.2021 damage estimation, and DCCAM state asset database

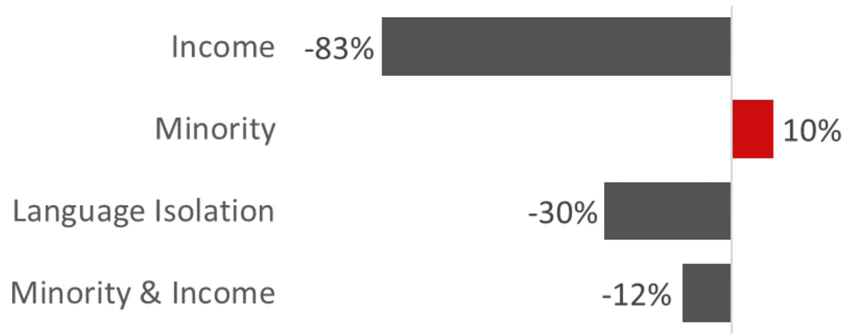
Disproportionality

Exposure to this impact has **limited** disproportionate exposure.[138] Populations living in EJ block groups defined on the basis of minority block groups have a 10 percent higher likelihood of experiencing damage to state-owned structures from coastal flood risks than the rest of the Commonwealth.

138 Although this analysis does not find a quantitative correlation between the locations of exposure to this impact and EJ block groups, it is important to note that not all populations will have the same experience with the effects of climate change and this impact because of pre-existing social vulnerabilities that are difficult to measure or comprehensively quantify across the Commonwealth.

Figure A31. Disproportionality of Exposure of State-owned Buildings to Coastal Flood Risk

Comparison of the coastal flood risk to state-owned buildings 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 of the main report for further description of the EJ block group definitions.



In the Infrastructure sector, Coastal impact category, when considering the coastal flood risk for all buildings in Massachusetts (as opposed to state-owned buildings), most properties that are particularly vulnerable to coastal flooding, and the most severe impacts, tend to be in areas that do not overlap with the Commonwealth-designated EJ Block Groups. For the sub-group of state-owned buildings, however, the risk of disproportionate exposure is somewhat higher but still relatively low.

Adaptation

There is a **moderate** adaptation gap to addressing the hazards that threaten state and municipal buildings and land along the coast. There is a great deal of action being taken to address coastal flooding and sea level rise on a broader scale. As a result, there are spillover effects of those adaptations that also protect state and municipal buildings and land. Such adaptation actions range from early-stage planning efforts like coastal infrastructure vulnerability studies to site-specific implementation actions like living shorelines or seawall reconstruction. That said, additional approaches are available and those already in use could be more widely implemented to address the hazards that threaten coastal state and municipal buildings and land.

For example, rezoning efforts are underway in several coastal communities, and may be effective adaptation measures to prevent damage and a proactive way to lead communities by example. Few plans indicate efforts to retrofit existing municipal buildings to improve coastal flooding and storm resiliency. Nature-based solutions like living shorelines, coastal rain gardens, and sand fences are being implemented in some coastal communities, but their use could be significantly expanded.

Example Adaptation Plan with Actions Addressing this Impact

- Dynamic Adaptation Pathways and Prioritized Resilient Design Solutions for Historic Sandwich Village includes actions such as coastal flood modeling, managed retreat planning and coastal resilience zoning for new development
- Ready for Tomorrow - The City of Salem Climate Change Vulnerability Assessment and Adaptation Plan includes living shorelines and seawall redesign and reconstruction

Sensitivities and Uncertainty

The results presented here are likely conservative estimates of future damage, as they reflect current DCAMM inventory replacement values, and also exclude state-owned land which might be vulnerable. The current trend is for rapidly increasing structure values in the vulnerable coastal zone, although the rate of property value growth may change in the future in response to climate risks and/or the implementation of adaptation measures. Increasing degrees of sea level rise and storm surge risks over time may also trigger changes in the demographics of the population at risk, which could alter the assessment of disproportionality in exposure to coastal flood impacts. These results also exclude potential damage to these buildings from coastal extreme windstorm risks – data on wind damage are not available at the individual building level. These results exclude the potential impact of changes to the frequency or severity of extra-tropical storms (one category of which is referred to as “Nor’easters” in New England) – consistent with advice to the Commonwealth of a peer review panel of climate science experts.

Related Impacts

Table A35 lists the impacts in other sectors that have a connection to this impact.

Table A35. Additional Impacts related to Damage to Coastal State and Municipal Buildings and Land

Sector	Impact	Connection
Economy	Reduction in the Availability of Affordably Priced Housing	Any publicly owned affordable housing may be affected by coastal flooding.
Infrastructure	Damage to Coastal Buildings and Ports	Low-lying buildings that are privately owned, including residences and commercial structures, may be damaged by coastal flooding.

Governance Sector: Urgent Impact #5

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 relevant to this assessment, 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 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 – an increase could have significant but currently unknown 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.

Impact Summary

Climate change impacts may challenge existing government human resource and coordination capacity to provide adaptation planning support, including the need for additional full-time employees and specialized training. Coordination of adaptation planning across governmental levels (Commonwealth, regional, municipal, and Federal) may also become more challenging, in part because climate stressors do not manifest neatly along political boundaries but follow watersheds, airsheds, climatic regions, elevation contours, and land use/land cover classifications.

In addition, state and municipal policies will need to be reviewed, modified, and updated in response to changing conditions and uncertainty associated with climate change. This may require additional full-time employees and specialized training. The need to modify building codes (at the state level) and land use regulation (at the local or regional level, primarily) in response to the changing nature of flood, extreme weather event, and other climate related risks is a prominent example of this impact.

The current context for these impacts includes additional capacity and expertise at the municipal level needed to implement the Commonwealth's decarbonization plan for greenhouse gas emissions reductions to meet net-zero energy goals. Multiple agencies, including EEA are providing support for this expansion. There may be synergies possible in coordinating the staffing and other support needed for climate mitigation goals and adaptation needs.

Urgency Ranking Results

This impact is ranked as a **lower priority** because of the assessment of challenges in coordinating adaptation actions across government levels and aligning building code, zoning, and land use regulation with emerging climate risks to people, infrastructure, and property, especially among small and poorly resourced municipal governments. Sparse information currently exists to assess the magnitude of consequence, however, or the disproportionate impacts, but there is potential for small governments in particular to face new adaptation and policy review challenges, or to evaluate specific adaptation initiatives.

> *"Smaller towns or municipalities with constrained budgets do not have equal access to the technical expertise they need to guide them through this tricky work; programming should be designed to pair those that need it with the help that is needed in a step towards equity."*
>
> *"So many communities are understaffed and unable to do anything but manage the day-to-day 'fire drills' of running a municipality."*
>
> *"Climate change will be hard on governments - the increased demand for services and doing more with less. I do hope that there will be a severe increase in municipal climate adaptation expenditures!"*
>
> - Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

Incomplete evidence exists to quantitatively assess the consequences of governmental needs for adaptation coordination and policy review, but this impact is classified as **minimal** based primarily (through the Project Working Group, which consists of Commonwealth governmental and non-governmental expert advisors to the project, and other state agency consultations), and the need for effort at multiple governmental levels to both improve adaptation coordination and address policy review such as building code, land use, and zoning ordinance revisions to assess and respond to new climate risk information.

Beginning in 2008 with the passage of the Global Warming Solutions Act, followed by the 2011 publication of the Massachusetts Climate Change Adaptation Report, the 2018 SHMCAP, and the 2018 Environmental Bond bill, Massachusetts was one of the first states to pursue statewide adaptation planning, to incorporate adaptation planning in hazard mitigation planning, and to coordinate directly with local and regional entities to further climate adaptation goals.[139] State-local coordination is facilitated by the state's Municipal Vulnerability Preparedness (MVP) program, established in 2017 in response to an executive order from the governor.[140] Through the most recent 2022 grant cycle, the program has provided $100 million in funding to support resilience planning and adaptation action across the Commonwealth.

The program has continued to expand in recent years, with the 2021-22 program budget doubling from the previous year. Most of this funding is distributed to cities and towns, with 341 municipalities (97 percent) enrolled in the program as of late 2021, but regional

139 https://www.georgetownclimate.org/adaptation/state-information/massachusetts/overview.html#local-regional-plans
140 https://resilientma.mass.gov/mvp/index.html

partnerships are also eligible for grants.[141] The program injects significant state money directly into supporting and expanding focused, action-oriented, local adaptation efforts and facilitating regional coordination and capacity-building statewide. In addition to this state funding, federal money has also been directed toward adaptation coordination efforts. Most recently, the state has earmarked hundreds of millions of dollars in funding from the American Rescue Plan Act for climate resilient infrastructure projects and other environmental initiatives.[142]

Providing state dollars to municipal governments and regional coalitions that better understand areas of need and have existing community partnerships enables more efficient use of government funding, which will only become more important as climate threats worsen. While the MVP program is a substantive commitment by the state to coordination and fund adaptation efforts, sustained action is needed to continue to address the need to address regional scale concerns, such as watershed-scale water resource management and flooding concerns, which in most cases has been coordinated through efforts of regional planning agencies and non-governmental watershed organizations.

Substantial effort has been made to update state and local building codes and align zoning and land use regulation with the latest climate science. To date, building code refinements have focused on building energy efficiency, and less attention has been developed to hazard mitigation in response to elevated climate risk. For example, in 2009 the Massachusetts Department of Energy Resources (DOER) amended the state building code to include a set of energy efficiency standards and goals that emphasize energy performance beyond the requirements of the current building code through cost-effective measures. Municipalities can opt-in to this building code appendix, called the “Stretch Energy Code”. Since its establishment, 299 out of Massachusetts’ 351 cities and town have adopted the Stretch Code. In 2021, Massachusetts passed a climate bill that called for development of an even greener slate of opt-in building codes, this time including the definition of “net-zero” buildings and net-zero performance standards, in support of the goal of net zero emissions by 2050. Presently, the DOER has published a draft of the new “Specialized Stretch Energy Code”; they plan to engage with the public during community feedback sessions and publish a final draft by the end of 2022.

The stretch code has focused on the energy component of the state building code, but other aspects of the code (structural and electrical, for example) could also be refined to address changes in climate hazards, to harden further building structures against flood, extreme event, and perhaps even mold risks. Some efforts have been made to clarify how these refinements might be pursued within the context of state requirements for municipal adoption of the state building code (effectively prohibiting municipalities from adopting design and construction standards more stringent than those in the Massachusetts State Building Code); periodic review requirements that are part of the enabling legislation; and the challenges; and integration of

[141] https://www.mass.gov/news/baker-polito-administration-awards-21-million-in-climate-change-funding-to-cities-and-towns

[142] Massachusetts Bill H.4219. 2021. https://malegislature.gov/Bills/192/H4219

both building code and zoning ordinance tools for adapting to climate risks.[143] In addition to the policy challenges identified through work of stakeholders engaged in the issue, significant human and financial capacity challenges remain at the municipal level to understand and respond to complex and uncertain climate science which might affect refinements of building codes and zoning ordinances.[144] Most smaller municipalities in particular do not have the technical capacity to interpret climate science for these policy objectives and likely rely on the state and other actors to provide readily actionable advice for future climate focused adaptation and policy review. Additional evidence on the impacts of potential staffing and policy assessment gaps for municipal governments would provide a better basis for assessing this emerging Governance impact.

Disproportionality

Based on currently available information, this impact is classified as having **potential** for disproportionate exposure. There is limited evidence on which to conclude whether the costs of responding to the challenge of adaptation coordination and policy review would fall disproportionately on local governments in areas with a concentration of EJ population block groups. Nonetheless, smaller government entities, and also those with lower income and lower property tax bases, tend to have fewer resources. Research for this assessment shows that at least some of the more than 250 municipal governments with population less than 20,000 residents have roughly the same size staff for building and planning policy, zoning, and building code functions (about 15 employees per municipality, including the 41 with less than 1,500 residents). Smaller, poorly resourced local governments may not have the staffing levels, required expertise and experience seeking grants, or the ability to manage grants, and could bear a disproportionate burden in addressing policy review and adaptation coordination tasks. Concerns for the ability of smaller municipal government to meet new policy review and adaptation coordination demands suggests a potentially disproportionate impact on lower income residents of these communities, if adaptation actions are limited by staffing levels and expertise. Consistent application of the disproportionality metric used throughout this assessment also requires analysis of the proportion of EJ block groups in smaller population municipalities that are of concern for this impact relative to the state as a whole. The results indicate that towns with 1,500 or fewer residents have about 10 percent of their population in any type of EJ block group, and 8 percent in a low-income block group, compared to 45 percent and 20 percent statewide. For towns with 5,000 residents or fewer, the comparable results are 13 percent of the population in any EJ block group, and 10 percent in a low-income block group. These data do not support a finding of disproportionate impact, but the qualitative assessment that smaller municipalities have a reduced ability to pay for enhanced adaptation capacity suggests there remains potential for disproportionate effects on the populations in those EJ designated block groups in smaller towns.

[143] Conservation Law Foundation, 2019. The Massachusetts State Building Code & Climate Change: A legal primer and summary of convenings. Published March 2019.

[144] Lauren Urbanek, 2018. *The Climate is Changing. So Why Aren't State Building Codes?,* National Resources Defense Council, web site blog of Apr. 5, 2018. https://www.nrdc.org/experts/lauren-urbanek/climate-changing-why-arent-state-building-codes

Adaptation

There is a **minimal** adaptation gap to prevent increases in government service expenditures and adaptation coordination. Incorporating future climate effects into policy requires significant resource investment, but modeling and assessment of a wide range of climate hazards and vulnerabilities is underway across the Commonwealth. This current work to better understand the risks and expected outcomes will increase policymaking efficiency and reduce costs in the long run. However, not all municipalities have the funding and expertise to make the necessary progress in these areas. As highlighted throughout this report, models for many of the key adaptation actions are already in place in some capacity in the Commonwealth, and the potential for knowledge sharing is an important opportunity to be explored. Adaptative management planning, climate database development, data collection, and resiliency toolkit development for vulnerable communities are just some examples of actions that will help mitigate demand for government expenditures on adaptation coordination in the future.

Sensitivities and Uncertainty

Existing information to quantify impacts of this governance category is limited. This assessment relied on qualitative information and the input of relevant experts, particularly those on the Project Working Group, to evaluate the magnitude of consequence and potential for disproportionality components of the overall ranking methodology. As a result, there remain large uncertainties in assessing the impact of climate adaptation coordination and policy review activities on Massachusetts.

Related Impacts

Table A36 lists the impacts in other sectors that have a connection to this impact.

Table A36. Additional Impacts related to Increase in State and Municipal Expenditures for Policy Review and Adaptation Coordination

Sector	Impact	Connection
Economy	Reduction in the Availability of Affordably Priced Housing	High building standards may increase the cost of housing in general which could contribute to diminished affordability for housing overall. Requirements to enhance adaptative capacity in buildings may also increase climate gentrification.
Governance	Increase in Demand for State and Municipal Government Services	Increased expenditures for government services overall could put added pressure on municipal and state budgets to address adaptation coordination and policy review.
Governance	Increase in Costs of Responding to Climate Migration	Development pressure in areas receiving climate migrants may complicate building and zoning code review.
Infrastructure	Damage to Inland Buildings; Damage to Costal Buildings and Ports	The incidence of flooding, extreme weather event, and wind damage could affect efforts to adapt building codes and policies and elevate the need for adaptation coordination.

Governance Sector: Urgent Impact #6

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.

Impact Summary

State owned buildings are potentially vulnerable to inland flooding from two major sources. Flood risk from high excessive riverine flow has been documented to be widespread in the contiguous U.S. 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. Heavier downpours can result in more extreme flooding, which may affect state-owned properties in the inland floodplain.

Another category of impact, the effects of extreme heat on the deterioration of building envelope, has been incompletely evaluated in the existing literature. Existing quantitative evidence for this type of effect of extreme heat on buildings is currently limited to anecdotal or non-U.S. sources, and as a result is not considered here, but may be an emerging risk to evaluate in future work.

Urgency Ranking Results

This impact is ranked as a **lower priority** because the identified impacts to government owned structures are minimal. The relative absence of siting of state-owned buildings in the inland flood risk 100-year floodplain, or in an area likely to be flood vulnerable, suggests strong attention to inland flooding risk by the Commonwealth and a minimal adaptation gap.

The analysis relied on an inventory of major buildings owned by the Commonwealth and maintained by the Division of Capital Asset Management and Maintenance (DCAMM), intersected spatially with available data on the 100-year floodplain for inland flood types (maintained by FEMA), as well as available information on change in expected annual damage (EAD) from flooding at residential properties in the Commonwealth. The data on inland flood risk at residential properties is useful because it is available at the block group level, but it is employed here only as a potential flood risk index to examine the possibility of severe flood damage to Commonwealth-owned properties if they may also be located in the FEMA 100-year floodplain.

> *"Potential damage to land and municipal buildings from flooding and worsening weather can result in significant increase in municipal expenditures to manage results."*
>
> - Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The consequences of inland flooding are projected to be **minimal** due to the small number of properties identified in the FEMA 100-year flood plain (see Table A37 below), coupled with the relatively low potential for severe flooding at those properties as estimated from currently available comprehensive flood risk data.[145] Table A37 indicates that 53 of the 1,977 state-owned major buildings (or about 3 percent) are located in the FEMA 100-year inland flood plain.[146] These buildings were further examined to determine whether they might be in areas where the inland flooding risk estimates (from the Infrastructure sector analysis) might suggest the potential for a relatively large annual expected damage, of as large as 0.5 percent of structure value. Put in context, a generic guideline for property managers is that annual maintenance and repair costs of all types for a property should be not less than approximately 1 percent of the total structure value to maintain the long-term – some data puts this value as high at 2 percent annually. Only 2 state-owned buildings in the 2030 era, and 7 in the 2050 era or later, statewide, could have expected flood damage of as high as 0.5 percent annually. While those buildings might see a substantial increase in maintenance costs to respond to and repair flood damage, the analysis suggests that there are very few buildings statewide where even moderate flood risks may be likely to present as a result of climate change. Of the seven buildings identified as potentially at greatest risk, three are owned by the Department of Conservation and Recreation and are recreation facilities sited along bodies of water; two are former mill buildings that are part of the University of Massachusetts/Lowell; and two are owned by the Essex County Sheriff's office in Lawrence.

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[145] The 100-year flood is the flood that has a 1 percent chance of being equaled or exceeded each year. The 100-year flood is the standard used by most federal and state agencies. For example, it is used by the National Flood Insurance Program (NFIP) to guide floodplain management and determine the need for flood insurance.

[146] In the Commonwealth's 2018 State Hazard Mitigation and Climate Adaptation Plan (SHMCAP), analysis summarized in Table 4-3 on page 4-21 identifies 135 state-owned buildings in the FEMA 100-year A zone, with a total replacement value exceeding $122 million. The data presented here updates that prior analysis using the 2022 DCAMM facility inventory, and the 2022 FEMA flood maps available at MassGIS. Replacement value of structures is not reported here, in part because available flood risk modeling suggests a relatively small number of affected buildings and a relatively low estimated Annual Expected Damage (see the Infrastructure sector, Inland Flood category for details of the flood risk analysis methods, based on riverine flow modeling in Wobus et al. 2021 and data provided to support USEPA (2021).

Table A37. Summary of State-owned Major Buildings Potentially at Risk for Inland Flooding

Major buildings in DCAMM data base by region, including state-owned buildings, state-owned buildings in the floodplain, and state-owned buildings both in the FEMA floodplain and subject to annual expected damage as large as 0.5 percent annually, 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).

				State-owned major buildings in the FEMA 100-yr floodplain and potentially vulnerable to 0.5% annual average flood damage			
Region	**All DCAMM Major Buildings**	**State-Owned Buildings**	**Buildings in Floodplain**	**2030**	**2050**	**2070**	**2090**
Berkshires & Hilltowns	101	79	0	0	0	0	0
Greater Connecticut River Valley	582	447	0	0	0	0	0
Central	313	258	0	0	0	0	0
Eastern Inland	717	637	3	1	4	4	4
Boston Harbor	285	262	21	0	2	2	2
North & South Shores	150	128	14	1	1	1	1
Cape, Islands, & South Coast	221	166	15	0	0	0	0
Statewide	**2,369**	**1,977**	**53**	**2**	**7**	**7**	**7**

Source: Analysis of FEMA floodplain, Wobus et al. 2021 inland flood damage estimation, and DCCAM state asset database

The FEMA floodplain may not reflect assessment of all possible impacts of inland flooding to commercial structures and may omit risks of pluvial flooding. Pluvial flooding is related to high precipitation events and poor or inadequate drainage. Consideration of pluvial flood risks would increase the estimates presented, but the magnitude of consequence for pluvial flooding of state-owned structures is currently unknown.

Disproportionality

Exposure to this impact shows **limited** disproportionality, but analysis is not site-specific and based only on limited information.[147] The number of major buildings owned by the Commonwealth that are potentially at risk of inland flooding is estimated to be small. None of the identified buildings are located in a Commonwealth-designated EJ block group.

Adaptation

There is a **minimal** adaptation gap for this impact. The best evidence of a small gap is that of the more than 2,000 major buildings in DCAMM's database, only 7 statewide may be subject to

[147] Although this analysis does not find a quantitative correlation between the locations of exposure to this impact and EJ block groups, it is important to note that not all populations will have the same experience with the effects of climate change and this impact because of pre-existing social vulnerabilities that are difficult to measure or comprehensively quantify across the Commonwealth.

significant flood risk. This suggests that the Commonwealth has already considered this risk in siting and leasing buildings for state use, meaning the adaptation gap is small.

Sensitivities and Uncertainty

While this analysis uses specific locations of state-owned buildings and best available information on inland flood risk, it does not reflect any site-specific modeling of inland flood risk at state-owned buildings. Additional effort to model flood risk more rigorously at buildings which are located in the FEMA 100-year return floodplain would improve the estimates presented here. In addition, privately owned affordable housing, which may be the subject of cooperative agreements with the Commonwealth to serve eligible populations, are not included in the DCAMM database, so are not analyzed here.

Related Impacts

Table A38 lists the impacts in other sectors that have a connection to this impact.

Table A38. Additional Impacts related to Damage to Inland State and Municipal Buildings and Land

Sector	Impact	Connection
Economy	Reduction in the Availability of Affordably Priced Housing	Any publicly owned affordable housing may be affected by inland flooding.
Infrastructure	Damage to Inland Buildings	Low-lying buildings that are privately owned, including residences and commercial structures, may be damaged by inland flooding.

Economy Sector

The Economy sector includes 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 affordably priced housing. Extreme events, dangerous heat, and transportation delays will all affect business and people's ability to work, earn a living, and make a home. Less productive fisheries and changing agricultural yields cause indirect impacts throughout the Commonwealth's economy. Increased risk of flooding, climate-driven relocation, and stronger building standards put pressure on housing supply and demand, impacting housing affordability.

Table A39. Economy Sector Impacts Ranked by Urgency Score

IMPACT	MAGNITUDE	DISPROPORTIONATE EXPOSURE	ADAPTATION GAP	URGENCY SCORE
Reduced Ability to Work (MOST URGENT)	Extreme	Disproportionate	Moderate	89
Decrease in Marine Fisheries and Aquaculture Productivity (MOST URGENT)	Major	Disproportionate	Moderate	80
Reduction in the Availability of Affordably Priced Housing (MOST URGENT)	Major	Disproportionate	Moderate	80
Economic Losses from Commercial Structure Damage and Business Interruptions	Extreme	Potential	Moderate	72
Damage to Tourist Attractions and Recreation Amenities	Moderate	Disproportionate	Moderate	72
Decrease in Agricultural Productivity	Major	Potential	Moderate	64

Economy Sector: Urgent Impact #4 (tie)

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.

Impact Summary

Climate change can damage structures that house places of business, resulting in costs to repair the structures and indirect costs associated with business interruptions. This impact category focuses on the reduction in economic outputs during business closures that could result from increased flooding and storm damage to places of business. It also addresses reduction in economic outputs due to extreme weather shutdowns, including effects on supporting infrastructure, supply chains, and utilities (i.e., power and communications).

Urgency Ranking Results

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

Impacts are evaluated based on four lines of evidence:

- Estimates of direct damages to commercial and industrial structures from coastal flooding – these are a subcategory of the damages to all structures considered in the Infrastructure sector – Damages to Coastal Buildings and Ports impact category.
- Direct damages to commercial structures and indirect damages in the form of business interruptions from three types of flooding: riverine (fluvial) floods; high precipitation event (pluvial) floods; and coastal storm surge and tidal flooding, from a recent First Street Foundation report.[148]
- Estimates of the impact of power outages on commercial and industrial entities

[148] First Street Foundation and Arup. 2021., The 4th National Risk Assessment: Climbing Commercial Closures. December 13, 2021, available at: https://firststreet.org/research-lab/published-research/article-highlights-from-climbing-commercial-closures/. Additional methodological information available in Porter, Jeremy R., Using a High-Precision Flood Risk Assessment Tool to Understand Commercial Building and Market Impacts in the United States (December 8, 2021). Available at SSRN: https://ssrn.com/abstract=3981118 or http://dx.doi.org/10.2139/ssrn.3981118

- Qualitative analysis of the potential impact of climate change on supply chains and the resulting impact on business activity.

> *"We have the impact of supply chain interruption during the pandemic. Changes in weather can even more severely impact our power supply, the ability of businesses to open and operate and the ability to produce our food."*
>
> *"Our City's economy is very dependent on commuters for the workforce and customers from surrounding communities. When the weather is so bad that people hunker down, our City's economy suffers."*
>
> *"Stockbridge is beginning to draw remote workers. These professionals heavily rely on fast Internet and the lines in rural communities such as ours are not buried."*
>
> *"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 estimate of the economic impact of business interruptions statewide, as well as the estimated need for expenditures to repair coastal flood damages for commercial and industrial building stock.

Estimates of the projected direct flood damage to commercial and industrial structures in the Commonwealth's coastal areas can be readily identified from the results of the Infrastructure sector analyses. Table A40 presents data for coastal regions on the current (using 2008 sea level as a baseline) and expected future annual damage to these structures and shows that statewide these damages are expected to more than double by 2030 and the incremental cost could reach as high as $270 million annually by 2090, more than ten times higher than current levels. These direct impacts of flooding are largest and grow most rapidly in the Boston Harbor region, where a large portion of the Commonwealth's commercial economic base is located.

Table A40. Annual Expected Flood Damages to Commercial and Industrial Sector Coastal Properties

Annual expected flood damage to coastal properties in millions from sea level rise and changes in coastal storms. This includes impacts on commercial and industrial properties and excludes damages to residential properties. 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). Results are not available from the underlying model for 2090 (end of century, 2080-2099). Values may not sum due to rounding.

	Annual total expected damage ($millions)			
		Change from Current		
Region	**Current**	**2030**	**2050**	**2070**
Eastern Inland	$0.1	$0.1	$0.3	$0.6
Boston Harbor	$15	$30	$89	$240
North & South Shores	$2	$2	$4	$7

Region	Current	Annual total expected damage ($millions) Change from Current 2030	2050	2070
Cape, Islands, & South Coast	$6	$2	$9	$15
Statewide	**$22**	**$34**	**$100**	**$270**

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

Source: Project Team analysis of MC-FRM flood risk and damage estimation methods from Neumann et al. (2021)

The direct impacts of flooding summarized in Table A40 are one part of the impact of climate change on Massachusetts commercial and industrial operations, but the indirect impacts of these events could be more consequential in economic terms. Table A41 shows estimates from recent analysis by the First Street Foundation and Arup to quantify the statewide and metro Boston area direct and indirect structural and indirect business interruption damages associated with all types of flooding – including coastal, riverine, and "flash flooding" associated with high rainfall events where drainage processes are overwhelmed. The indirect losses from business downtimes are estimated to be six to seven times larger than the direct structure damages, and could increase by over $800 million above the current baseline by 2050. The First Street analysis also estimates that the largest losses can be expected in the Boston metropolitan area – reflecting the overall concentration of business activity in that region but also the potentially high vulnerability of that business base to coastal and other types of flooding.

Table A41. Annual Expected Direct and Indirect Flood Damages to Commercial Properties – Current and in 2050

Annual expected direct flood damage to properties and indirect flood damages from business interruption from all types of flooding (coastal from sea level rise and changes in coastal storms, in millions). This includes impacts on office buildings, retail buildings, and multi-unit residential properties. The Boston Metropolitan Area is Census-defined area that includes Suffolk, Middlesex, Norfolk, Essex, and Plymouth counties. It primarily covers the Boston Harbor region but also includes parts of Eastern Inland and North and South Shore regions. Values may not sum due to rounding.

	Annual total damage ($millions)			
	Current		Additional by 2050	
Region	**Structure Damage**	**Downtime Losses**	**Structure Damage**	**Downtime Losses**
Boston Metropolitan Area	$331	$2,471	$86	$782
All other parts of Massachusetts	$113	$163	$29	$50
Statewide	**$444**	**$2,634**	**$115**	**$832**

Note: Estimates for "All other regions" derived as the difference between results for Massachusetts and the Boston Metropolitan Area in the source report. Further disaggregation of results by type of flood hazard or location is not currently available for analysis.

Source: Adapted from First Source Foundation and Arup 2021

Weather is directly linked to electric power interruptions caused by snow and ice, high winds, lightning strikes, and extreme heat, among others. These events cause about 78 percent of major power interruptions in the U.S. power distribution system.[149] These interruptions are extremely costly to the U.S. economy and are likely worsening with climate change.[150] Analyses of the vulnerability of grid infrastructure and connections between climate change and power outages are described in more detail in the Infrastructure sector, based on existing research on stressor-response relationships on the U.S. electrical grid (Fant et al. 2020) as well as work on the costs of power interruptions led by Lawrence Berkeley National Laboratories (Larsen et al. 2018).[151] The costs of power interruptions rely on the ICE Calculator, a publicly available online tool that estimates the direct economic costs that electricity customers experience when their power is interrupted.[152] The tool is based on over 100,000 responses provided by electric utility customers to questions posed in utility-sponsored surveys conducted between 1993 and 2019,[153] and was also highlighted in the 2021 Government Accountability Office (GAO) report on electricity grid resilience and climate change.[154] Larsen et al. (2018) reports that more than 95 percent of the costs of power interruptions are from impacts to the commercial and industrial sector, particularly associated with business interruptions – meaning that the climate change impacts to businesses account for most of the roughly $45 million estimated costs of grid interruptions in 2030 and over $200 million by 2090 estimated for the Infrastructure sector analysis.

Climate change could also affect the sometimes complex national and international supply chains of Massachusetts businesses. Disruptions to supply chains for energy, raw materials, and intermediate goods essential to manufacturing can affect Massachusetts businesses' ability to meet customer orders and keep their workforce fully engaged. Climate disruptions can also affect the transportation links in supply chains, for example when a hurricane damages port facilities. The U.S. Fourth National Climate Assessment identified the link between climate change and supply chain reliability in 2018, and highlighted it as a key message in the chapter

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[149] Mills, E. (2012). Extreme Grid Disruptions and Extreme Weather, Lawrence Berkeley National Laboratory, U.S. Disaster Reanalysis Workshop, May 3, 2012, http://evanmills.lbl.gov/presentations/Mills-Grid-Disruptions-NCDC-3May2012.pdf.

[150] Campbell, R.J. (2012). Weather-Related Power Outages and Electric System Resiliency. Congressional Research Service Report for Congress. 7-5700 R42696. www.crs.gov.

[151] 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. https://doi.org/10.1016/j.energy.2020.116899; Larsen, P.H., B. Boehlert, J.H. Eto, K. Hamachi LaCommare, J. Martinich, and L. Rennels. (2018). Projecting future costs to U.S. electric utility customers from power interruptions. Energy, 147, 1256–1277, doi:10.1016/j.energy.2017.12.081.

[152] More information about the ICE Calculator and the ICE Calculator 2.0 is available at: icecalculator.com/home

[153] There is a national initiative underway to significantly update and upgrade the ICE Calculator. LBNL is currently soliciting utilities to join this national initiative.

[154] GAO. 2021. Electricity Grid Resilience: Climate Change is Expected to Have Far-Reaching Effects and DOE and FERC Should Take Actions. Available at https://www.gao.gov/products/gao-21-423t.

on Climate Effects on U.S. International Interests.[155] This chapter also noted that there is a lack of research on this topic – however recent supply chain disruptions have prioritized supply chain risk assessments (which can include climate disruption as a factor) for businesses that depend critically on reliable and timely supply chain delivery for their operations.

Disproportionality

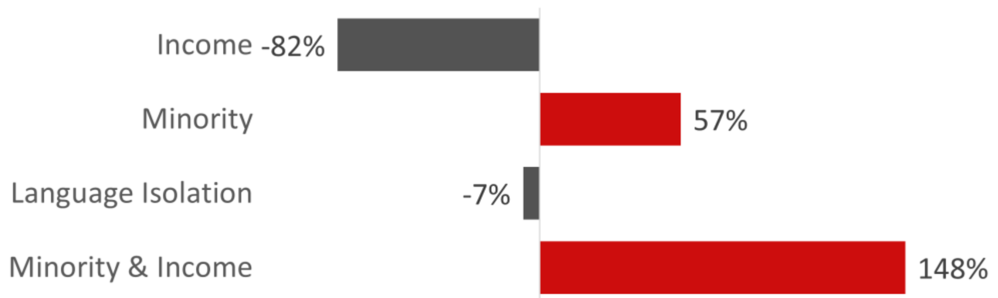
Exposure to this impact is **potentially** disproportionate. A comparison of risk of structural damage to nearby commercial and industrial buildings (using the data from Table A41 rather than the more precise business interruption results in Table A40) for individuals living in EJ block groups defined on the basis of:

- minority population have 57 percent higher risk of damage to nearby commercial and industrial buildings compared to the rest of the Commonwealth
- minority population and income have 148 percent higher risk of damage to nearby commercial and industrial buildings compared to the rest of the Commonwealth

While the data in Figure A32 suggest a high degree of disproportionality at the state level, this disproportionality is not seen in the Boston Harbor region, where the metric actually shows negative disproportionality. Other regions do show some disproportionality, but with much lower Magnitude of Consequence. Because the Boston Harbor region accounts for over 90 percent of the total damages for this impact, the disproportionality score for this impact acknowledges that disproportionate exposure is evident in some locations, but is not evident in the critically important Boston Harbor region where the largest impacts are anticipated.

Figure A32. Disproportionality of Coastal Flood Risk Damage to Commercial and Industrial Buildings

Comparison of expected annual damage ratios (estimated structure damage as a portion of total value) in 2070 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 of the main report for further description of the EJ block group definitions.



[155] Smith, J.B., M. Muth, A. Alpert, J.L. Buizer, J. Cook, A. Dave, J. Furlow, K. Preston, P. Schultz, and L. Vaughan, 2018: Climate Effects on U.S. International Interests. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 604–637. doi: 10.7930/NCA4.2018.CH16

No other literature or analyses on the possible incidence of direct damage and business interruptions costs among EJ populations was identified, but it is reasonable to conclude that small businesses would face greater affordability challenges for structure repair and to weather business interruptions. Small business ownership among minority groups in particular has been linked to poor access to capital, for example.[156]

Adaptation

There is a **moderate** adaptation gap to addressing the losses from damages to business caused by climate-related hazards and interruptions. Few actions in the reviewed climate action plans seek to prevent damage to business infrastructure exclusively. That said, businesses will be co-beneficiaries of many of the actions taken that improve general infrastructure resilience to extreme weather events and sea level rise. Business-focused adaptation plan examples include work by Cambridge and New Bedford to support commercial resilience by developing climate education and resilience toolkits for small businesses.

Private sector adaptation planning, particularly through business insurance, may be critical in closing this adaptation gap. Flood insurance, for structure repairs, and business interruption insurance may be available to businesses but uptake may need to be increased. Efforts to provide better education about the nature and extent of climate-related risks to business operations and options for and restrictions of insurance coverage may leverage public sector efforts to limit business exposure to climate risks. For example, many standard business interruption policies may require that a parallel claim for physical damages is filed to claim business interruption losses – a situation that may limit these types of claims where an extended power outage closes operations but no direct physical damage is present.

Example Adaptation Plans with Actions Addressing this Impact

- Climate resilience toolkit development for small businesses – Cambridge, New Bedford
- Flood resilience education for local businesses – Cambridge

Sensitivities and Uncertainty

Quantified estimates of impacts to businesses are limited to direct structural and indirect business interruption losses associated with flooding. While these components of the overall impact are large enough to raise concern about the magnitude of consequence, they are incomplete and underestimate the potential impacts of climate change to businesses in the Commonwealth.

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[156] Toussaint-Comeau, M. and Williams, V. 2020. Secular Trends in Minority-Owned Businesses and Small Business Finance. ProfitWise News and Views, No. 2, May 2020, published by the Federal Reserve Bank of Chicago, available at: https://www.chicagofed.org/publications/profitwise-news-and-views/2020/secular-trends-minority-owned-businesses-small-business-finance

The inability to allocate business interruption costs by region or, within the Boston metropolitan area, by block group means that these estimates of disproportional exposure are also incomplete – a more highly resolved spatial analysis might reveal higher or lower estimates of disproportionate exposure to this risk. In addition, the disproportionality metric is based on where people live, not on business ownership patterns relative to the climate risk exposure.

Ongoing research to improve estimates of the links between climate change and power and communications interruptions could improve estimates for this route of impact, which are estimated based on qualitative analysis of broader areas of the U.S. beyond the Commonwealth to be potentially large, but which could be more or less severe for businesses in the Commonwealth.

Related Impacts

Table A42 lists the impacts in other sectors that have a connection to this impact.

Table A42. Additional Impacts related to Economic Losses from Commercial Structure Damage and Business Interruptions

Sector	Impact	Connection
Infrastructure	Damage to Coastal Buildings and Ports; Damage to Inland Buildings	Direct impacts to commercial and industrial buildings are a subset of the total flooding impacts to all buildings. Ports are also commercially important.
Infrastructure	Damage to Electric Transmission and Distribution Infrastructure	Impaired grid infrastructure can lead to power outages, which contributes to business interruptions.
Infrastructure	Damage to Roads and Loss of Road Service; Damage to Rails and Loss of Rail/Transit Service	Transportation closures and delays can impact businesses through supply chain disruptions and the inability of workers and customers to get to places of business.
Economy	Reduced Ability to Work	Disruptions and delays on commuting routes lead to loss of work and productivity for businesses.

Economy Sector: Urgent Impact #4 (tie)

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.

Impact Summary

The tourism industry is a key contributor to the Commonwealth's economy. According to the 2020 Massachusetts Office of Travel and Tourism (MOTT) Annual Report, in 2018 visitor expenditures supported over 125,000 jobs, generated $1.3 billion in state and local tax revenue, and contributed $25 billion in direct economic impact with an additional $13.6 million indirect and induced impact.[157,158] At least 10 percent of domestic visitors participate in each of the following climate-vulnerable activities during trips to Massachusetts: beaches, rural sightseeing, urban sightseeing, historical places/churches, museums, and state/national parks.[159] While the City of Boston is a major tourist destination and receives the highest expenditures, tourists visit all regions of the Commonwealth (see Table A43). The Cape, Islands, and South Coast generate the highest local taxes per capita from tourism and the Berkshires and Hilltowns have the highest tourism-related employment per capita.

[157] Massachusetts Office of Travel & Tourism. 2020. 2019 Annual Report. Available at: https://www.visitma.com/wp-content/uploads/2020/06/2020_Annual_Report.pdf.

[158] The 2021 annual report is also available however the more recent figures from 2020 reflect the disruptions to the tourism industry of the Covid-19 pandemic. In 2020, visitor expenditures supported over 100,000 jobs in 2020 and generated $879.9 million in state and local tax revenue. Figures are provided by county and converted to Climate Assessment regions by population.

[159] Massachusetts Office of Travel & Tourism. 2020. 2019 Annual Report. Available at: https://www.visitma.com/wp-content/uploads/2020/06/2020_Annual_Report.pdf.

Table A43. Economic Contributions of Tourism (2018)

Data available from MOTT at county-level and recalculated at Climate Assessment region based on population. Note, data are from 2018, the most recent available data that does not include the significant impacts of Covid-19 on tourism.

Region	Expenditures ($ Millions)	Employment (Thousands)	State Tax Receipts ($ Millions)	Local Tax Receipts ($ Millions)
Berkshires & Hilltowns	$495	4.2	$26	$15
Greater Connecticut River Valley	$902	5.6	$51	$21
Central	$1,243	8.4	$69	$30
Eastern Inland	$3,276	25.2	$184	$92
Boston Harbor	$11,201	61.3	$349	$225
North & South Shores	$917	6.4	$50	$29
Cape, Islands, & South Coast	$1,829	14.3	$82	$94
Statewide	**$19,864**	**125.4**	**$811**	**$504**

Source: MOTT 2019 Annual Report

Beyond value for tourism, residents also enjoy the sights and recreational opportunities available in the Commonwealth. Opportunities for recreational activities will face many changes, often in conflicting directions. For example, winter sport participation is likely to decrease during milder winters while participation in water sports and other warm weather activities are expected to increase, particularly during warmer spring and fall seasons. Environmental health stressors may decrease participation across activities—for example, higher rates of childhood asthma, increased aeroallergens, threats of vector borne disease, decreased air quality due to wildfires, in addition to extreme heat days in the summer. More frequent extreme weather, such as hurricanes, could disrupt travel and damage coastal infrastructure like hotels and rental homes.

Urgency Ranking Results

This impact is characterized as a **high priority** due to moderate impacts, with damages concentrated in specific industries and worker populations.

Impacts to tourism and recreation are measured in a variety of ways. First, changes in winter recreation and general recreation are cited from the literature (winter recreation from Wobus et al. 2017[160] and general recreation from Chan and Wichman 2018[161]). Next, tourism and recreation impacts are drawn from other impacts analyzed in this Climate Assessment. In particular, coastal erosion and beach recreation, health risks and general recreation, and coastal property damage and coastal recreation. These connections are discussed qualitatively

[160] Wobus, C., Small, E.E., Hosterman, H., Mills, D., Stein, J., Rissing, M., Jones, R., Duckworth, M., Hall, R., Kolian, M. and Creason, J., 2017. Projected climate change impacts on skiing and snowmobiling: A case study of the United States. Global Environmental Change, 45, pp.1-14.

[161] Chan, N. and Wichman, C. 2017. The effects of climate change on leisure demand: Evidence from North America. Resources for the Future Working Paper 17-20-REV.

and put into context using data from the 2020 MOTT Annual Report. Disproportionality is evaluated on the basis of employment in the leisure, tourism, and recreation sector.

> *"Tourism is another large part of the local economy. Our beaches and harbors are extremely vulnerable to sea level rise and more intense storms. Their demise means a demise to our tourist industry."*
>
> - Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

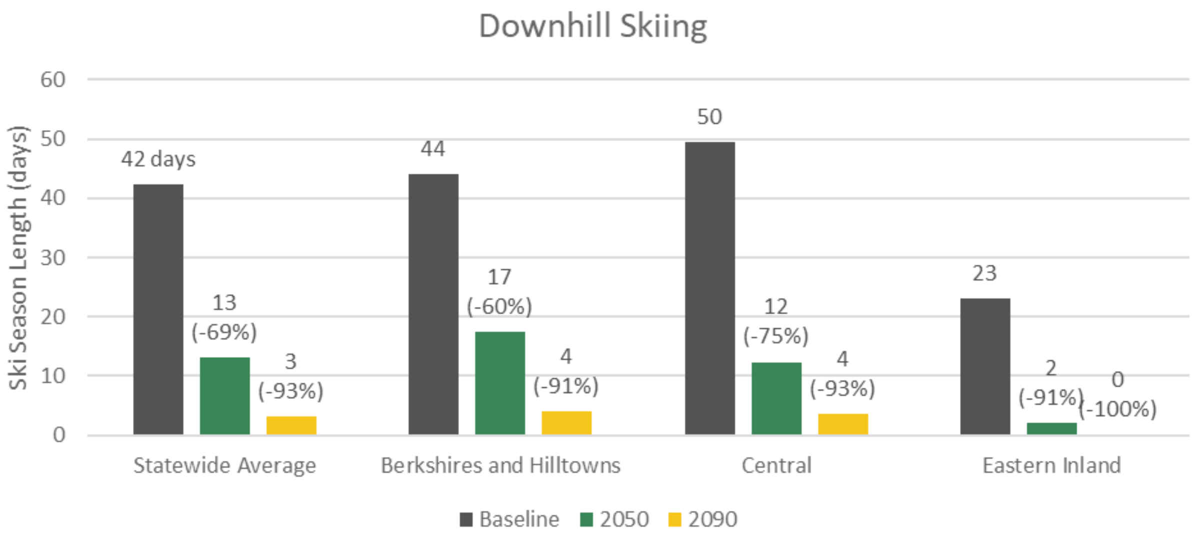
The magnitude of consequence for this sector is characterized as **moderate** due to the severe declines in some subindustries of tourism and recreation (e.g., winter sports) offset by significant projected increases in other subindustries (e.g., water sports and boating).

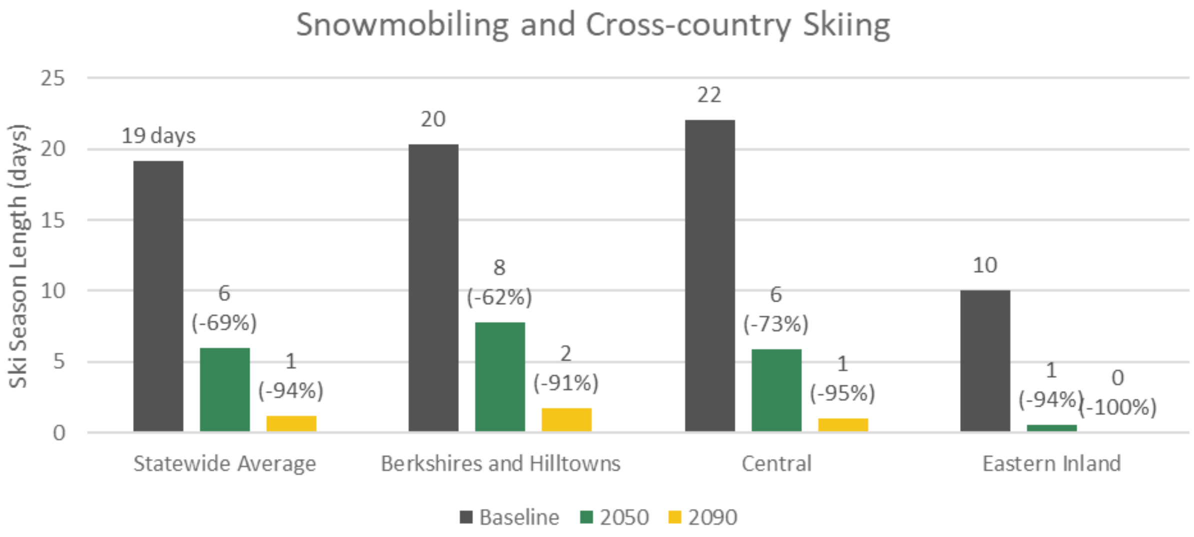
Studies of the future of winter recreation in the Northeast show major decreases in season length, even with available snowmaking technologies. Even modest shortening of seasons may not be financially viable for ski areas dependent on revenues generated during the winter holiday season.[162] Figure A33 shows the projected change in season length for downhill skiing, snowmobiling and cross-country skiing for ski areas in Massachusetts. Reductions of nearly 70 percent by 2050 will be very difficult to withstand and by 2090 very few days of ski conditions will remain in the Commonwealth. Residents may still be able to enjoy skiing in more northern parts of New England, but the Commonwealth's winter sport industry will have fewer options to adapt.

[162] Scott, D., Steiger, R., Knowles, N. and Fang, Y., 2020. Regional ski tourism risk to climate change: An inter-comparison of Eastern Canada and US Northeast markets. Journal of Sustainable Tourism, 28(4), pp.568-586.

Figure A34. Change in Downhill Skiing, Snowmobiling, and Cross-country Skiing Season Length

Baseline (in days per season) and percent change in season length under RCP8.5 for ski areas in Massachusetts. Values are averaged by region, across six ski areas total. No ski areas included in the study were located in the four regions not listed in the table. Future impacts presented for two time periods identified in the figure by their central year: 2050 (mid-century, 2040-2059) and 2090 (end of century, 2080-2099).





Source: Adapted from Wobus et al. 2017

Changes in participation in response to changing climate vary by activity. While conditions for winter sports are projected to become less frequent, conditions for other activities like biking, hiking, and water sports, are likely to become more common, particularly in the spring and fall seasons. Chan and Wichman (2017) estimate that demand for cycling in Massachusetts in 2060 will increase by 5.04 percent based on changing weather conditions, and assuming that increase holds true for other outdoor recreation activities, the value of additional demand could be as high as $589 million.[163]

Longer summer and shoulder seasons (i.e., spring and fall) could extend the high season for tourism for many destinations, however extended summer seasons could have negative effects for shoulder season draws. The timing of changing foliage colors and maple sugaring may become more unpredictable in the future, thus making it difficult to plan seasonal festivals and tourism draws around these. For example, in 2021, March was officially designated “Maple Month” in Massachusetts to encourage visits to maple sugaring operations.[164] Maple syrup relies on temperate days and freezing nights to flow. Currently March provides ideal temperatures for sap flow but that could move earlier in future years.

Impacts described in the Natural Environment sector also have recreation and tourism effects. Beachgoers place a lower value on trips to narrower beaches[165], which may result in less frequent and lower-value trips to shoreline recreation sites due to sea level rise and coastal erosion. Figure A35 identifies whether average historical erosion rates for marine beaches are positive (accretion is occurring) or negative (erosion is occurring). Beaches experiencing historical erosion include Cape Cod National Seashore from Eastham to Provincetown, Crane Beach in Ipswich, Nantasket Beach in Hull, and Horseneck Beach in Westport. Water quality issues such as harmful algal blooms (increasing in frequency with warmer water temperatures[166]) and increased nutrient loading (from runoff and combined sewer overflows following extreme precipitation events[167]) could also limit opportunities to recreate in reservoirs, lakes, ponds, and nearshore coastal waters.

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[163] Other outdoor recreation activities include baseball, playing basketball, biking, boating, climbing/spelunking/caving, participating in equestrian sports, fishing, playing football, golfing, hiking, hunting, playing racquet sports, participating in rodeo competitions, rollerblading, running, playing soccer, softball, walking, participating in water sports.

[164] https://www.mass.gov/news/baker-polito-administration-declares-march-massachusetts-maple-month-1

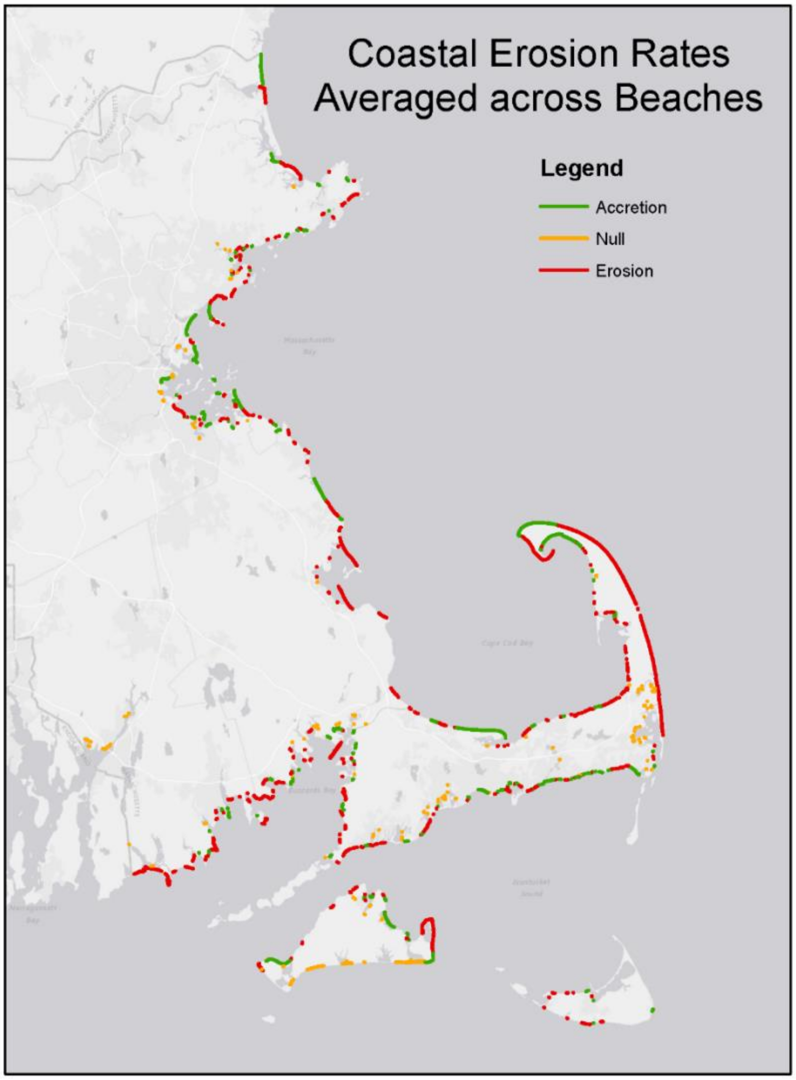
[165] Parsons, G.R., Chen, Z., and Hidrue, M.K. 2013. Valuing Beach Width for Recreational Use: Combining Revealed and Stated Preference Data. Marine Resource Economics, 28(3), 221-241.

[166] Chapra, S.C., Boehlert, B., Fant, C., Bierman Jr, V.J., Henderson, J., Mills, D., Mas, D.M., Rennels, L., Jantarasami, L., Martinich, J. and Strzepek, K.M., 2017. Climate change impacts on harmful algal blooms in US freshwaters: a screening-level assessment. Environmental Science & Technology, 51(16), pp.8933-8943.

[167] Jagai, J.S., Li, Q., Wang, S., Messier, K.P., Wade, T.J. and Hilborn, E.D., 2015. Extreme precipitation and emergency room visits for gastrointestinal illness in areas with and without combined sewer systems: an analysis of Massachusetts data, 2003–2007. Environmental health perspectives, 123(9), pp.873-879.

Figure A35. Coastal Erosion and Accretion at Massachusetts Beaches

Direction of long-term rates of shoreline change from the USGS-CZM Massachusetts Shoreline Change Mapping and Analysis Project, based on the historical record shoreline positions extending back to 1845.



Health concerns may limit certain types of recreation and continued recreation in these conditions can lead to adverse health outcomes. For example:

- Heat stress and illness during athletic and outdoor recreation activity is a growing concern, particularly for youths. The Massachusetts Interscholastic Athletic Association enacted a policy in 2019 that limits outdoor playing time at wet bulb globe temperature (WBGT, similar to the "feels like" temperature metric that considers relative humidity and temperature) above 81.1 degrees and cancels activities above 86.1 degrees. These types of cancellations and restrictions to protect athlete health will become more common, and necessary, under a warming climate.
- Air quality concerns, and specifically poor air quality attributable to more frequent wildfires (even beyond New England), can lead to lower recreation levels and/or negative health outcomes. A 2021 study in the western U.S. found that campsite

occupancy rates were only 1.3 percent lower on days with adverse smoke conditions compared to other days, suggesting people may continue some types of recreation at the risk of adverse health effects, particularly those that require advanced reservations and planning.[168]

- Increased time outdoors extends exposure to vector-borne disease, while at the same time, some recreators may choose to forgo or shorten activities due to the threat of vector borne disease. A 2019 study found that people in Sweden who live in high-risk areas for tick-borne disease were willing to pay less to reduce their risk of Lyme disease compared to people living in emerging risk areas, suggesting averting behaviors may be temporary as people gain knowledge of how to avoid infections and shift expectations.[169]

Impacts to infrastructure, particularly those described in the Damage to Coastal Buildings and Ports impact, may have indirect damages to the tourism industry. Coastal hotels and lodgings, port infrastructure, and road delays could cause significant disruption at coastal destinations. Damages to historical and cultural buildings and monuments could also depress tourism–12 percent of tourists visit historical sites/churches (see Damage to Cultural Resources in the Human sector). In general, extreme weather can deter visits. However, because nearly half of visitors in Massachusetts come from New England states and 71.6 percent of domestic visitors arrive by private vehicle (compared to 15 percent arrive by airplane) travelers may have some flexibility in working around extreme weather events.[170]

Disproportionality

Although on net, everyone in the Commonwealth stands to benefit from additional recreational opportunities, exposure to this impact is **disproportionate** due to the potential impacts on the tourism industry and the demographic characteristics of workers in this industry.

Hispanic or Latino workers make up a disproportionate share of the labor force in leisure and hospitality and therefore would be disproportionally affected by declines in the industry. In Massachusetts Hispanic or Latino workers account for 14 percent of workers in the leisure, hospitality, and tourism industry while they make up only 8 percent of the total employed workforce. Income in this industry also tend to be lower than other industries: 11 percent of workers in this industry live in poverty (based on federal poverty guidelines) compared to four percent in other industries.[171]

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[168] Gellman, J., Walls, M. and Wibbenmeyer, M., 2022. Wildfire, smoke, and outdoor recreation in the western United States. Forest Policy and Economics, 134, p.102619.

[169] Slunge, D., Sterner, T. and Adamowicz, W., 2019. Valuation when baselines are changing: tick-borne disease risk and recreational choice. Resource and Energy Economics, 58, p.101119.

[170] MOTT 2020.

[171] Melnik, M., Tumber, C., Williams, E., McNally, M., & Motamedi, R. 2018. The work of leisure: Behind the scenes of the Massachusetts leisure, hospitality and tourism industry. Eds. Corcoran, R. & Kendall, S. Prepared for The Boston Foundation. Available at: https://www.tbf.org/-/media/tbf/reports-and-covers/2018/2018-work-of-leisure-reportpdf.pdf?la=en

As opportunities for warm weather recreation increase, benefits should be shared by all. This depends in part in how equitable access to recreation activities, particularly shoreline and water-based activities with projected increased demand, is improved and maintained.

Adaptation

There is a **moderate** adaptation gap to addressing the damage to tourist attractions and recreation amenities caused by climate change. Very little action is being taken to directly address losses and damage to the state's tourism sector caused by climate change. Some plans refer generally to actions that address flooding in parks and recreation areas, and there are municipal initiatives underway to increase public engagement on open space and recreation opportunities. The timeliness with which hazards need to be addressed to prevent damage to tourism and recreation amenities is highly dependent on the individual tourist attraction or recreation amenity and is therefore difficult to assess generally. Specific industries have also taken action to expand offerings to be more resilient. For example, many ski areas in Massachusetts offer activities year-round such as events and festivals, zip lines, adventure parks, and scenic chairlift rides.

Example Adaptation Plans with Actions Addressing this Impact

- Resilient North River Canal Corridor redevelopment plans – Peabody – See plan to elevate riverwalk and generally improve park accessibility
- Medford Open Space and Recreation Plan Update includes an effort to elicit public engagement on the best ways to improve recreational opportunities
- Planning for a 'floodable park' in Lowell along Claypit Brook

Sensitivities and Uncertainty

A lack of definitive literature on traveler behavioral responses to weather and climate limits a concrete prediction of how tourism may be affected by increasing probability of extreme weather. Similarly, it is difficult to predict how tourism in Massachusetts may be impacted by changing conditions elsewhere. For example, even warmer summer temperatures in the Southern U.S. may make New England a more appealing option compared to alternative sites.

Related Impacts

Table A44 lists the impacts in other sectors that have a connection to this impact.

Table A44. Additional Impacts related to Damage to Tourist Attractions and Recreation Amenities

Sector	Impact	Connection
Human	Damage to Cultural Resources	Damage to culturally and historically important resources could impact visitation in Massachusetts.
Human	Increase in Mental Health Stressors	Availability of recreation opportunities is critical for mental health. Increased

Sector	Impact	Connection
		recreational opportunities may offer one benefit to mental health outcomes in the presence climate change.
Human	Various health impacts	Illness and threat of contracting disease and/or heat stress may depress demand for recreation.
Infrastructure	Damage to Inland Buildings; Damage to Coastal Buildings and Ports	Damage to infrastructure can cause disruptions in tourism services, particularly following extreme weather.
Natural Environment	All impacts	Natural landscapes and amenities are a large draw for tourists and recreators. Degrading the quality of ecosystems can diminish the value of recreation trips to these areas.
Economy	Reduced Ability to Work	Disruptions to the tourism and leisure industries could result in job losses for sector employees.
Governance	Reduction in State and Municipal Revenues	Disruptions to the tourism and leisure industries would result in tax losses to state and local governments.

Economy Sector: Urgent Impact #6

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.

Impact Summary

Massachusetts is home to over 7,000 farms which produce $475 million in agricultural products annually.[172] In terms of revenue generated, the top five agricultural products in the Commonwealth are greenhouse and nursery commodities, followed by cranberries, sweet corn, and apples—each of which have important cultural values and face their own challenges related to climate change.

Temperature and precipitation pattern changes may make it difficult to grow crops historically grown in the area and potentially open the opportunity for new crops to harvest. However, new crops come with associated challenges of marketing and lack of existing production and processing infrastructure. Additional pressures such as loss of pollinators, extreme storms, invasive species and pests, and saltwater intrusion introduce further uncertainty into the agriculture industry. All of these effects bring uncertainty to the agriculture industry, which is already facing economic pressures.

Urgency Ranking Results

This impact is ranked as a **medium priority** because the expected effect has the potential to be large but uncertainty still exists regarding the full extent. The 2017 U.S. EPA's Climate Change Impacts and Risk Analysis report includes an agricultural yield and revenue analysis from which yield impacts for Massachusetts for corn, hay, and potatoes are extracted for this analysis.[173] The Climate Change Impacts and Risk Analysis report followed the work of Beach et al. (2015) which uses the EPIC biophysical crop model to generate changes in crop yield, by agricultural

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[172] USDA. 2017. 2017 Census of Agriculture State Profile: Massachusetts. Available at: https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/County_Profiles/Massachusetts/index.php

[173] USEPA. 2017. Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. U.S. Environmental Protection Agency, EPA 430-R-17-001.

region, due to precipitation, relative humidity, wind speed, and solar radiation, with varied impacts by regional climate, soil type, irrigation status, and CO2 levels.[174] The three modeled crops account for approximately $37 million in annual production value but can provide broader insights into growing conditions.[175] Effects on cranberries and apples are addressed qualitatively.

> *"I am most concerned about how decreases in agricultural productivity may further pressure Massachusetts farmers to give up agriculture entirely."*
>
> *"It is impossible for farmers to adapt quickly to changing weather patterns. The farmers in our CSA have noted this repeatedly and certain crops have lower yields."*
>
> \- Stakeholder Survey Respondents (See Appendix C for details)

Magnitude of Consequence

The consequences of a decrease in agricultural productivity are expected to be **major** due to the uncertainty introduced by climate change and the change in expected yields over the remainder of the century.

Cranberries face climate challenges due to warming temperatures and unpredictable rainfall. A recent study in southeastern Massachusetts found cranberry plants flower two days earlier for every one-degree Celsius increase in May temperatures. This can lead to uncertainty in planting and harvest times for growers, as well as a domino effect on other species dependent on the cranberries, such as the bog copper.[176] The plants require cool temperature during fruit maturation and freezing temperatures to bear fruits. With climate change, it is less certain Massachusetts cranberries will see the ideal conditions of 62 days of temperatures below 45 degrees Fahrenheit. Fewer cool days can lead to abnormal blossoming and yield reductions of up to 50 percent.[177] With an annual production value of $65 million per year[178], that could result in a loss of over $30 million per year.

Table A45 shows the lost production value expected by region and time period, relative to current production values for corn, hay, potatoes.[179] The Greater Connecticut River Valley

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[174] Beach, R., Y. C, A. Thomsom, X. Zhang, R. Jones, B. McCarl, A. Crimmins, J. Martinich, J. Cole, S. Ohrel, B. DeAngelo, J. McFarland, K. Strzepek, and B. Boehlert. 2015. Climate change impacts on US agriculture and forestry: benefits of global climate stabilization. Environmental Research Letters. doi:10.1088/1748-9326/10/9/095004.

[175] Baseline production value is the average values, collected every five years, from 2007 to 2017 from the USDA Agricultural Census: USDA. 2017. National Agricultural Statistics Service Quick Stats. Available at: https://www.nass.usda.gov/Quick_Stats/

[176] Ellwood, E.R., Playfair, S.R., Polgar, C.A. and Primack, R.B., 2014. Cranberry flowering times and climate change in southern Massachusetts. International Journal of Biometeorology, 58(7), pp.1693-1697.

[177] Gareau, B.J., Huang, X., Pisani Gareau, T. and DiDonato, S., 2020. The strength of green ties: Massachusetts cranberry grower social networks and effects on climate change attitudes and action. Climatic change, 162(3), pp.1613-1636.

[178] USDA. 2017. National Agricultural Statistics Service Quick Stats. Available at: https://www.nass.usda.gov/Quick_Stats/

[179] Results also include soybean production, however baseline annual soybean production is less than $25,000 statewide.

region will experience the largest percent reduction due to its higher proportion of potatoes, which are expected to experience a 30 percent drop in yield in Massachusetts by 2090 (see Figure A36). Statewide, yields of these four crops are projected to decrease by nearly 10 percent by 2030 and up to 18 percent by 2070 and 2090.

Table A45. Projected Decrease in Agricultural Productivity due to climate impacts: Field Crops

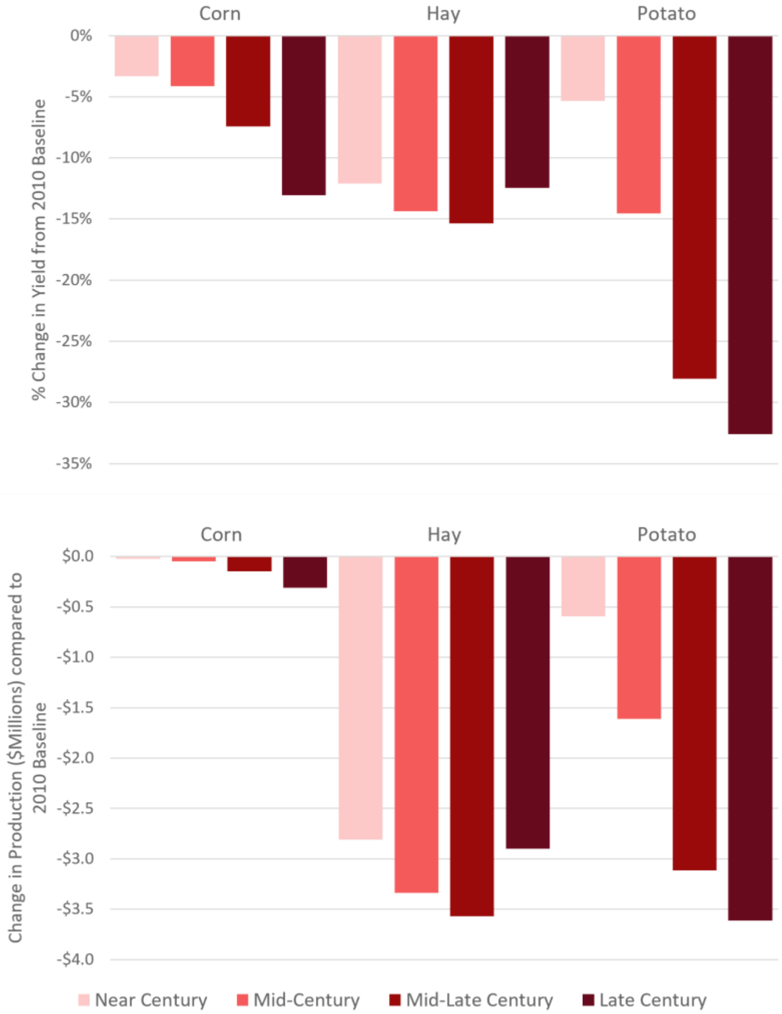
Reduction in total annual agriculture production value for corn, hay, potato, and soybean due to precipitation, relative humidity, wind speed, and solar radiation. Future impacts presented for four time periods identified in the table by their central year: 2030 (near-term, 2020-2039); 2050 (mid-century, 2040-2059); 2070 (mid-late century, 2060-2079); and 2090 (end of century, 2080-2099). Values may not sum due to rounding.

		Lost production value ($millions)			
Region	**Current**	**2030**	**2050**	**2070**	**2090**
Berkshires & Hilltowns	$6.4	$0.7	$0.9	$1.0	$0.8
Greater Connecticut River Valley	$21	$1.6	$2.7	$4.3	$4.7
Central	$4.2	$0.5	$0.6	$0.6	$0.5
Eastern Inland	$3.0	$0.4	$0.4	$0.5	$0.4
Boston Harbor	<$0.1	<$0.1	<$0.1	<$0.1	<$0.1
North & South Shores	$0.2	<$0.1	<$0.1	<$0.1	<$0.1
Cape, Islands, & South Coast	$2.6	$0.3	$0.4	$0.4	$0.3
Statewide	**$37**	**$3.5**	**$5.0**	**$6.8**	**$6.8**

Source: Analysis of U.S. EPA (2017) and Beach et al. (2015)

Figure A36. Change in Yield for Corn, Hay, and Potatoes

Changes in yield presented as percent changes from 2010 crop yield levels, as modeled in EPIC for the Massachusetts region. Changes in sales calculated as change in yield multiplied by baseline production by crop (2007-2017) from the USDA National Agricultural Statistics Service. Results shown for RCP8.5, averaged across five GCMs. Note that while this report generally presents adverse impacts as positive values, in this graphic, negative changes in yield and sales represent reductions from the baseline.



Source: Analysis of U.S. EPA (2017) and Beach et al. (2015)

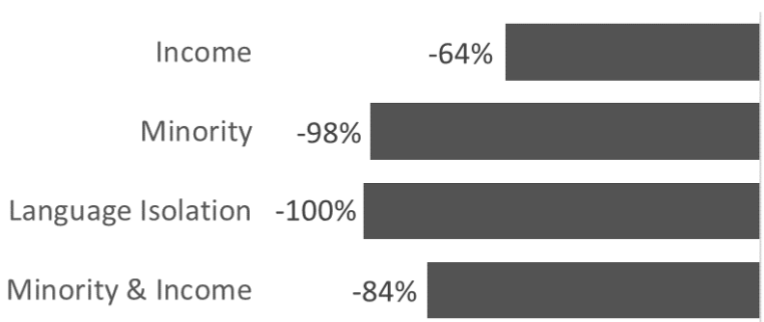
Less is known about the specific climate impacts to fruit trees, such as apple trees, although general tree stressors such as drought and increased pest presence could affect tree harvests. Like cranberries, apple trees and traditions around apple picking play an important role in the identity of the Commonwealth. Festivals, cultural events, and tourism built around these crops could also see disruptions (see discussion of Cultural Resources in the Human sector).

Disproportionality

This impact shows a **potential** for disproportionate exposure for groups defined by the state EJ criteria.[180] The quantitative analysis of the spatial distribution of lost farm revenues and EJ block groups shows that effects of this impact fall primarily in areas with higher incomes, lower proportions of minority populations, and high proportions of individuals with English language proficiency. This analysis focuses on place of residence and farm productivity and therefore does not capture disproportionate impacts to workers in the agricultural industry that do not reside in the same block group as their place of employment. In Massachusetts, 97 percent of farmer producers identify as white, however 33 percent of farms in Massachusetts hire additional farm labor who are less likely to be captured in the USDA surveys that capture demographic information.[181] Nationally, Hispanic or Latino workers (of any race) make up 34 percent of the crop production labor force, while only representing 18 percent of the total workforce but this information is not available for Massachusetts specifically.[182] Additionally, minimum wage for farmworkers in Massachusetts is currently $8.00 per hour, compared to $14.25 for other industries.[183] This suggests that a diverse set of people working in the agriculture industry could be affected by diminished revenues, and there is the potential for disproportionate exposure, particularly if the reduction in revenues results in fewer job opportunities.

Figure A37. Disproportionality of Decrease in Agricultural Productivity

Comparison of the reduction in agricultural productivity 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.



[180] Although this analysis does not find a quantitative correlation between the locations of exposure to this impact and EJ block groups, it is important to note that not all populations will have the same experience with the effects of climate change and this impact because of pre-existing social vulnerabilities that are difficult to measure or comprehensively quantify across the Commonwealth.

[181] USDA. 2017. 2017 Census of Agriculture State Profile: Massachusetts. Available at: https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/County_Profiles/Massachusetts/index.php

[182] Bureau of Labor Statistics. 2021. Employed persons by detailed industry, sex, race, and Hispanic or Latino ethnicity. https://www.bls.gov/cps/cpsaat18.htm

[183] https://www.mass.gov/service-details/minimum-wage-and-overtime-information

While the changes in production are not disproportionality borne by socially vulnerable groups, there are indirect impacts to food security that are impacted by local agriculture. Although food security is covered more comprehensively in the Human sector, the indirect linkage is considered here as well. Agricultural production in the Commonwealth is also a source of nutrition for residents. Massachusetts has the fifth highest direct market sales of all states at over $100 million annually.[184] Since 2017, the Commonwealth has run the Healthy Incentives Program (HIP) which provides a dollar-for-dollar reimbursement for Supplemental Nutrition Assistance Program (SNAP) recipients for purchases of local produce from farmers markets, farm stands, mobile markets, and community supported agriculture farm shares. As of April 2022, the program has reimbursed over $34 million, including nearly $10 million in 2021, representing a growing share of direct market sales.[185] While this specific program reflects a small portion of total SNAP benefits distributed ($2.35 billion in 2021[186]), HIP and the local food sources provide an important source of fresh fruits and vegetables to individuals receiving SNAP benefits.

Adaptation

There is a **moderate** adaptation gap to address climate-related decreases to agricultural productivity with few relevant actions identified in the reviewed plans. Of the plans that address this impact, most focus on research and increasing available funding rather than implementation of adaptation approaches. The Massachusetts Department of Agricultural Resources is developing a Farmland Action Plan for the state which could provide a much-needed statewide approach for protecting farmland from development and other land use changes and facilitate efficient use of state and municipal funding. Increasing education, technical support, and funding for implementation of healthy soil management practices on agricultural lands is another important step being undertaken at the state level via the Coordinated Soil Health Program and other initiatives. Coupling these high-level approaches with expansion of local farm-to-school programs and farmers' markets could help to ensure a reliable market for producers.

Example Adaptation Plans with Actions Addressing this Impact

- Comprehensive Climate Adaptation and Resilience Action Plan and Interactive Community Dashboard
- Pioneer Valley Climate Action and Clean Energy Plan

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[184] Data as of 2017. https://www.mass.gov/info-details/agricultural-resources-facts-and-statistics
[185] Miller, R. 2022. Healthy Families, Sustainable Farms: Lessons learned from the campaign for Healthy Incentives Program funding. Massachusetts Food System Collaborative. Available at: https://secureservercdn.net/45.40.145.201/ghl.292.myftpupload.com/wp-content/uploads/2022/05/HIPcampaignreport.pdf
[186] Center on Budget and Policy Priorities. 2022. Massachusetts Supplemental Nutrition Assistance Program. 25 April 2022.

Sensitivities and Uncertainty

As part of a larger natural system, crops are vulnerable to tipping points in ecological systems that could cause larger impacts. For example, if pollinator species experience large scale extinction, the effects on the agricultural industry would be intense. Limited literature focuses on the impacts of loss of pollinators and other stressors on the crops of highest production value in Massachusetts (i.e., greenhouse and nursery plants, cranberries, and apples).

The analyses above assume a constant area under harvest each year for the analyzed crops. Uncertainty exists regarding future land area held for agriculture as competition for land, particularly in the western parts of the state, may reduce farmland. Additionally, with an aging farmer population, there is concern the added financial uncertainty introduced by climate change may further dissuade new farmers from entering the industry. Behavioral responses may also mitigate the expected impact. For example, increased irrigation or switching crops to those more suited for new climate regimes may mitigate risk.

Finally, demographic information on farmworkers (rather than farm owner data referenced here) is not readily available. A better understanding of this may allow for more certainty in the identification of disproportionate impacts.

Related Impacts

Table A46 lists the impacts in other sectors that have a connection to this impact.

Table A46. Additional Impacts related to Decrease in Agricultural Productivity

Sector	Impact	Connection
Natural Environment	Soil Erosion	Soil erosion around farmlands can lead to decreases in yields.
Economy	Damage to Tourist Attractions and Recreation Amenities	Some farms and communities generate additional revenue through tourism and recreation centered around crops (e.g., apple picking, corn mazes, berry picking).
Economy	Reduced Ability to Work	Agricultural workers are exposed to climate conditions and may experience reduced hours or heat stress while working.
Human	Reduction in Food Safety and Security	Food production within the Commonwealth contributes directly to food security of its residents.
Human	Damage to Cultural Resources	Farming as a way of life and the ability to know the farm where food is grown both hold cultural value. Certain crops such as cranberries are an important part of the Commonwealth’s historical identity.