REPORT TO THE LEGISLATURE

MARCH 2026

Minnesota climate adaptation and resilience cost study

The projected costs of climate change impacts and adaptation actions under future emissions scenarios

MINNESOTA POLLUTION CONTROL AGENCY

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Report to the Legislature, March 2026

Legislative charge

2024 Session Laws, Chapter 116, Article 2, Section 33 required the MPCA to carry out a study on climate adaptation and resilience costs and submit the report to the Legislature.

Prepared for MPCA by:

Industrial Economics, Inc.
University of Minnesota Climate Adaptation Partnership
Two Degrees Adapt
Consensus Building Institute

Full contributions and acknowledgements provided in Appendix C.

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Minnesota Pollution Control Agency

520 Lafayette Road North | Saint Paul, MN 55155-4194 |

651-296-6300 | 800-657-3864 | Or use your preferred relay service. | Info.pca@state.mn.us

This study is available in alternative formats upon request, and online at www.pca.state.mn.us.

Document number: lrcc-mn-1sy26

Foreword

With this report on the study of the costs of climate change and climate adaptation measures, the Minnesota Pollution Control Agency (MPCA) meets the requirements of 2024 Session Laws, Chapter 116, Article 2, Section 33. This law required the agency to research and report on the projected costs in Minnesota of climate change adaptation and resilience measures needed to mitigate the projected impacts of climate change.

This study shows that climate change is expensive for Minnesotans.

The study finds that without additional adaptation efforts, Minnesota can expect to see more than $20 billion worth of climate change impacts per year under a high greenhouse gas (GHG) emissions scenario. By the end of the century, if global GHG emissions continue to rise and no adaptation actions in Minnesota are taken, estimated annual costs of climate change are more than $50 billion. These impacts cross economic sectors and affect the day-to-day lives of Minnesotans. For example, climate change makes air quality worse, leading to more asthma attacks and more early deaths. Larger rain events – driven by climate change – mean more buildings and infrastructure will be affected by overland flooding.

At the same time, the study shows that Minnesota can act – through government and organizations as well as individuals – to adapt to climate change. Even more importantly, the study shows adaptation actions are much less expensive than the costs of climate change. For the costs analyzed in this study, acting to adapt to climate change is eight to 15 times less expensive than the costs of future climate change impacts not addressed by adaptation actions.

The findings of this study underscore the importance of achieving the vision of Minnesota's Climate Action Framework – which is a Minnesota that is carbon-neutral, resilient, and equitable.

The MPCA contracted economic and climate experts, with experience at the state- and national levels, to complete this study and report. The findings are based on analysis that relied on dozens of peer-reviewed studies and developed with a process that engaged dozens of Minnesotans who work on issues affected by and/or are responding to climate change. The engagement process is documented in Appendix A. The cost estimates are likely conservative – i.e. costs of climate change impacts and adaptation actions are likely higher than what the analysis in this study finds. All methods are documented in an extensive methodology appendix (Appendix B).

Contents

Abbreviations

CDC	U.S. Centers for Disease Control and Prevention
CSBR	Center for Sustainable Building Research
MN CliMAT	Minnesota Climate Mapping and Analysis Tool
EAB	Emerald Ash Borer
ED	Emergency department
EPA	U.S. Environmental Protection Agency
FEMA	Federal Emergency Management Agency
FrEDI	Framework for Evaluating Damages and Impacts
GCM	Global climate model
GDP	Gross domestic product
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
IRI	International roughness index
MCAP	University of Minnesota Climate Adaptation Partnership
MMCD	Metropolitan Mosquito Control District
MNDNR	Minnesota Department of Natural Resources
MNDOT	Minnesota Department of Transportation
MPCA	Minnesota Pollution Control Agency
NAAQS	National Ambient Air Quality Standard
NOAA	National Oceanic and Atmospheric Administration
NWR	National Wildlife Refuge
OSHA	U.S. Occupational Safety and Health Administration
PM	Particulate matter
RMAT	Resilient Massachusetts Action Team
SSP	Shared Socioeconomic Pathway
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
VOC	Volatile organic compound
VSC	Value of a statistical case
VSL	Value of a statistical life
WTP	Willingness to pay

Executive summary

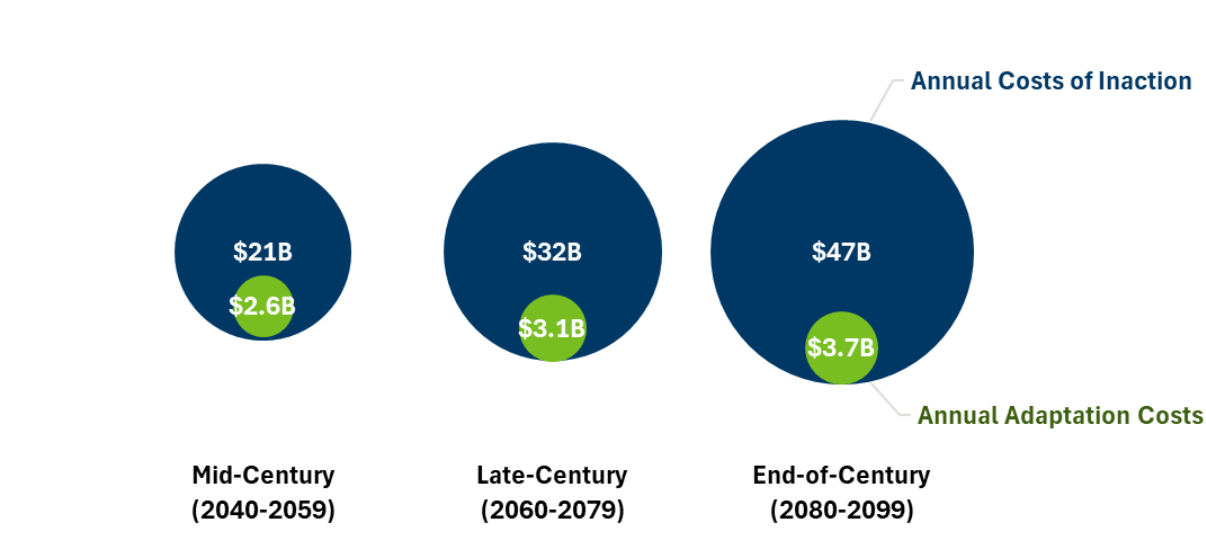
Study objectives and key takeaways

2024 Session Laws, Chapter 116, Article 2, Section 33 required the Minnesota Pollution Control Agency (MPCA) to carry out a study on climate adaptation and resilience costs and submit it to the Legislature. This study represents the fulfillment of this requirement.

- **Adapting and building resilience to climate change will require additional investment.** The costs of adapting to the projected impacts of climate change in Minnesota will require an additional investment of $2.5 to $4.1 billion per year on average over the analyzed period (2040–2099).
- **Failure to adapt to climate change will be costly.** The quantified impacts of climate change in Minnesota without further adaptation investment are $17 to $22 billion per year by Mid-Century (2040–2059) and increase to $36 to $57 billion per year by End-of-Century (2070–2099).
- **Investing in climate adaptation will avoid costs in the future by lessening costly climate impacts.** The quantified annual costs of inaction on climate adaptation are eight to 15 times larger than the quantified adaptation costs for the categories analyzed in this study.
- **The costs presented in this study provide a useful, yet incomplete, accounting of the total costs of climate impacts and climate adaptation.** This analysis provides an evidence-supported estimate of the magnitude of adaptation investments to address climate impacts. The results likely underestimate both the costs of inaction and the costs of adaptation because the study only quantifies a subset of the significant and likely costs of climate change. The evidence from this report supports taking action on climate adaptation, while learning and adjusting as new information becomes available.

Annual Costs of Inaction and Adaptation Costs

The figure shows study results for three time periods and the High emissions scenario. The annual costs of inaction are eight to 15 times higher than the annual adaptation costs in this scenario.



Purpose and scope of this study

This study quantifies the projected cost of adaptation under future emissions scenarios beyond current costs. This study should not be considered a comprehensive accounting of all potential adaptation actions in Minnesota nor is it a prescriptive roadmap for adaptation in the state. Rather, this analysis provides a well-founded estimate of the magnitude of necessary adaptation investments to address projected climate impacts.

How to interpret the results of this study

While the focus of this study is on the costs of adaptation, this analysis quantifies three climate cost components.

- In a scenario with no additional adaptation action,
  - The **costs of inaction** are the monetized impacts of climate change, incremental to costs in the baseline period, and without further adaptation intervention.
- In a scenario with adaptation action taken,
  - The **costs of adaptation** are the investments required to prepare for and adjust to the projected impacts of climate change, and
  - **Residual risks** are the climate-driven impacts that remain after adaptation investments.

Understanding the consequences of not adapting helps decision makers navigate important tradeoffs and recognize the benefits smart climate adaptation can provide.

The study organizes costs into five categories:

Health and Wellbeing
Heat, Air Quality, and Vector-borne Disease and Illness

Agriculture and Livestock
Crops and Livestock

Transportation and Electricity Infrastructure
Transportation and Electricity

Buildings
Flooding and Wildfire and Other Natural Hazards

Ecosystems
Terrestrial and Aquatic

These categories help organize costs for the purpose of the analysis but are not intended to suggest adaptation should be "siloed" by cost category. In fact, adaptation in one area can often have positive (or negative) effects in another area. For example, improving road resilience can improve the ability to get agricultural products to market, and limiting wildfire risks through forest management can enhance ecosystem health and protect buildings.

The study presents results for three scenarios that represent a range of potential climate futures based on global greenhouse gas emission levels and three time periods. The scenarios of potential climate futures are Intermediate, High, and Very High. The three time periods are Mid-Century (2040–2059), Late-Century (2060–2079), and End-of-Century (2080–2099). All costs are measured as over and above costs incurred in a baseline period (1995–2014). These emissions scenarios and time periods are consistent with the dimensions available from the Minnesota Climate Mapping and Analysis Tool (MN

CliMAT).[1] The estimated adaptation costs and costs of inaction represent average annual costs for the specified emissions scenario and time period in 2024 U.S. dollars.

Important notes on the costs in this study

When interpreting the costs presented in this study, it is important to remember:

- The costs quantified in this study are **incremental to baseline** costs already experienced in Minnesota, which means the quantified costs are in addition to expected costs without any future climate change.
- The costs represent the **subset of all potential costs** that could be quantified for this study.
- Presented costs represent **average annual costs** for the specified time period and future scenario.

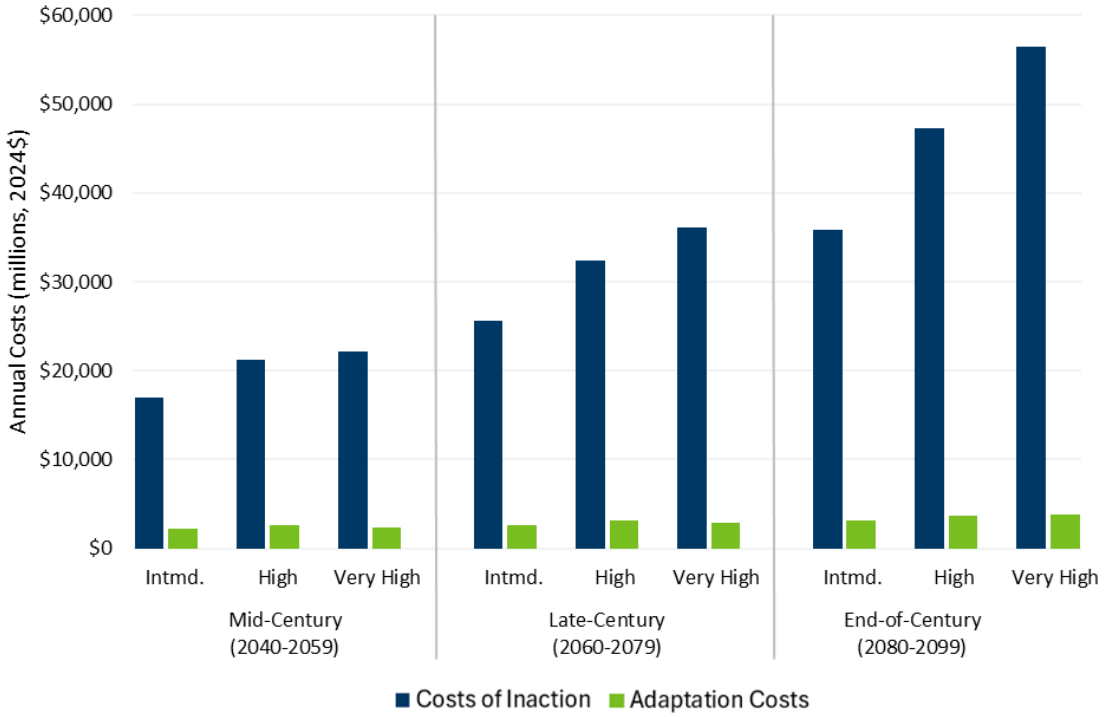
Summary of quantified adaptation costs

The adaptation costs needed to address the projected impacts of climate change reach $3.8 billion per year by the End-of-Century time period under the High emissions scenario (range from $3.3 to $4.1 billion when considering the Intermediate and Very High emissions scenarios). While these quantified costs are large, compared to the consequences of not acting, the benefits of adaptation are clear. The annual quantified costs of inaction are eight to 15 times the quantified adaptation costs for the categories analyzed in this study.

[1] See more information at: https://climate.umn.edu/MN-CliMAT.

Figure ES-1. Annual Costs of Inaction and Adaptation Costs by Emissions Scenario

Summarized costs of inaction (first set of bars, in dark blue) and adaptation costs (second set of bars, in green) per year, above baseline, for three time periods and three emissions scenarios (defined as Intermediate [Intmd.], High, and Very High; see Section 2.2.2 for more details). For accurate comparison, this figure excludes adaptation costs that don't have a corresponding cost of inaction and costs of inaction without a quantified adaptation cost.t address costs of inaction not quantified in this study and costs of inaction without quantified adaptation costs.

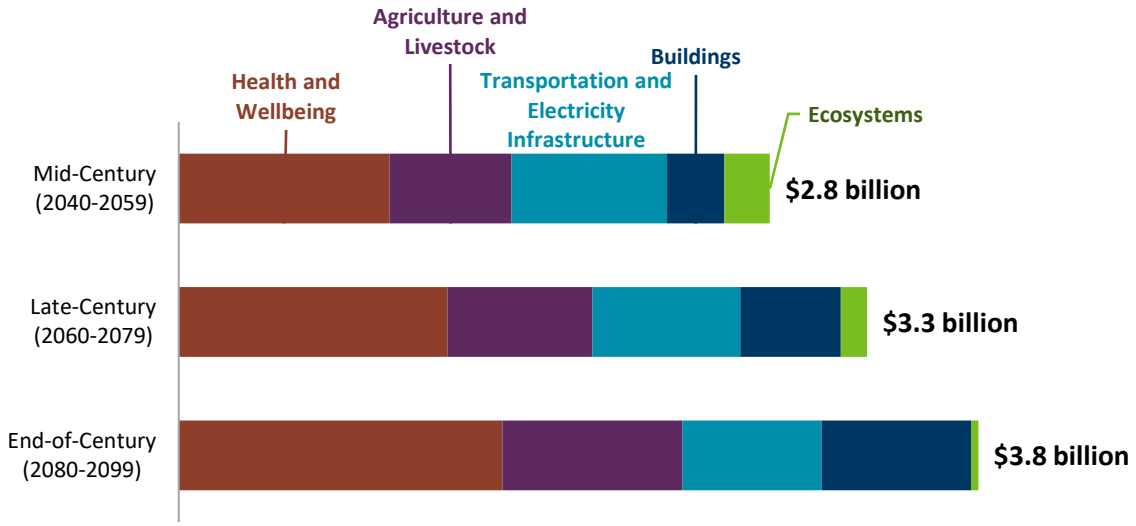


These costs represent the subset of adaptation costs that **could be quantified** in this study. Not all future costs have been quantified due to lack of data, significant uncertainty, or complex modeling requirements that were outside of the scope of the study. This is especially the case in the Ecosystems category where adaptation actions are particularly site-specific and difficult to estimate. Comprehensively valuing damages to ecosystems requires significant analysis and stakeholder engagement. Throughout the study, non-quantified costs are discussed through qualitative descriptions of those costs and/or as limitations in the cost estimates provided.

Adaptation costs increase over time as climate stressors worsen. Significant investment is already needed by Mid-Century to reduce the impacts of climate change on people and communities. Earlier investment (i.e. before Mid-Century, pre-2040) will also help reduce impacts, though earlier costs are not included in this study. For reference, projected annual adaptation costs by Mid-Century are less than one percent of Minnesota's estimated 2024 annual gross domestic product (GDP) of just over $500 billion.[2]

[2] Source for 2024 GDP estimate: https://mn.gov/deed/data/economic-analysis/compare/compare-minnesota/economy/gdp.jsp - data derived from U.S. Department of Commerce, Bureau of Economic Analysis.

Figure ES-2. Quantified Annual Adaptation Costs for the High Emissions Scenario, by Cost Category
Quantified annual costs (2024$) by category for the High emissions scenario in each time period.

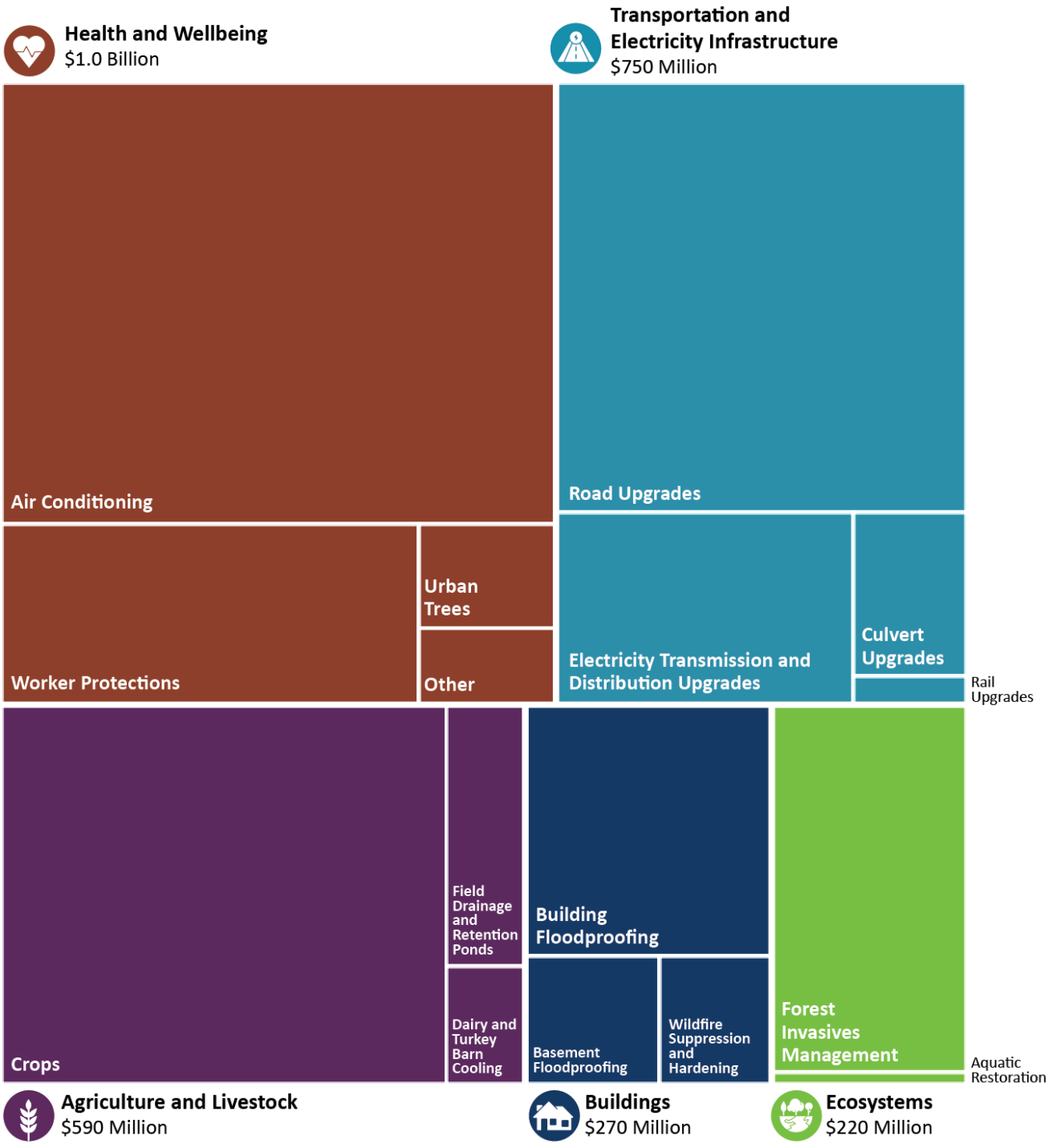


In the Mid-Century (2040–2059), High emissions scenario, projected annual adaptation costs are highest in Health and Wellbeing. Air conditioning in homes, schools, and other public commercial buildings being the single largest investment quantified. The next largest category is Transportation and Electricity Infrastructure, where investment in road upgrades is the second largest investment overall.

Proactive road adaptation investments early in the study period result in declining adaptation costs over time. Flood adaptation and irrigation needs, on the other hand, increase over the study period, and by End-of-Century, projected adaptation costs for floodproofing (building and basement) and irrigation both exceed road adaptation costs. Air conditioning costs remain the single largest investment category across all time periods.

Figure ES-3. Quantified Annual Adaptation Costs by Action and Cost Category, High Emissions Scenario, Mid-Century

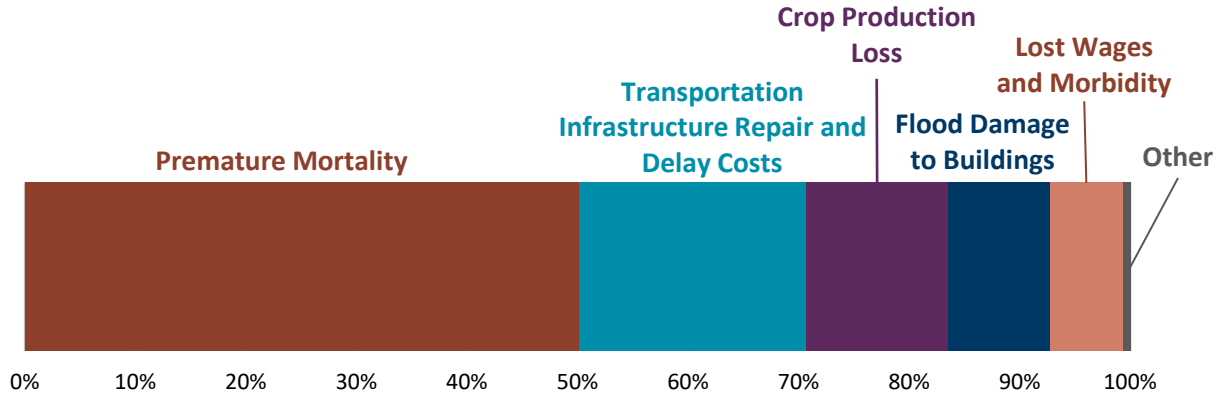
Annual quantified adaptation costs (in 2004 $) by category and action for High emissions Scenario at Mid-Century.



Investing in adaptation reduces costly risks to the state and its residents. The costs of inaction include a variety of impacts, monetized with different methods, depending on the type of impact measured. The largest portion of the cost of inaction is premature mortality – from heat and air quality – which makes up about half of the quantified cost of inaction. Mortality is valued using the Value of a Statistical Life (VSL), which represents what society is willing to pay to reduce mortality risk. In the scenario shown in Figure ES-4, the cost to society of increased mortality is about $10 billion per year, representing 450 additional deaths per year.

Figure ES-4. Breakdown of annual costs of inaction, Mid-Century, High Emissions Scenario

Summary of the breakdown of annual cost of inaction, above baseline, in Mid-Century (2040–2059) for the High emissions scenario, averaged across six climate models.



Investing in climate adaptation will not fully eliminate all future risks from climate change. For example, some individuals, specifically unhoused populations and outdoor workers, will still experience significant heat exposure and adverse effects even when buildings are cooled. Floodproofing offers another example – it is not feasible to protect every home in the state against extremely low-probability flood events (e.g., a flood that may occur once every 500 years), leaving some risk remaining after adaptation. Where possible, this study reassesses projected climate impacts with adaptation in place to quantify the residual risk, or the impacts projected to remain even with adaptation investment. The difference between the costs of inaction and the residual risk can be interpreted as the avoided costs, or the benefits, from adaptation.

Overall, the study likely underestimates both the costs of inaction and the costs of adaptation. The study highlights other non-quantified costs of inaction, and adaptation measures which are likely to be cost-effective but could not be quantified at this time. Further, this study focuses on the direct costs of climate change, but there are also numerous indirect costs of inaction that are not quantified here, such as effects on business interruption and impacts to industries that support or rely on a productive agricultural sector, reliable transportation and electricity infrastructure, safe buildings, a healthy workforce, and healthy ecosystems. Many assumptions are necessary to generate these estimates, but where made, these assumptions are usually conservative, meaning the reported costs of climate impacts and adaptation needs are most likely underestimates. There is also the potential that technological innovations over time may reduce the cost to adapt or effectively eliminate some relevant risk within the cost categories analyzed. For example, the availability of a vaccine for Lyme disease could substantially reduce the impacts of those infections, or advances in heat pump or geothermal technology could reduce the cost of cooling homes, schools, and other buildings.

Conclusions and next steps

The analysis in this study shows climate change is expensive for Minnesotans. The costs of climate change affect many sectors and aspects of people's lives. The study also shows clear economic benefits for investing in a range of climate adaptation actions to address the impacts of climate change on the health and wellbeing of Minnesotans as well as the built infrastructure and natural systems of the state.

This study significantly advances the understanding of the costs of climate change and climate adaptation in Minnesota. To make progress on climate adaptation to protect Minnesotans from the impacts of climate change, further work is needed, including:

- **Sharing the conclusions of this study via a publicly available dashboard or interactive website.** Ideally the dashboard would be integrated into a growing suite of climate planning and analysis tools, including Minnesota's Climate Mapping and Analysis Tool (MN CliMAT).
- **Developing a state adaptation plan or series of hazard-focused adaptation plans that build on this study and Minnesota's Climate Action Framework.** The plans would create specific actionable adaptation paths for different sectors and include guides and other support for local governments as they cost, plan, and implement climate adaptation.
- **Developing a plan for adaptation financing.** This plan would identify existing sources of finance and the strengths along with limitations of types of financing. It would also provide recommendations for new mechanisms to fund adaptation action that consider State government, local government, private sector, and other sources of implementation funding. Considering the scale of funding needed for adaptation will be particularly important to make the financing plan effective.
- **Developing a process to test and evaluate adaptation action.** The iterative work of adaptation is most effective when it includes sharing lessons learned on past and existing resilience investments. Additional information from near-term testing of actions assessed in this study and other related Minnesota-specific evidence (e.g., University of Minnesota Climate Adaptation Partnership reports) can also improve adaptation action.

1. Introduction and study overview

1.1. Study scope and objective

2024 Session Laws, Chapter 116, Article 2, Section 33 required the Minnesota Pollution Control Agency (MPCA) to carry out a study on climate adaptation and resilience costs and submit it to the Legislature. This study represents the fulfillment of this legislative requirement.

Minnesota has already experienced impacts of natural hazards that can be expected to increase in frequency and intensity as climate change advances – as a result, decision makers across the state are incorporating expectations for future climates into their investment decisions. Looking to the end of the century, the need for adaptation will generally increase as the climate continues to change and impact the state. If additional adaptation investments are not made, the state will instead be faced with increasing costs and damages from the impacts of climate change.

Understanding the scale of investment required to adapt to climate change can facilitate appropriate adaptation. To provide the State with sound information, this study:

- Relies on established lines of work and builds on existing evidence,
- Is transparent about assumptions made and the influence of those assumptions, and
- Communicates clearly what the study can and cannot provide.

This study quantifies both the projected cost of adaptation under future emissions scenarios and the quantified costs of inaction (i.e., impacts of climate change without further adaptation) for critical context. These estimates represent costs above and beyond those currently being borne by Minnesotans. This study should not be considered a comprehensive accounting of all potential adaptation actions in Minnesota. Rather, this analysis provides a well-supported estimate of the magnitude of necessary adaptation investments to address projected climate impacts. Table 1-1 provides further clarification of what this study is and is not.

Table 1-1. Costs of Inaction (Climate Impacts) and Potential Adaptation Actions for Health and Wellbeing

This Study IS:	This Study IS NOT:
• A well-supported, transparent estimate of the magnitude of necessary adaptation investment to address projected climate impacts.	• A comprehensive accounting of all potential adaptation actions that may be relevant to decision makers.
• An objective analysis of the cost of select adaptation actions that represent potentially applicable adaptation costs where methods are available for costing.	• A prescriptive recommendation or roadmap of the types of adaptation actions that are most appropriate and beneficial to pursue.
• A statewide study, with underlying analysis often performed at the state or county level.	• A source of geographically specific information intended to guide local resilience planning and project siting; or a detailed distributional analysis of climate impacts between and within communities of different socioeconomic and demographic makeups.
• An analysis of the adaptation investment required under three potential future emissions scenarios.	• A cost estimate of the greenhouse gas mitigation measures described in the 2026 Climate Action Framework.

This study provides a multi-sectoral projection of the economic costs of climate change in Minnesota and estimates of the need for adaptation investments to counteract these risks to the natural, built, and social environment of Minnesotans. These estimates provide a foundation for a series of potential next steps to guide adaptation planning, finance, and a continuous process of iterative climate risk management, at multiple levels of government and within the private and non-profit sectors.

Study roadmap

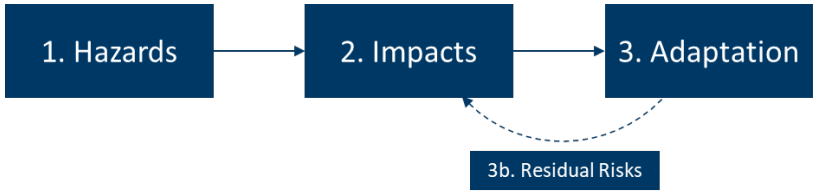
- The remainder of this chapter (**Chapter 1**) provides an overview of the methods used in this study and presents a summary of the key results – how much climate adaptation will cost in Minnesota and what impacts will be experienced if further adaptation action is not taken.
- **Chapter 2** explains the types of costs included in this study and provides additional detail on the methodologies used in the study.
- **Chapter 3** reviews historical and projected changes in key climate indicators in Minnesota. These physical changes motivate the need for adaptation investments.
- **Chapters 4** through **8** report further details on the costs of inaction and adaptation costs across five cost categories: Health and Wellbeing (**Chapter 4**), Agriculture and Livestock (**Chapter 5**), Transportation and Electricity Infrastructure (**Chapter 6**), Buildings (**Chapter 7**), and Ecosystems (**Chapter 8**). Further details on the analyses underlying the results in these chapters can be found in **Appendix B.**
- **Chapter 9** presents several frameworks for considering the tradeoffs between investing in adaptation and incurring the adverse effects of climate impacts. These frameworks can be used to support smart implementation of adaptation actions.
- Finally, **Chapter 10** provides recommendations on next steps and highlights areas for further research. This study represents a significant first step towards understanding the costs of adaptation in Minnesota, but gaps remain, and future research is needed to complete the picture.

1.2. Methods overview

1.2.1. Process for linking climate change to adaptation actions

This study follows a three-step approach to quantify the costs of climate change, shown in Figure 1-1. The costs of adaptation calculated in this study are driven by projected climate hazards in Minnesota and the subsequent impacts on the natural, built, and social environment. Understanding the consequences of not adapting helps decision makers navigate important tradeoffs between adaptation actions and recognize long-term benefits of climate adaptation-focused options. This approach is frequently applied in analyses of the economic cost of climate change and was adopted in the Economics chapter of the Fifth National Climate Assessment (USGCRP 2023).[3]

Figure 1-1. Overview of methodology for climate change costing



[3] The 2023 National Climate Assessment is available at the NOAA Institutional Repository.

The approach is as follows:

1. This analysis begins with a summary of projected **climate hazards** across the state using data from MN CliMAT (Minnesota CliMAT). The results of this step are summarized in Chapter 3. The level of adaptation investment required is scaled to meet the projected impacts of climate change, making this an important starting point.

2. Next, hazards are translated into **climate impacts.** Climate impacts in this study use peer-reviewed literature on well-established pathways linking climatic hazard exposure to monetized impacts. Many of the impacts are quantified using a peer-reviewed and publicly available U.S. Environmental Protection Agency (EPA) tool called FrEDI (Framework for Evaluating Damages and Impacts).[4] Impacts not included in FrEDI, but important to the state and/or highlighted by stakeholders, are quantified using other peer-reviewed sources and Minnesota-specific data inputs, or are discussed qualitatively. The identified impacts give a sense of where adaptation actions are likely to focus. Appendix B provides more details on FrEDI and documents all the methods and data used in this study.

3. The final step involves identifying the **climate adaptation** actions that will allow Minnesota to prepare for and adjust to the climate impacts from step 2 and estimating the costs of those actions. Quantified adaptation actions do not represent the only recommended action(s) for that category. Instead, quantified actions are the ones in which methods exist to scale the adaptation need to the climate conditions under each emissions scenario. The report also provides discussion of adaptation actions that were not quantified in this analysis.

   For several of the adaptation cost categories, the last step of the analysis is extended to calculate the **residual risk** – that is, the impacts that remain after implementing the quantified adaptation actions. This is Step 3b in Figure 1-1 above. It is not possible to eliminate all risks from climate change. Adaptation actions reduce climate risk, but there are situations where additional adaptation costs far exceed the

Key term definitions

Definitions are sourced from the 2025 Climate Action Framework (CAF) unless otherwise noted.

- **Adaptation:** Taking action to prepare for and adjust to both the current and projected impacts from climate change. For both natural and built systems, humans may intervene to help adjustment.
- **Hazard:** The potential occurrence of a natural or human event that may cause damages to health, property, infrastructure, and ecosystems.
- **Impacts** (from climate change): The consequences of realized risks on natural and human systems, where risks result from interactions of climate-related hazards, exposure, and vulnerability (NCA5). Sometimes referred to as the **costs of inaction.**
- **Mitigation** (of climate change): A human intervention to reduce emissions or enhance the removal of a greenhouse gas from the atmosphere (e.g., through carbon sequestration in plants). Note this study does not focus on mitigation. See the Climate Action Framework for more information on the State's mitigation plans.
- **Resilience:** The capacity of individuals, communities, businesses, buildings, infrastructure or the natural environment to prevent, withstand, respond to, and recover from disruptive events and continue to perform despite persistent stresses imposed by climate change. Both **mitigation** and **adaptation** are necessary for long-term resilience.

[4] FrEDI is a reduced-form model developed by the U.S. Environmental Protection Agency that uses custom temperature projections for the contiguous United States.

benefit they could provide, and therefore some residual climate risks will remain. In the figures in this study, residual risks are shown as added costs, on top of adaptation costs, because they are part of the overall costs of a scenario in which adaptation is implemented.

Appendix B provides additional details on the steps described above. The appendix also documents key assumptions and limitations in the analysis, and the potential impact of these assumptions on the results presented in this study.

The study organizes costs into five categories:

Health and Wellbeing
Heat, Air Quality, and Vector-borne Disease and Illness

Agriculture and Livestock
Crops and Livestock

Transportation and Electricity Infrastructure
Transportation and Electricity

Buildings
Flooding and Wildfire and Other Natural Hazards

Ecosystems
Terrestrial and Aquatic

These categories are useful for organizational purposes but are not intended to suggest adaptation should be "siloed" by cost category. In fact, adaptation in one area can often have benefits in another area. For example, improving road resilience can improve the ability to get agricultural products to market, improving the resilience of the electric grid to natural hazards can provide benefits to all users of electricity, and limiting wildfire risks through forest management can enhance human and ecosystem health as well as protect structures.

The study presents results for three future scenarios that represent a range of potential climate futures (Intermediate, High, and Very High) consistent with the best available climate hazard data specific to Minnesota from the University of Minnesota Climate Adaptation Partnership's (MCAP's) Climate Mapping Analysis Tool (known as MN CliMAT). Each emissions scenario reflects different social and economic decisions, including (but not limited to) population growth, technical developments, and land-use changes that will impact future greenhouse gas emissions trajectories. A set of six global climate models (GCMs) informs MN CliMAT by providing temperature and precipitation projections to reflect potential outcomes of the three emissions scenarios, resulting in a range of future climate hazard projections that accounts for uncertainty of future climate change across our quantified impacts. The study also presents results across three time periods: Mid-Century (2040–2059), Late-Century (2060–2079), and End-of-Century (2080–2099), incremental to a baseline period (1995–2014).[5] The findings of this study represent the average annual costs for each of the 20-year time periods and the three emissions scenarios above and beyond the costs incurred in the baseline period. Chapter 2 (Section 2.2) provides further details on each of these dimensions.

[5] These scenarios and time periods are consistent with the dimensions available from the Minnesota Climate Mapping and Analysis Tool (MN CliMAT). See more information at: https://climate.umn.edu/MN-CliMAT.

1.2.2. Defining the components of the cost of climate change

This study quantifies three different cost components:

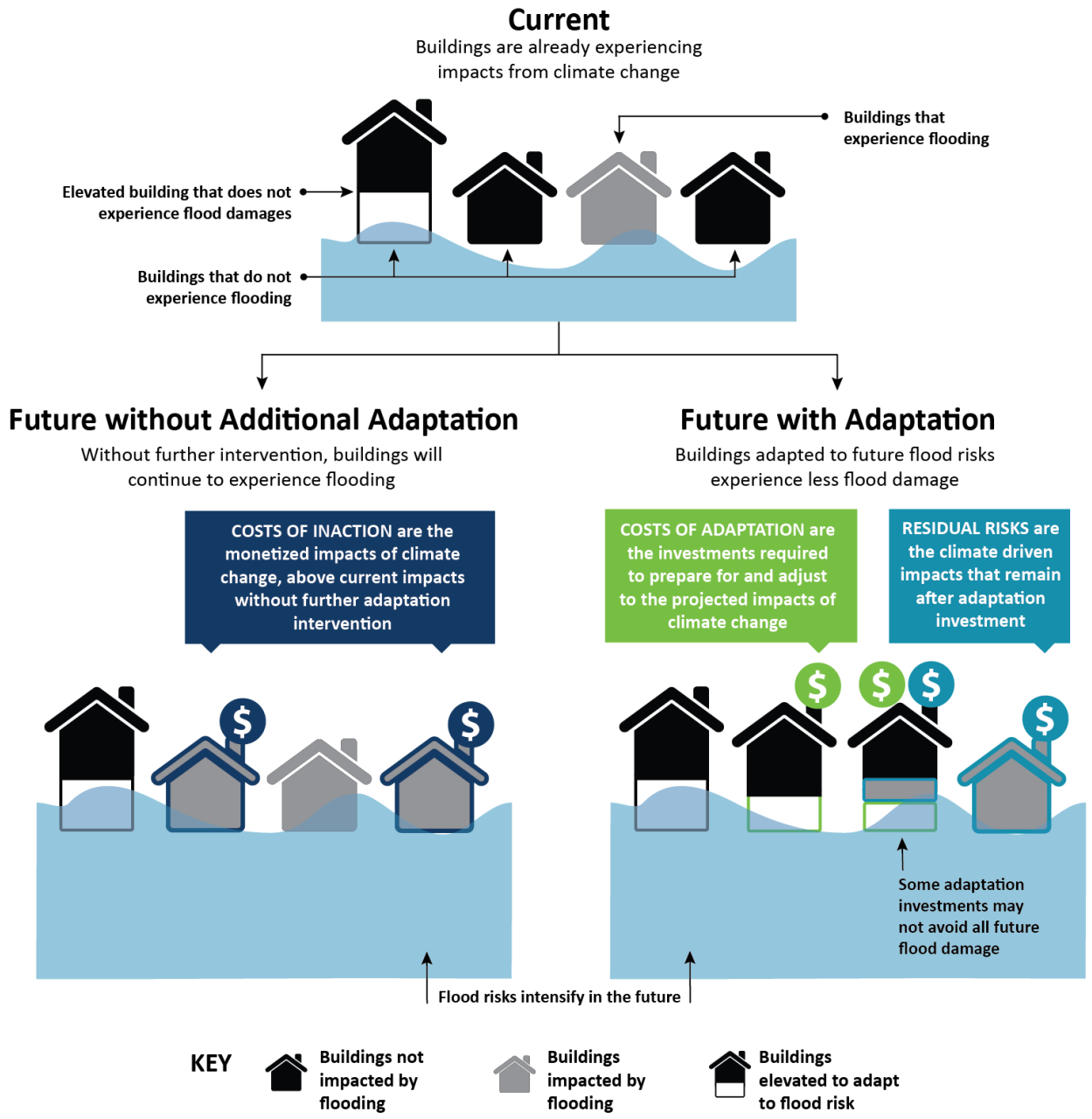
- **Costs of inaction** are the monetized impacts of climate change, incremental to costs in the baseline period, and without further adaptation intervention.
- **Costs of adaptation** are the investments required to prepare for and adjust to the projected impacts of climate change.
- **Residual risks** are the climate-driven impacts that remain after adaptation investments.

Figure 1-2 illustrates these key concepts – cost of inaction, adaptation cost, and residual risk – using flooding damage as an example. The scenario in the top panel of the figure represents the current level of flooding hazard, current protections in place, and the current level of flooding damage. In this current scenario, some buildings have already made the decision to adapt (see the elevated building on the left). These buildings do not experience flood damages. Of the buildings that have not yet adapted, some already experience flood damages (see the gray building) and some do not (see the black buildings on either side of the gray building).

In the future, the models used in this analysis show an increase in flood risk (illustrated by the higher water level in bottom two panels compared to the top panel). Two scenarios are possible:

- In the scenario without additional adaptation investment ("Business as Usual," the lower left panel), more buildings will experience flood damage as flood risks worsen. The additional damages that occur in the future compared to today are referred to as the **costs of inaction.** These are represented by the gray buildings outlined in dark blue.
- In the scenario with additional investment ("Adaptation," the lower right panel), more property owners decide to adapt. The newly elevated buildings are shown with raised foundations outlined in green. The **costs of adaptation** are the costs of floodproofing buildings that are not currently floodproofed. Even in a scenario with adaptation, not all property owners will fully adapt if they don't think the flood risk is worth the costs of adaptation. **Residual risks** are the flood damages that still occur in the "adaptation" scenario. In the figure, two buildings experience residual risk, outlined in light blue. One property owner (the third building in the panel) invested in adaptation, and the building experienced less damage than it would have without adaptation, but it was not enough to fully protect against the increased future flood risk. The other building on the far right of the panel did not adapt and therefore experienced flood damages. Both damages are considered residual risk in this analysis.

Figure 1-2. Illustrative example of the Costs of Climate Change: Costs of Inaction, Adaptation Costs, and Residual Risks



1.3. Climate cost results summary

This study shows that adapting and building resilience to climate change will require additional investment, failure to adapt to climate change will be costly, and investing in climate adaptation will save money in the future by lessening costly climate impacts.

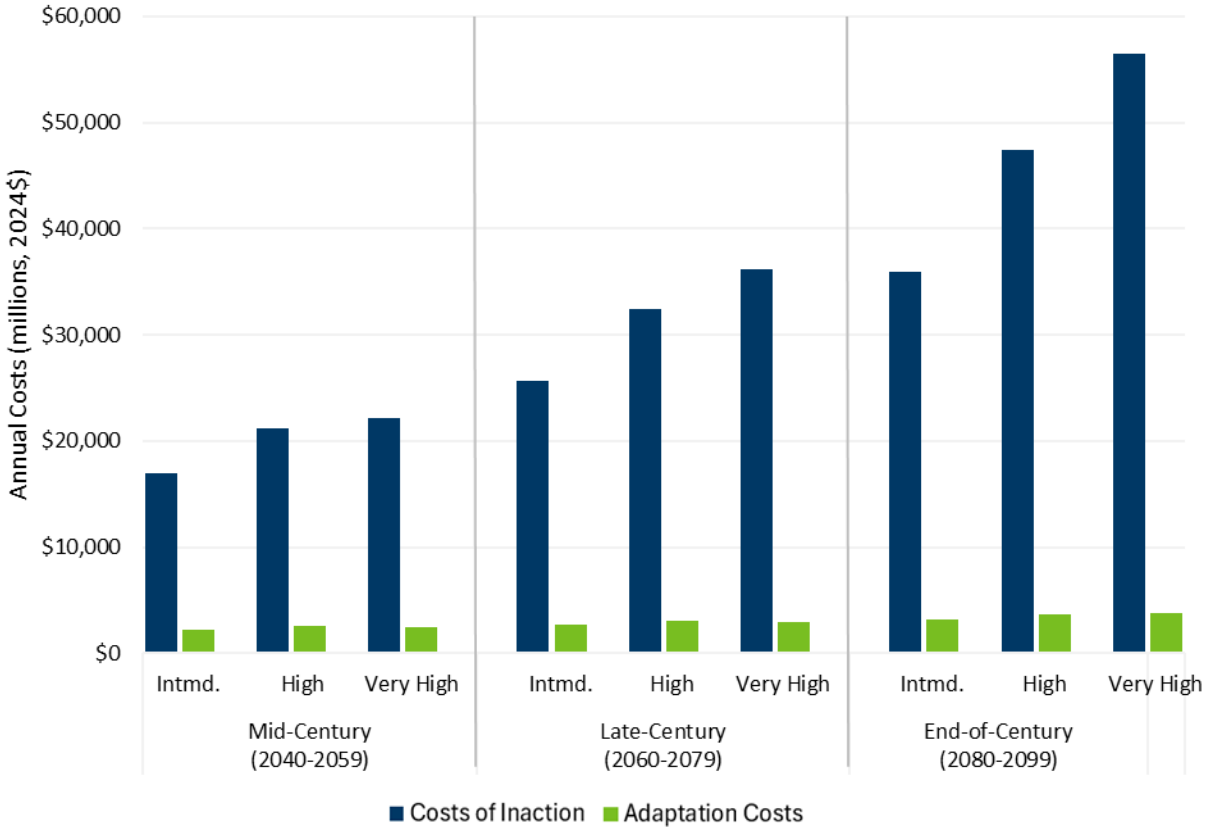
1.2.3. Comparison of overall costs of inaction and costs of adaptation

The adaptation costs that would be needed to mitigate the projected impacts of climate change reach $3.8 billion per year by the End-of-Century time period under the High emissions scenario (and a range of $3.3 to $4.1 billion when considering the Intermediate and Very High emissions scenarios).

While these quantified costs are large, the benefits of adaptation become clearer when understood in the context of the consequences of not acting. The annual quantified costs of inaction are six to 15 times the quantified adaptation costs for the categories analyzed in this study. While adaptation will not be able to fully eliminate these future climate risks, effective adaptation will significantly reduce potential harms to the State. Figure 1-3 compares the costs of inaction to adaptation costs for each scenario and time period.[6]

Figure 1-3. Annual Costs of Inaction and Adaptation Costs by Emissions Scenario

Summary of cost of inaction (first set of bars, in dark blue) and adaptation costs (second set of bars, in green) per year, above baseline. Results for three time periods and three emissions scenarios (defined as Intermediate [Intmd.], High, and Very High; see Section 2.2.2 for more details), averaged across six climate models. For comparison purposes, this figure excludes adaptation costs that address costs of inaction not quantified in this study and costs of inaction without quantified adaptation costs. For consistent interpretation across time periods, some results are estimated using interpolation between time periods.



These costs represent the subset of adaptation costs that *could be quantified* in this study. Not all future costs have been quantified due to lack of data, significant uncertainty, or complex modeling requirements that were outside of the scope of the study. This is especially the case in the Ecosystems category where adaptation actions are particularly site-specific and difficult to estimate and comprehensively valuing damages to ecosystems requires significant analysis and stakeholder

[6] Note that there are several specific costs (both costs of inaction and adaptation costs) where the analysis does not include the corresponding cost type – for example, the analysis includes projected costs of improving drainage and water storage on farms in response to increasing soil moisture but does not include an estimate of productivity losses when soil moisture makes it difficult for machinery to work the fields during critical planting seasons. To allow for a better comparison between the two sets of cost, these "unpaired" estimates are excluded from the figure.

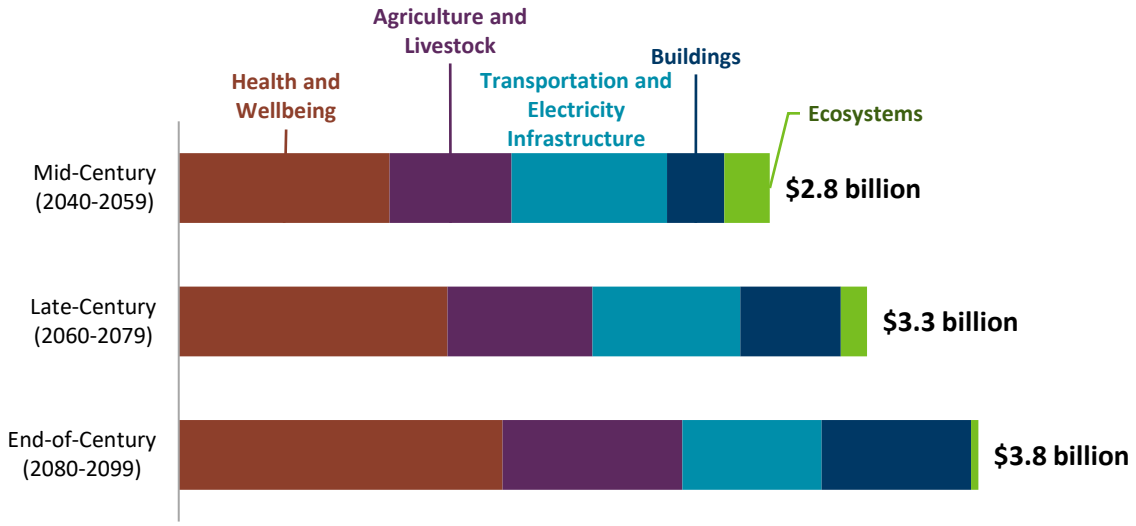
engagement. Throughout the study, non-quantified costs are discussed through qualitative descriptions of those costs and/or as limitations in the cost estimates provided.

As shown in Figure 1-4, adaptation costs increase over time as climate stressors worsen, but significant investment by Mid-Century is needed to reduce the impacts of climate change on people and communities. Earlier investment (i.e., before Mid-Century, pre-2040) will also help reduce impacts, though earlier costs are not included in this study. For reference, projected annual adaptation costs by Mid-Century are less than one percent of Minnesota's estimated 2024 annual GDP of just over $500 billion.[7]

1.2.4. Adaptation costs by impact category

Quantified annual adaptation costs for most cost categories increase over time as climate hazards increase, though long-lived proactive road adaptation investments (within the Transportation and Electricity Infrastructure category) early in the study period result in declining adaptation costs over time. Building-level flood adaptation, on the other hand, increases over the study period, and by End-of-Century, projected flood-related adaptation costs (buildings and basements) exceed road adaptation costs. The quantified annual Ecosystem adaptation costs decrease over time as well, though adaptation costs are likely underestimated, particularly in later time periods. The majority of quantified adaptation costs in the Ecosystem category represent adaptation to a select set of invasive species that are currently flagged as concerns. By the End-of-Century, however, there may be additional species rising to similar levels of concern which are not currently identified, but which might require additional adaptation response.

Figure 1-4. Quantified Annual Adaptation Costs for the High Emissions Scenario by Cost Category
Quantified annual costs (2024$) by category for the High emissions scenario in each time period. For consistent interpretation across time periods, some results are interpolated between time periods.



Each of the adaptation categories includes costs for multiple types of action or investment. Figure 1-5 provides a breakdown of annual costs in the Mid-Century, High emissions scenario, by action. For this scenario and time period, projected annual adaptation costs are highest in Health and Wellbeing, with

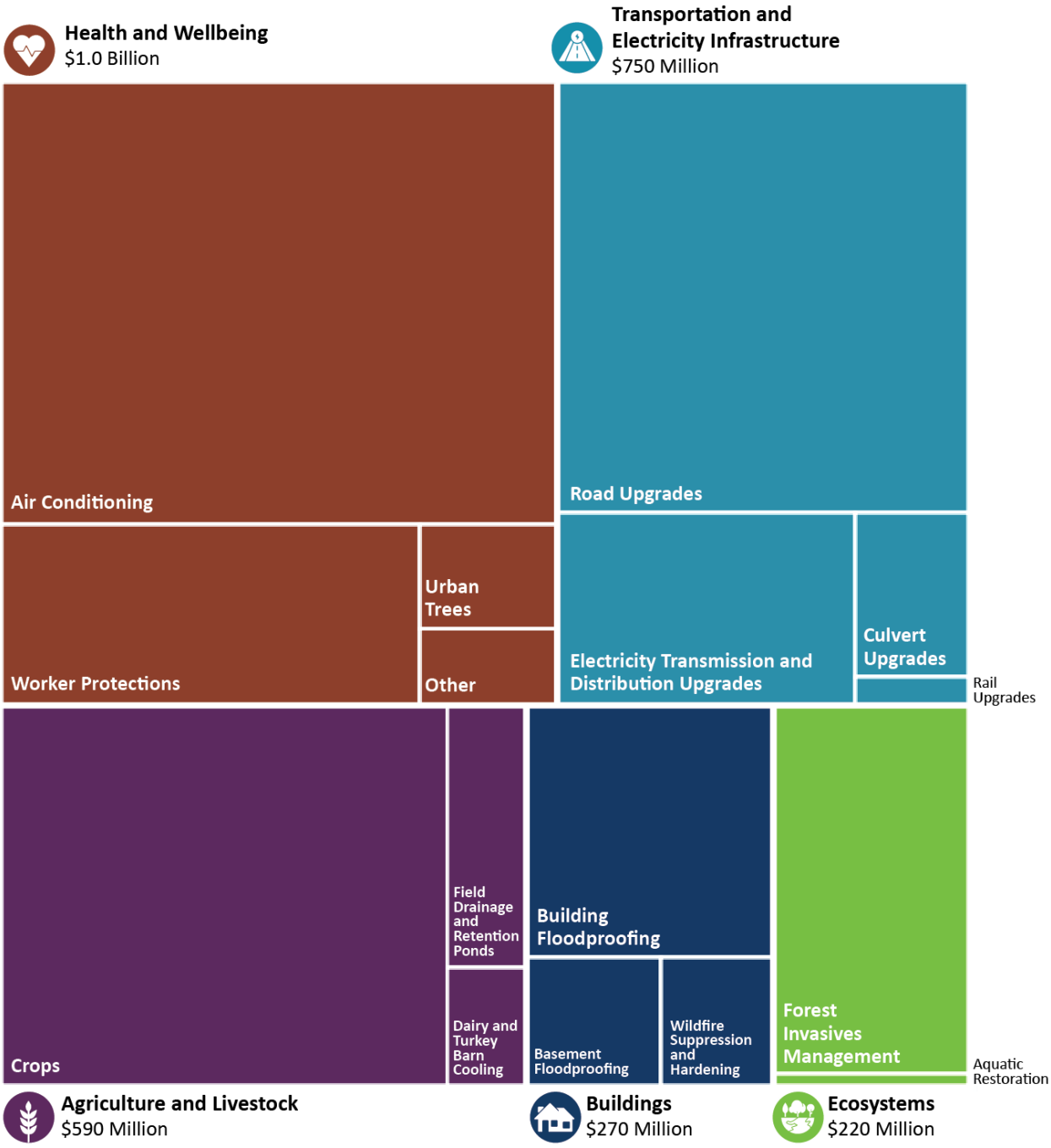
[7] Source for 2024 GDP estimate: https://mn.gov/deed/data/economic-analysis/compare/compare-minnesota/economy/gdp.jsp - data derived from U.S. Dep't of Commerce, Bureau of Economic Analysis.

air conditioning in homes, schools, and other public commercial buildings being the single largest investment quantified. The next largest category is Transportation and Electricity Infrastructure, where investment in road upgrades is the second largest investment overall.

The share of total costs per action shifts over time – by End-of-Century, projected floodproofing (building and basement) and irrigation costs both exceed road adaptation costs. Air conditioning remains the largest single investment category across all time periods.

Figure 1-5. Quantified Annual Adaptation Costs by Action and Cost Category, High Emissions Scenario, Mid-Century

Annual quantified adaptation costs (2024$) by category and action.



1.2.5. Cost of inaction by impact category

Investing in adaptation reduces costly risks to the state and its residents. The costs of inaction include a variety of impacts, monetized with different methods, depending on the type of impact measured. The largest portion of the cost of inaction is premature mortality – from heat and air quality – which makes up about half of the quantified cost of inaction. Mortality is valued using the Value of a Statistical Life (VSL), which represents what society is willing to pay to reduce mortality risk. In the scenario shown in Figure 1-6, the value of increased mortality is about $10 billion per year, representing 450 additional deaths per year.

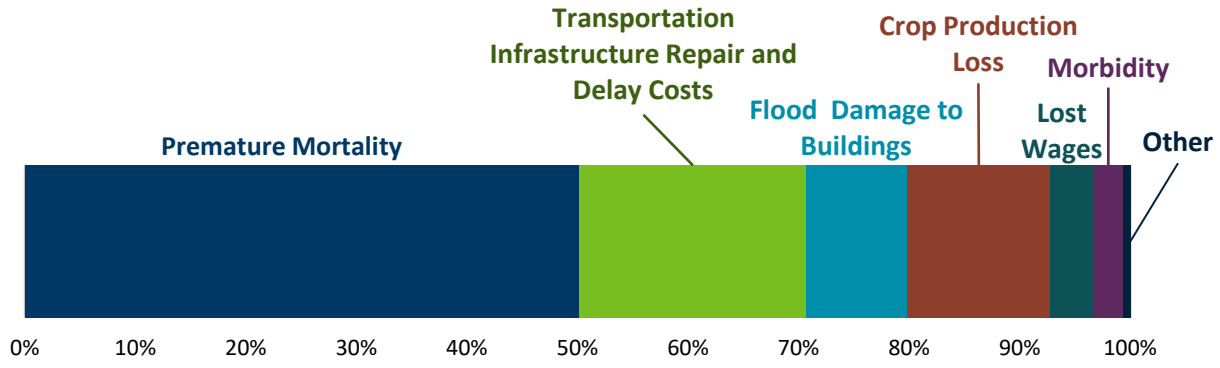
Cold-related premature mortality is projected to decrease as temperatures warm. However, this study aims to quantify the costs of adaptation to climate change, and therefore does not include potential cost savings from decreased mortality from warming winters because these benefits do not trigger significant adaptation costs (see Section 4.1 for further discussion).

Other major quantified impacts include:

- Transportation infrastructure (road and rail) repair costs, and user delays during closures for repairs,
- Flood damage to buildings,
- Crop production loss from increasing water deficits (limited to corn, soybean, and wheat in this analysis),
- Lost wages from reduced outdoor worker activity on high heat days and projected future earnings losses from learning losses, and
- Cost of non-fatal health outcomes (morbidity) such as new cases of childhood asthma and Lyme disease.

Figure 1-6. Breakdown of Annual Costs of Inaction, Mid-Century, High Emissions Scenario

Summary of the breakdown of annual cost of inaction, above baseline, in Mid-Century (2040–2059) for the High emissions scenario, averaged across six climate models.



1.2.6. Residual risks and avoided costs

Investing in climate adaptation will not fully eliminate all future risks from climate change. For example, some individuals, specifically unhoused populations and outdoor workers, will still experience significant heat exposure and adverse effects even when buildings are cooled. Floodproofing offers another example; it is not feasible to protect every home in the state against extremely low-probability flood events (e.g., a flood that may occur once every 10,000 years), leaving some risk remaining after

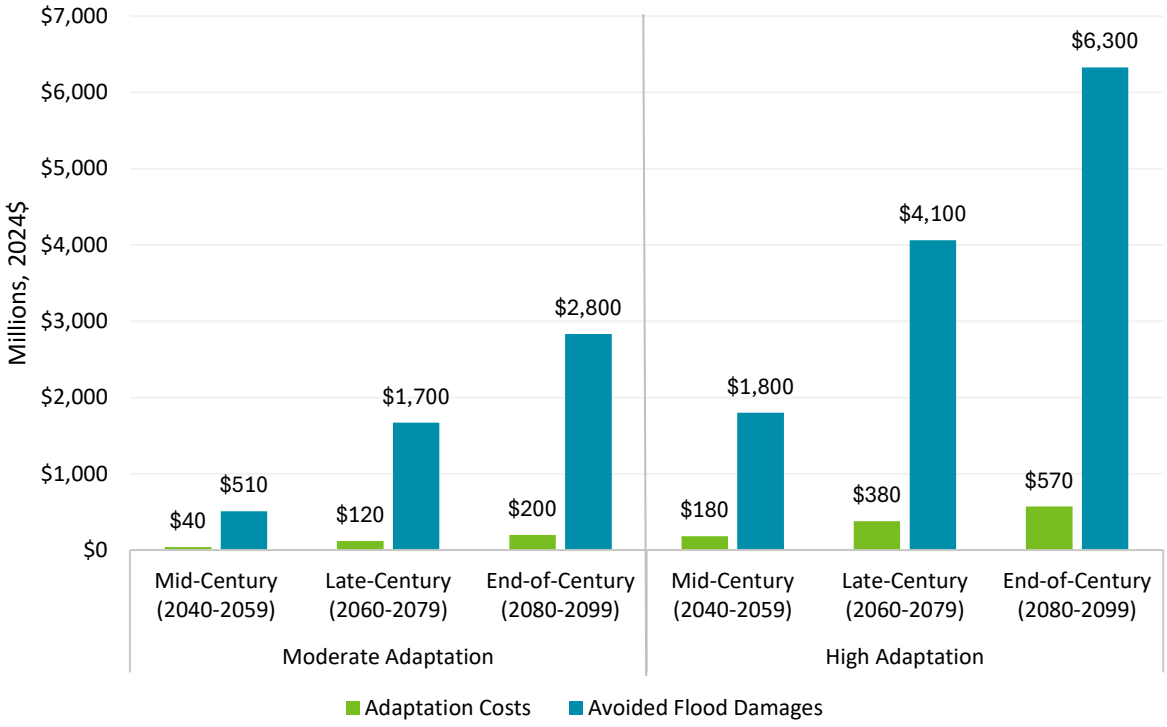
adaptation. Where possible, this study reassesses projected climate impacts with adaptation in place to quantify the residual risk, or the impacts projected to remain even with adaptation investment.

The difference between the costs of inaction and the residual risk can be interpreted as the avoided costs, or the benefits, from adaptation actions. Figure 1-7 provides an example of flood damages avoided by investing in elevating and/or floodproofing buildings at risk for two levels of investment (moderate and high adaptation), for the High emissions scenario. Even in the earliest time period and at the moderate adaptation level, investment saves about a half billion dollars per year. By End-of-Century, avoided costs reach $2.8 to $6.3 billion for moderate and high adaptation levels, respectively.

This study was not able to quantitatively measure the reduction in risk for all impact and adaptation action combinations. However, the avoided impacts from adaptation in the four analyses where this was possible (flooding damages and protection, crop productivity and irrigation, road damages and upgrades, and dairy productivity and barn cooling) exhibit the potential for cost-effective adaptation investment. Evidence suggests adaptation in the remaining categories, especially for heat and air quality impacts, is likely to be highly effective as well, further supporting adaptation as a good investment.

Figure 1-7. Annual Avoided Costs and Adaptation Investments: Flood Protection Example

Annual avoided costs (millions, 2024$) reflect the difference between costs of inaction (with no additional adaptation) and residual risk (with adaptation). The presented results reflect the High scenario. See Section 7.1 for more details on the two adaptation levels.



1.2.7. Key limitations and uncertainties

Overall, the study likely underestimates both the costs of inaction and the costs of adaptation. The study highlights other non-quantified costs of inaction, and adaptation measures which are likely to be cost-effective but could not be quantified at this time. Further, this study focuses on the direct costs of climate change, but there are also numerous indirect costs of inaction that are not quantified here, such as effects on business interruption and impacts to industries that support or rely on a productive agricultural sector, reliable transportation and electricity infrastructure, safe buildings, a healthy

workforce, and healthy ecosystems. There is also the potential that technological innovations over time may reduce the cost to adapt or effectively eliminate some relevant risk within all cost categories analyzed. For example, the availability of a vaccine for Lyme disease could substantially reduce the impacts of those infections, or advances in heat pump or geothermal technology could reduce the cost of cooling homes, schools, and other buildings.

The investments described in this study as adaptation efforts serve to resolve climate impacts to return to baseline or present-day conditions. This does not imply that the conditions of today are optimal or good for all communities across Minnesota.

Many assumptions are necessary to generate these estimates, but where made, these assumptions are usually conservative, meaning the reported costs are most likely underestimates. This study clearly documents assumptions made and the potential bias of each assumption – see the *Limitations and Uncertainties* sections in each results chapter (Chapters 4 through 8) and the *Sources of Uncertainty* tables in Appendix B. The Appendix B tables provide key assumptions and/or sources of uncertainty, the direction of potential bias on adaptation costs (underestimate/overestimate/unknown), and the likely effect of the uncertain on results (minor/major/unknown).

2. Calculating the costs of climate change in Minnesota

2.1. What are the costs of climate change?

2.1.1. Types of climate change impacts and the costs of inaction

Minnesota has already experienced the types of impacts that can be expected from future climate change. The box below on the impacts of the July 2011 heat wave provides just one historical example of how heat can affect human health and multiple sectors of the economy, including roads, agriculture, and livestock.

Impacts of the July 2011 heat wave

July 2011 brought record-breaking extreme heat to Minnesota, most notably during a heat wave from July 17–20. In addition to many "routine" record-breaking high temperatures and warm low temperatures across the state, this four-day heat wave was particularly notable for its high humidity, with the Minneapolis–St. Paul International Airport observing a record 82°F dew point on July 19. On the same date, Moorhead, MN set two Minnesota records as a state-record 88°F dew point combined with a 93°F temperature combined to produce an also-state-record 134°F heat index that easily cleared the previous record of 124°F.

While the event fortunately didn't result in as widespread human life loss as other remarkable Midwestern heat waves (such as the 1995 Chicago heat wave estimated to have resulted in approximately 700 deaths), it was impactful nonetheless. Nearly 800 people in the metro region were treated in the emergency department or hospitalized for heat-related illness with multiple fatalities reported. Infrastructure was impacted with the Minnesota Department of Transportation (MNDOT) reporting numerous points of road buckling, including on I-94 in Minneapolis. The heat wave also led to substantial agricultural losses with more than 100,000 turkeys and 1,500 cattle perishing, resulting in an estimated economic cost of $1.1–1.6 million.

Natural hazards such as heat waves happen without climate change, but a change in frequency and/or intensity of these hazards is a consequence of climate change. The changes in natural hazards resulting from climate change have real economic implications. Some examples of direct impacts of climate change include:

- Medical treatment costs of sickness associated with extreme heat and air pollution;
- Lost crop and livestock productivity;
- Damaged roads, culverts, and electricity infrastructure;
- Flooded or wildfire-damaged buildings; and
- Natural ecosystems that are damaged to the point where they no longer support recreational activity or provide other important flood protection or water quality services.

The impacts of climate change are not limited to these examples of direct impacts, however. There are also countless indirect impacts of climate change. Some examples include the lost productivity of workers who are sickened by extreme heat events; lost revenue from businesses that support the agricultural and forestry economies in the state; the extra time travelers must spend navigating around

damaged roads; the difficulties presented by power outages if electric infrastructure fails; and the business interruptions caused by flooding of a wide range of business locations. Some of these indirect impacts are included in the costs of inaction in this study, but others are more difficult to estimate or require additional data or methods which could not be readily accessed for this analysis. Where not quantified, these indirect impacts are discussed qualitatively.

The costs of inaction associated with climate impacts are borne by Federal, state, local, and tribal governments; private entities; and individuals. The tools used in this study measure a range of losses to these actors: changes in expenditures for things like snowmobile trips, lost wages, and also economic welfare, which is a term economists use for things that affect people but are not traded in markets – such as the pain and suffering associated with adverse health effects, or effects on cultural values and Indigenous lifeways. The costs of inaction in this study include costs to all potential payers. Each results section in Chapters 4 through 8 includes a section that discusses the distribution of costs across payers (see *Who bears the costs of inaction?*).

The methods used in this study to estimate economic impact provide results in several ways. Some costs are estimated in terms of market impacts, such as the crop revenue lost when there is insufficient irrigation water, the medical cost to treat an illness, or the expense to repair a road or bridge damaged by a natural hazard. In other cases, well-established methods have been applied to estimate economic impact where no market transaction takes place, such as when an individual dies prematurely from a climatic hazard or when water quality is impaired. In cases where no market price is available to provide a valuation estimate, the method to estimate economic impact involves the use of welfare economic techniques. Welfare economic techniques estimate what individuals would be willing to pay to avoid the risk of an undesirable outcome. The welfare economic methods applied in this study are well-established in the economics profession and are supported by a wide range of peer-reviewed literature – their application represents standard practice for valuation of the adverse impact.

2.1.2. Types of adaptation costs

Adaptation is most often undertaken to alleviate a specific undesirable impact. The adaptation is, therefore, adopted or planned in response to the impact. In most of the literature used to estimate adaptation costs in this study, adaptation takes two broad forms:

- **Reactive response:** Defined as the costs incurred to respond or react to the impacts of natural hazards. The reactions might be subtle, almost automatic shifts in behaviors, such as farmers changing planting dates or irrigation patterns. Reactive responses could also involve an expected, but more frequent and costly, response, such as repairing roads or treating heat-stress victims more often.
- **Proactive adaptation:** Defined as a forward-looking approach to investing in resilience, which usually involves advanced planning; changing standard operating procedures; investment in new infrastructure or upgraded equipment, sometimes with long-term financing; and often coordination of multiple actors and actions.

The goal in this study is to provide estimates for proactive adaptation. In Chapter 7 (Transportation and Electricity Infrastructure), however, the available methods and data also make it possible to report estimates for both reactive and proactive adaptation responses to the impacts of climate change. The chapter concludes that proactive adaptation is more cost-effective than reactive response, even though it requires more investment in early years to achieve the largest resilience payoff. All aggregations of adaptation costs presented in the report reflect proactive adaptation costs for these cost categories.

It is also possible to structure adaptation to take best advantage of positive impacts of climate change. Examples of this kind of adaptation include facilitating warm season recreation as climate change

extends spring, summer, and fall; or providing additional medical support or building improvements to ensure that a shortened winter results in improved longevity and fewer winter season communicable illnesses. This study does not focus on potential positive impacts of climate change. These potential benefits of climate change may be realized regardless of adaptation action, although some could also be enhanced through new investments.

The methods applied yield estimates of the direct cost of the identified adaptation actions, including both annualized capital costs and ongoing annual operating costs. The study focuses on statewide costs, but for many of the analyses it is possible to show county-level adaptation cost results as well. Some of the county-level results are provided in maps in Chapters 4 through 8.

Importantly, the costs of adaptation are borne by a wide range of actors – Federal, state, local, and tribal governments; private entities; and individuals.

2.1.3. Classes of adaptation costs not estimated in this study

The methods used in this study yield a multi-sectoral projection of the cost of adaptation measures that, if implemented, could cost-effectively mitigate the projected impacts of climate change in Minnesota. Nonetheless, some categories of a full accounting of adaptation costs are omitted from this study. These include the following:

- **Financing costs** and the **costs of acquiring funding** (for example, the costs of grant writing). Many of the adaptation measures involve investments in new or upgraded capital stock, which typically require public or private financing. Costs for the interest on loans or bonds that might be necessary to fund these measures are omitted, primarily because the terms of finance faced by the actors involved in implementing adaptation measures vary widely by industry, entity type (business, government, household, individual), and other factors. In addition, the costs of staff and individual time within these entities to secure financing have not been estimated.
- **Costs of planning.** Proactive adaptation can involve advanced planning, technical analyses, coordination of activities with other entities, and permitting. Time spent studying, information gathering, and planning adaptation are not included in the estimates presented here, except for partial quantification of costs for extreme heat planning.[8]
- **Cost of developing partnerships, institutions, and governance structures** that support and enable effective actions. Stakeholders engaged through the course of this study pointed out that significant hidden costs are often missed in existing models of adaptation costs, and that these activities should be resourced going forward to use adaptation funds effectively. These hidden costs include the staff time required for interagency coordination and the administrative burden of navigating fragmented grant systems.
- **Changes in costs over time.** The study is rooted in the knowledge base of technologies available at the time this analysis was developed. Estimates reflect well-established, mature technologies where information is available to support cost estimates. Nonetheless, technology is always advancing, and it is reasonable to expect that the threat of large costs of inaction provides a strong incentive to develop new, better, and less expensive technologies to adapt. Even for established technologies, the "learning-by-doing" phenomenon suggests that costs decline over time as the product volume scales up over time. The effect of technological change over time is not modeled in this study.

[8] The Health and Wellbeing (Heat) category does include an adaptation cost for heat and resilience plan development. The included cost ($4.6 million per year) is not sufficient to cover all resilience planning in the state.

- **Economy-wide indirect costs and benefits.** Costs incurred and benefits realized in one sector can have ripple effects across other sectors of Minnesota's economy. For example, investments in a more climate-resilient electric grid could involve increases in electricity rates that affect many businesses and households and alter the way they conduct their activities. At the same time, a more reliable electricity delivery system provides broad-based benefits for these same businesses and households. Estimating the indirect, economy-wide implications of these adaptation investments is a complex task which is outside the scope of the current study.

2.2. How this study measures the costs of climate change

Beginning August 2025, MPCA and the consultant team (together defined as the Project Team) worked closely to define the scope and methods for the analysis. This study relies on peer-reviewed literature and methodologies, and on-the-ground information solicited from over 220 stakeholders representing a broad range of geographies and perspectives across the state. The following sections first provide an overview of the stakeholder engagement process that supported this study, then additional details of the three primary analysis steps: characterizing future climate hazards, quantifying costs of inaction, and quantifying adaptation costs.

2.2.1. Overview of stakeholder engagement

Figure 2-1 provides an overview of the study timeline and key touchpoints with stakeholders. First, the Project Team presented stakeholders with an overview of the projected climate hazards and the results of a screening-level assessment of projected climate impacts. Using feedback learned during the first wave of engagement, the Project Team performed more detailed analysis on the climate impacts (i.e., costs of inaction) and began scoping the climate adaptation cost analysis. During the second wave of engagement, the Project Team reported back to the stakeholders on the finalized climate impact analysis and presented proposed methods for adaptation costing. Stakeholders offered feedback on the adaptation costing methods and provided information and data to further refine the calculations. Finally, the Project Team brought the work together into a final report and supporting materials for dissemination.

Figure 2-1. Study development timeline

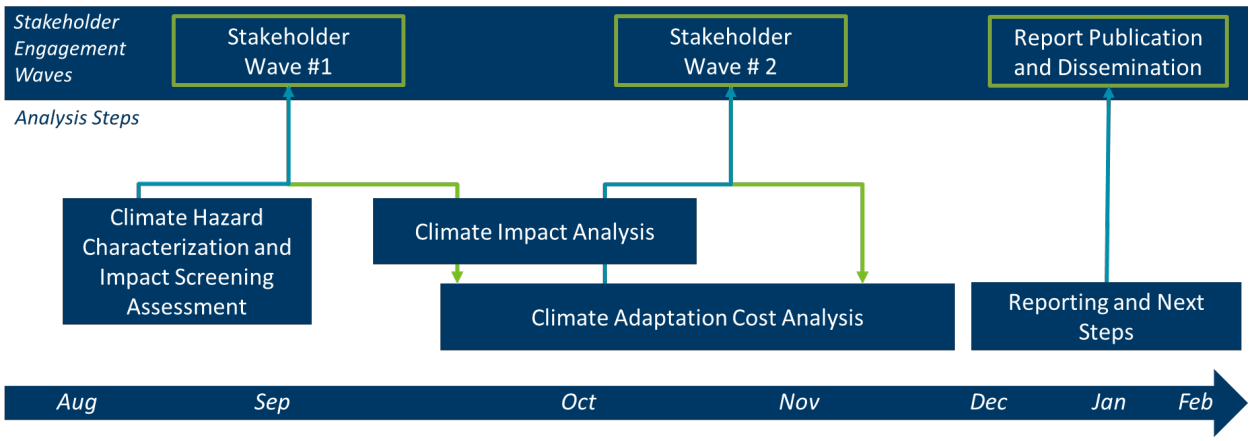
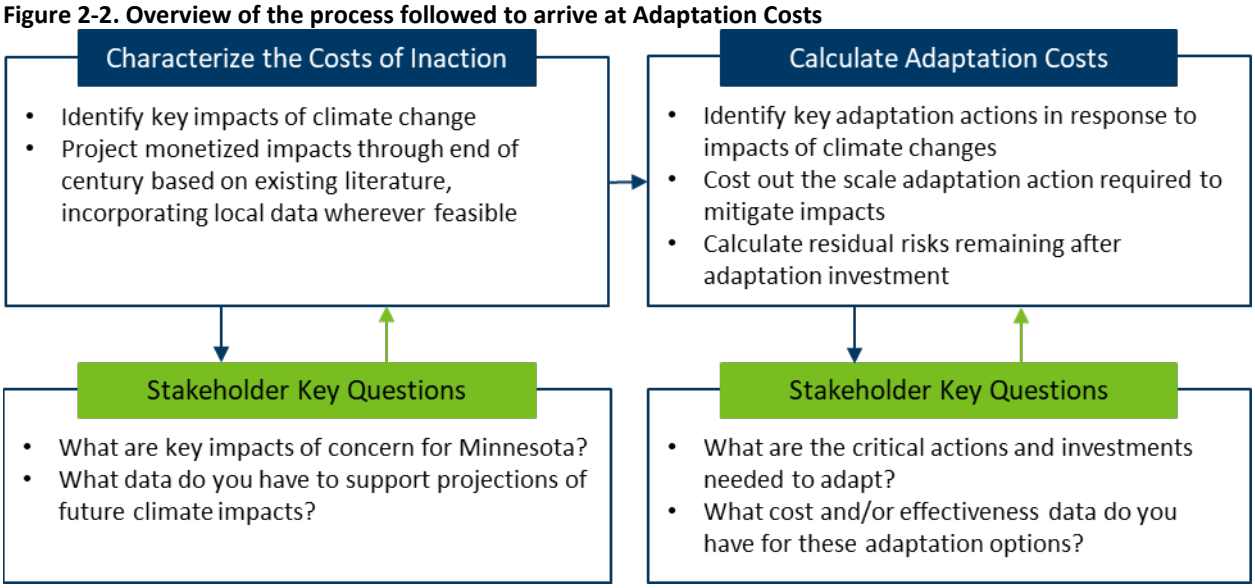


Figure 2-2 provides more details on the types of information elicited from stakeholders during plenary sessions, sector-based follow-up meetings, and one-on-one conversations. See Appendix A for more details on the stakeholder engagement process.

Figure 2-2. Overview of the process followed to arrive at Adaptation Costs



2.2.2. Characterizing future climate hazards

This analysis considers three future emissions scenarios, consistent with the scenarios included in the Minnesota Climate Mapping and Analysis Tool (MN CliMAT):

- **Intermediate scenario** (SSP2-4.5)
- **High scenario** (SSP3-7.0)
- **Very High scenario** (SSP5-8.5)

Each of these scenarios reflects different social and economic factors that will significantly impact future global greenhouse gas emissions trajectories, such as population growth, urbanization, economic growth, technological advances, biogenic and anthropogenic greenhouse gas and aerosol emissions, energy supply and demand, land-use changes, and more.[9] MN CliMAT analyzes the three selected scenarios to give a range of likely futures. Note that the low emissions scenario was not included because the Intergovernmental Panel on Climate Change (IPCC) reports indicate it is increasingly unlikely.[10]

What are SSPs?

- This analysis relies upon Coupled Model Intercomparison Project Phase 6 (CMIP6) climate data, downscaled for use in Minnesota by the University of Minnesota Climate Adaptation Partnership (MCAP).
- SSP stands for Shared Socioeconomic Pathway, the name for the five different emission scenarios created to guide simulations within CMIP6. SSPs reflect assumptions about how industrialization, fossil fuel dependence, land use, and population density, evolve in the future.

For more information see MCAP's Climate Model Primer

For each SSP, MN CliMAT provides temperature and precipitation projections from six climate models referred to as global climate models (GCMs). These models simulate future climates to reflect potential

[9] Clark, S., Roop, H.A., Meyer, N., Liess, S., Mosel, J., Hoppe, B., and Farris, A. (2023). Climate modeling: an introductory primer for practitioners. Report prepared by the University of Minnesota Climate Adaptation Partnership, Saint Paul, Minnesota. (version 1; May 2023). https://hdl.handle.net/11299/257948.

[10] IPCC, 2022: Summary for Policymakers [H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (eds.)]. In: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3-33, doi:10.1017/9781009325844.001.

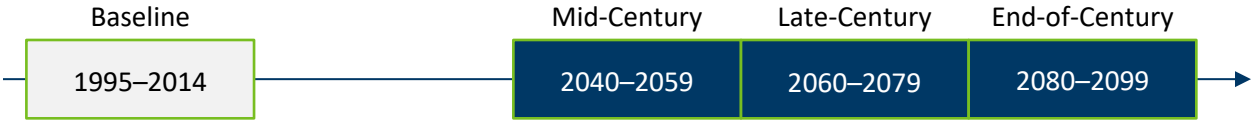
outcomes associated with each SSP. The range of outcomes across climate models reflects the uncertainty in how various emissions levels may manifest in terms of patterns of temperature and precipitation, among other climate outcomes. For more information on the climate data used in this analysis, see the University of Minnesota Climate Adaptation Partnership's (MCAP's) Climate Model Primer[11] and the MN CliMAT documentation.[12]

The cost of inaction and adaptation cost analyses use daily climate data from MN CliMAT, aggregated to the county level for consistency with other impact and costing model inputs. Example climate variables used in these analyses include daily average temperatures and daily precipitation amounts.

This study considers three future time periods, each representing 20-year time periods, as shown in Figure 2-4, consistent with the definitions used in MN CliMAT and the enabling legislation. The findings in this study represent average annual costs across the years included in each time period, above the average annual costs in the baseline period. Consistent with the language of the enabling legislation, this study is limited to consideration of costs starting in the Mid-Century period and does not consider costs for the current period through 2039.

Figure 2-3. Time periods of the analysis

This study analyzes annual climate costs averaged over three future time periods as shown in this figure. All costs presented are incremental to the historical baseline.



Chapter 3 presents an overview of the climate change hazards in Minnesota as modeled in MN CliMAT.

2.2.3. Quantifying costs of inaction

The quantified costs of inaction provide important context for the risks faced if further investment in climate adaptation is not taken. The costs of inaction quantified in this study use peer-reviewed literature on well-established pathways linking climatic hazard exposure to monetized impacts. To complete the broad, multi-sectoral analyses required within time and resource constraints, the majority of the results presented rely on existing models, methods, and data, but in several instances new analyses have been performed to fill potentially important gaps in existing literature.

Quantifying the costs of inaction began with EPA's Framework for Evaluating Damages and Impacts (FrEDI) tool. FrEDI is a reduced complexity model that projects the physical and economic impacts of future temperature changes within the United States at the state level for a broad range of economically and socially important impacts, including over 20 impacts relevant in Minnesota. FrEDI underwent a peer- and public-review process and draws heavily on peer-reviewed climate impacts literature. The

FrEDI Tool

U.S. EPA's FrEDI tool projects climate impacts at the state level for any climate scenario, defined by changes in temperature. FrEDI underwent a peer- and public-review process and draws heavily on peer-reviewed climate impacts literature.

For more information see U.S. EPA's FrEDI website.

[11] Clark, S., Roop, H.A., Meyer, N., Liess, S., Mosel, J., Hoppe, B., and Farris, A. (2023). Climate modeling: an introductory primer for practitioners. Report prepared by the University of Minnesota Climate Adaptation Partnership, Saint Paul, Minnesota. (version 1; May 2023). https://hdl.handle.net/11299/257948.

[12] https://docs.google.com/document/d/1fB9jtQRQDLX4rbdhl4_w5IPAdvaNWVFT/edit

FrEDI tool calculates annual climate impacts by impact type and state based on an input temperature change trajectory (average annual temperature for the contiguous U.S.), which in this case are the temperature trajectories for each SSP-climate model combination from MN CliMAT described in Section 2.2.2.

The first step in the costs of inaction analysis was a screening assessment using the FrEDI tool. The results of the screening analysis were reviewed by the analysis team and discussed with stakeholders to identify 1) important impacts missing from the FrEDI results, and 2) impact categories that would benefit from additional refinement through, for example, modeling at a finer spatial scale or inclusion of Minnesota-specific literature and data. Table 2-1 summarizes the approaches used for each of the quantified costs of inaction in this study. Many of the new, non-FrEDI analyses reflect stakeholder input that stressed the need for updated analyses for resources of particular importance to Minnesota that appear threatened by climate change. In some cases, non-FrEDI analyses are from recent peer-reviewed literature that has not yet been incorporated in FrEDI. An example is a 2025 study of the impacts of wildfire on air quality which significantly updates an older study that is in FrEDI. The new study includes impacts of Canadian wildfires that was not addressed in the older study. See Appendix B for detailed information on the methods used in each analysis to quantify costs of inaction.

Table 2-1. Summary of Cost of Inaction Quantification Approaches

FrEDI-Based Costs of Inaction	Non-FrEDI Costs of Inaction
Health and Wellbeing • **Heat.** Premature mortality,* student learning loss, lost labor participation • **Air Quality.** Climate-induced: ozone mortality, ED visits, ozone school days lost, ozone childhood asthma • **Vector-Borne Disease.** Lyme disease morbidity **Transportation and Electricity Infrastructure** • **Transportation.** Road and culvert repair and user delay,* rail repair and user delay • **Electricity.** Transmission and distribution infrastructure damage and repair **Ecosystems** • **Terrestrial Ecosystems.** Timber carbon flux, timber production losses,* lost activity opportunities: other activity (bike, hunt, hike, run), snow sport, alpine skiing, cross-country skiing, snowmobiling • **Aquatic Ecosystems.** Lost activity opportunities: recreational fishing, water sports	**Health and Wellbeing** • **Heat.** Pediatric Emergency Department (ED) visits • **Air Quality.** Wildfire (fine particulate matter ($PM_{2.5}$)) mortality • **Vector-Borne Disease.** West Nile virus mortality and morbidity **Agriculture and Livestock** • **Crops.** Lost corn, soybean, and wheat yields • **Livestock.** Decreased dairy production **Transportation and Electricity Infrastructure** • **Transportation.** Culverts repair and user delay **Buildings** • **Flooding.** Pluvial and fluvial building damages • **Wind and Wildfire.** Structure damage, wildfire suppression **Ecosystems** • **Aquatic Ecosystems.** Water quality, harmful algal blooms

*Indicates costs where FrEDI outputs were adjusted for this analysis.

In addition to the costs of inaction listed above, stakeholders highlighted several other impacts that are not quantified in this study. These impacts were not quantified for several reasons, including lack of clear evidence linking the impact to climate change and absence of available models of evidence-supported linkages. When determining where to focus efforts for non-FrEDI analyses, the expected magnitude of potential new impacts was considered in the context of the scope and objective of the study. Impacts with relatively small expected costs of inaction, that would not substantively change the main findings of the study, were given lower priority for further analysis.

The omission of an impact from the quantified cost of inaction does not necessarily mean the impact will be small. For example, hail damages are not quantified. Hail damage has large baseline costs and there is some evidence to suggest that hailstorms may worsen with climate change. However, the evidence is currently insufficient to reliably quantify a projection. In addition, even small magnitude (in the context of statewide costs) impacts can be highly meaningful in particular areas of the state or to specific populations and industries. This study includes qualitative discussions of unquantified costs throughout the results chapters and notes the omission of unquantified costs in all key findings summaries.

2.2.4. Quantifying adaptation costs

The primary objective of this study is to quantify adaptation costs. The impacts analyzed in the previous step serve as indicators of where adaptation action is most needed to reduce large costs of inaction. Using this framework, the analysis team engaged stakeholders to identify the most promising adaptation actions to address the largest costs of inaction.

This study quantifies a subset of the full possible set of adaptation actions. The adaptation costs quantified in this study represent actions and costs where methods exist to justifiably scale adaptation need to the climate conditions under each emissions scenario, sufficient data is available to cost the action, and evidence suggests the action is reasonably effective in addressing the projected impacts. The quantified adaptation costs do not represent recommended actions. Rather, they reflect actions that are representative of type of response that could occur and that could be costed for this study.

While the literature includes many studies that quantify (in dollar terms) the impacts of climate change, fewer peer-reviewed studies exist for adaptation costing. Each quantified adaptation cost in this study is the result of one of the following calculation methods.

- **Costs of inaction and adaptation costs are modeled together in the underlying study.** Some of the studies and methods used to quantify costs of inaction also calculate adaptation costs (for example, the roads and rail models). In these cases, the underlying study provides adaptation costs that reflect decision-making in response to anticipated impacts for the modeled scenario.
- **Quantified costs of inaction define the adaptation need.** Some adaptation costs are scaled based on the quantified costs of inaction. For example, floodproofing costs are a function of projected flooding damages. This reflects how a property owner will choose to invest in floodproofing when they expect the cost of adapting will be worth the avoided flood damages. A similar approach is followed to quantify irrigation expansion in response to crop yield loss. In both cases, a benefit-cost ratio threshold limits when investments are made to avoid including high adaptation costs for actions that are unlikely to be implemented.
- **Adaptation investments are made once climate conditions cross certain thresholds.** For some adaptation actions, the literature suggests climate thresholds at which people should adapt to avoid the majority of the costs of inaction. For example, studies suggest households should install air conditioning when they experience more than 15 days per year above 80˚F. In these cases, MN CliMAT data is used to estimate at what point adaptation investments will occur.
- **Adaptation is scaled based on increasing risk.** In the absence of data or methods to quantify adaptation costs using the above methods, future adaptation costs are projected by scaling current, documented spending proportionately to the change in risk. For example, future mosquito control costs reflect current annual spending, scaled in future years based on the projected rise in West Nile virus cases. Note this approach was only used when other methods were not possible because of known limitations of relying on current spending that is limited by available budget and for many reasons may not be adequate to address current risk.

Finally, where possible given data and modeling constraints, the final step is to calculate residual risk. Residual risk is only quantified across those impacts where evidence is sufficient to "optimize" the adaptation costs (crops, dairy, roads and culverts, and flooding). The optimization usually involves a life-cycle benefit-cost analysis to determine if the total cost of the investment justifies the benefits of climate risk reduction that adaptation provides. For all adaptation cost categories, residual risks are discussed, at least qualitatively, under the header *What residual risks remain after adaptation?* in Chapters 4 through 8.

3. Climate change in Minnesota

Minnesota is already experiencing the impacts of climate change, with warmer winters and summers, and increased annual precipitation. Analysis of climate projection data by MCAP shows these trends are expected to continue and become more extreme. This chapter first describes the historical, observed change in Minnesota's climate, then provides the projected changes in temperature and precipitation through the end of the century.

These physical changes in Minnesota's climate bring many impacts across human, natural, and built systems. For example, shifting patterns in temperature and precipitation increase the risk of flooding and flash drought, expand pest and disease pressure across natural and working lands, negatively impact human health and wellbeing through changes such as reductions in air quality and lengthened allergy seasons, and threaten culturally important ecosystem services.[13]

3.1. Observed climate change in Minnesota

Between 1895 and 2024, the average annual temperature in Minnesota has increased by 3.2°F.[14] This increase in temperature is driving changes in seasonal temperatures, decreasing the number of days per year with snow cover, increasing heavy rain events, and altering ecosystems across Minnesota. The warming trend has sharply accelerated in recent years: the years 2021, 2023, and 2024 are all in the top ten warmest on record in Minnesota.[15]

Winters have warmed faster than any other season in Minnesota. Average daily low temperatures in winter rose over 15 times faster than summer high temperatures between 1970 and 2024.[16] Since 1895, the state's average winter temperature has increased by 5.4°F and average winter low temperature has increased by 6.8°F. Average daily low temperatures have increased at more than twice the rate of average daily high temperatures.[17] **Minnesota has experienced the most significant winter warming of any state in the contiguous United States.**[18] Temperatures have not increased uniformly throughout the state. Northern Minnesota has seen a larger increase in average temperatures than southern and central Minnesota.

[13] Wilson, A.B., J.M. Baker, E.A. Ainsworth, J. Andresen, J.A. Austin, J.S. Dukes, E. Gibbons, B.O. Hoppe, O.E. LeDee, J. Noel, H.A. Roop, S.A. Smith, D.P. Todey, R. Wolf, and J.D. Wood, 2023: Ch. 24. Midwest. In: Fifth National Climate Assessment. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH24

[14] Climate trends. Minnesota Department of Natural Resources https://www.dnr.state.mn.us/climate/climate_change_info/climate-trends.html

[15] Ibid.

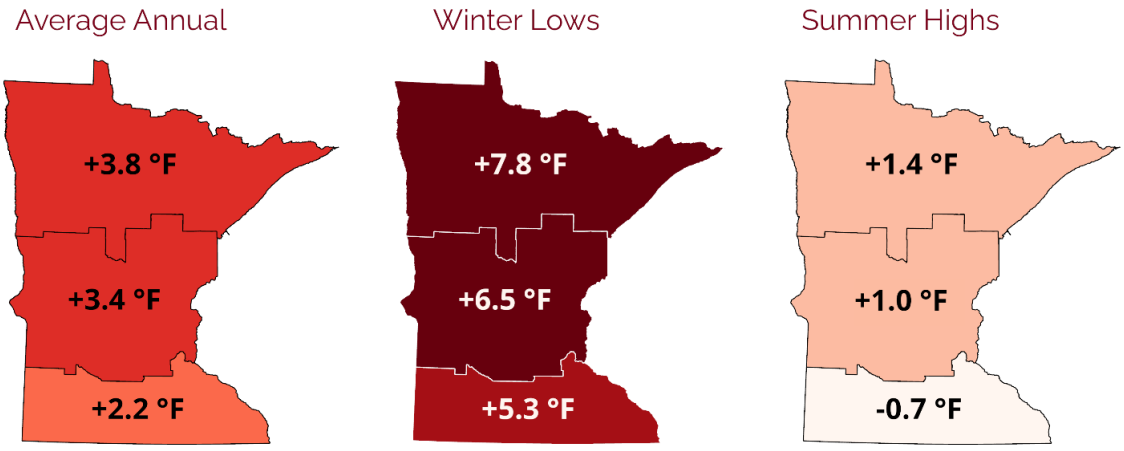
[16] Ibid.

[17] Ibid.

[18] NCEI. (2025). National trends temperature, precipitation, and drought. National Centers for Environmental Information (NCEI). Retrieved from https://www.ncdc.noaa.gov/temp-and-precip/us-trends/tavg/win

Figure 3-1. Observed Temperature Change, 1895–2025

Observed statewide temperature change between 1895 and 2025 in Minnesota. Temperature changes are shown for the annual average (left), the average winter low (center), and the average summer high (right).

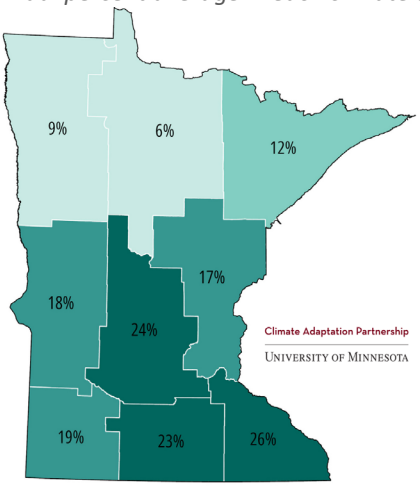


Source: University of Minnesota Climate Adaptation Partnership, 2025.
Data: Minnesota State Climatology Offices, 2025. Climate Trends in Minnesota. Accessed August 2025.

The timing and intensity of precipitation in Minnesota has also shifted. Minnesota's average annual precipitation has increased by 3.5 inches between 1895 and 2024.[19] The size of the heaviest rainfall of the year has grown by 13 percent, and the state is now experiencing more frequent and intense heavy rainfall events than ever recorded.[20] At the same time, Minnesota has experienced a rise in rapid transitions between wet and dry periods, resulting in flash drought conditions that increase moisture stress on both agricultural crops and native vegetation.[21]

Figure 3-2. Percent Change in Average Annual Precipitation, 1895–2024

Map of Minnesota showing percent change in total annual precipitation between 1895 and 2024 across Minnesota. Precipitation change is shown as the annual percent average in each climate division in Minnesota.



Source: University of Minnesota Climate Adaptation Partnership, 2025.
Data: Minnesota State Climatology Offices, 2025. Climate Trends in Minnesota. Accessed August 2025.

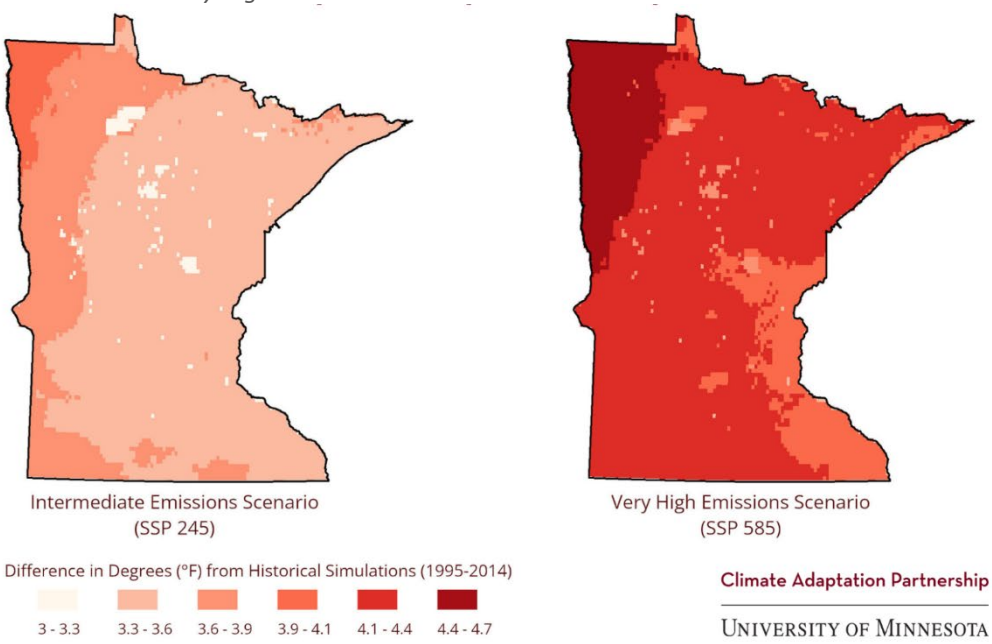
[19] Climate trends. Minnesota Department of Natural Resources https://www.dnr.state.mn.us/climate/climate_change_info/climate-trends.html.
[20] Minnesota is getting warmer and wetter | Our Minnesota Climate. https://climate.state.mn.us/minnesota-getting-warmer-and-wetter.
[21] Clark, S., Roop, H.A., Meyer, N., Mosel, J. (2023). Climate change and drought in Minnesota and the Midwest. Summary prepared for the University of Minnesota Climate Adaptation Partnership. Published October 2023 (v1).

3.2. Projected change in temperature

Future climate projections indicate Minnesota's average temperature will continue to rise, accompanied by increased humidity and greater seasonal variability.[22] By Mid-Century (2040–2059), the annual average daily maximum temperature in Minnesota is projected to increase between 3.6°F under an Intermediate emissions scenario and 4.2°F under a Very High emissions scenario[23] (all projected changes are relative to a 1995–2014 baseline).[24]

Like with observed trends, projected increases in wintertime lows are greater than projected increases in summertime highs. On average, daily minimum temperatures in the winter are projected to increase by 6°F and daily maximum temperatures in the summer are projected to increase by 4.9°F by Mid-Century under the Very High emissions scenario.[25]

Figure 3-3. Projected Difference in Average Annual Daily Maximum Temperature by Mid-Century (2040–2059)
Projected change in annual maximum temperature by Mid-Century relative to the historical baseline (1995–2014) under the Intermediate and Very High emissions scenarios.



Source: Liess et al., 2025.[26]

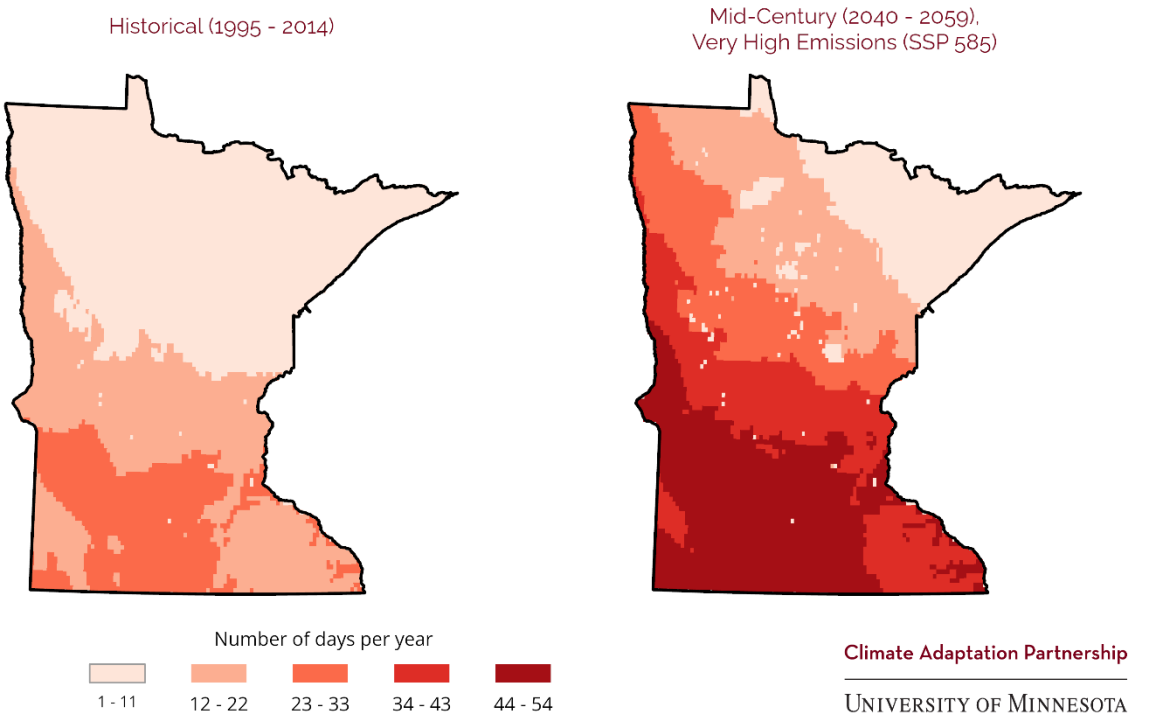
Warming could drive significant shifts in the state's seasonal extremes. Under the Very High emissions scenario, the number of days per year with minimum temperatures below freezing (32°F) could decline by nearly a month by Mid-Century, and by two months by End-of-Century.[27] During the summer months, temperatures exceeding 90°F are expected to increase significantly. By Mid-Century, the state is projected to experience 17 additional days per year above 90°F under the Very High emissions

[22] Liess, S., Roop, H.A., Twine, T.E., Clark, S., Coffman, D., Dolma, D., Farris, A., Fernandez, A., Gorman, J., Meyer, N. (2026): County-scale Climate Projections over Minnesota and the Effects of Lakes. Water Resources Research. *DOI: 10.1029/2025WR040415.* Available at: http://doi.org/10.1029/2025WR040415
[23] Ibid.
[24] See Section 2.2.2 for more details on the analyzed emissions scenarios and time periods.
[25] Liess, S., Roop, H.A., Twine, T.E., Clark, S., Coffman, D., Dolma, D., Farris, A., Fernandez, A., Gorman, J., Meyer, N. (2026): County-scale Climate Projections over Minnesota and the Effects of Lakes. Water Resources Research. *DOI: 10.1029/2025WR040415.* Available at: http://doi.org/10.1029/2025WR040415
[26] Ibid.
[27] Ibid.

scenario.[28] As with observed changes, warming is projected to vary across the state. For example, the average number of days per year above 90˚ F is expected to increase by 23 days in Minneapolis-St. Paul, seven days in Duluth, and 25 days in Fargo-Moorhead by Mid-Century under the Very High emissions scenario.[29]

Figure 3-4. Projected Number of Days per Year Over 90˚F, Historical and by Mid-Century

Historical (1995–2014) and Mid-Century (2040–2059) projected under the Very High emissions scenario number of days over 90˚F.



Source: University of Minnesota Climate Adaptation Partnership, 2025.

3.3. Projected change in precipitation

Precipitation changes are projected to vary by region, with the southeastern part of the state expected to see the largest increase in total annual precipitation. Climate projections indicate that by End-of-Century, under the Very High emissions scenario, this region could experience an additional 4.4 inches of annual precipitation (relative to 1995–2014).[30]

While annual precipitation is projected to increase overall, precipitation across Minnesota is also expected to become more intense, with more rainfall occurring in single events and longer dry periods in between.[31] Regionally, the Midwest is projected to experience the greatest increase in consecutive

[28] Ibid.
[29] Ibid.
[30] Ibid.
[31] Ibid.

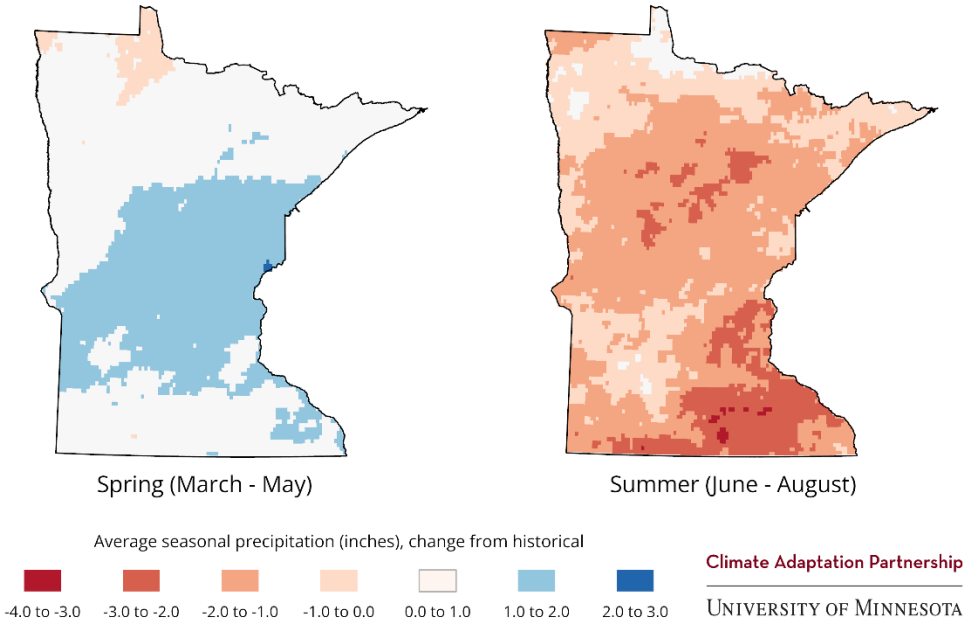
dry days in the U.S., with durations potentially extending by up to 25 percent by 2100.[32] Climate projections[33] suggest that Minnesota could experience faster transitions between wet and dry periods.[34]

The timing and intensity of precipitation is also expected to shift, with heavier rain events on average and longer dry spells without measurable rainfall.

Seasonal precipitation trends are projected to vary significantly, often with wetter winters and springs, drier summers, and shorter snow seasons. Climate projections indicate that by Mid-Century, the number of days per year with a snow cover depth greater than one inch is expected to decline by 12 (Intermediate emissions) to 15 (Very High emissions) days.[35]

Figure 3-5. Projected Change in Average Annual Precipitation by End-of-Century (2080–2099)

Map of Minnesota showing projected change in spring precipitation and summer precipitation by End-of-Century (2080–2099) relative to historical (1995–2014) under an Intermediate emissions scenario (SSP2-45).



Source: Liess, et al., 2025.[36]

[32] Clark, S., Roop, H.A., Meyer, N., Mosel, J. (2023). Climate change and drought in Minnesota and the Midwest. Summary prepared for the University of Minnesota Climate Adaptation Partnership. Published October 2023 (v1). https://hdl.handle.net/11299/257949.

[33] Ford, T. W., Chen, L. & Schoof, J. T. (2021). Variability and Transitions in Precipitation Extremes in the Midwest United States. https://doi.org/10.1175/JHM-D-20-0216.1.

[34] Clark, S., Roop, H.A., Meyer, N., Mosel, J. (2023). Climate change and drought in Minnesota and the Midwest. Summary prepared for the University of Minnesota Climate Adaptation Partnership. Published October 2023 (v1). https://hdl.handle.net/11299/257949.

[35] Liess, S., Roop, H.A., Twine, T.E., Clark, S., Coffman, D., Dolma, D., Farris, A., Fernandez, A., Gorman, J., Meyer, N. (2026): County-scale Climate Projections over Minnesota and the Effects of Lakes. Water Resources Research. *DOI: 10.1029/2025WR040415.* Available at: http://doi.org/10.1029/2025WR040415

[36] Ibid.

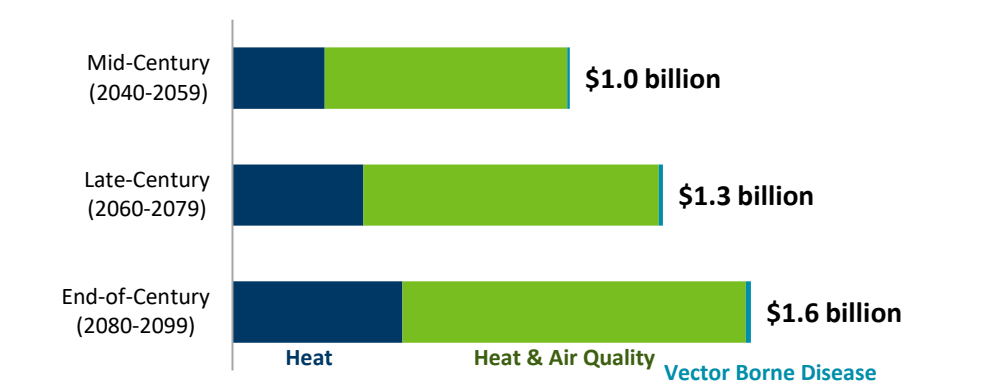
4. Cost of climate change: Health and Wellbeing

Key takeaways: Health and wellbeing

- Climate change will harm human health and wellbeing through many pathways. This analysis specifically considers the impacts associated with increased **heat** exposure, degraded **air quality,** and expanded conditions for **vector-borne diseases.** These climate hazards will lead to premature deaths, non-fatal illnesses and injuries, reduced learning opportunities for children, and decreased worker productivity in weather-exposed industries. This study quantifies the costs of various adaptation measures aimed at reducing these health and wellbeing impacts.
- Installing air conditioning in homes, schools, and other public buildings reduces exposure to heat and poor air quality, thereby reducing health risks and eliminating student learning losses. The costs of installing cooling technologies and the energy required to operate systems on hot days are expected to be substantial, exceeding one billion dollars annually by the end of century. While energy-efficient technologies have higher upfront installation costs, their energy savings during both warm and cool seasons offset these additional costs over the long term.
- This analysis quantifies several additional adaptation investments to limit climate-related health risks. Heat-related measures include implementing worker protections, maintaining tree canopies and playground shade structures in communities, opening cooling centers, and developing extreme heat response plans. Air quality measures include installing and operating air purifiers during poor air quality episodes. Finally, mosquito control programs reduce the transmission of vector-borne diseases.
- Additional adaptation needs not quantified in this analysis include investments in other green infrastructure to facilitate cooling, developing and implementing extreme heat early warning systems and education campaigns, reducing wildfires, using insect repellents, and implementing health surveillance.

Quantified Annual Adaptation Costs by Period (High Emissions Scenario)

These costs are incremental of baseline adaptation costs and only include the quantified adaptation actions.



Climate change plays a critical role in degrading human health and wellbeing through increased extreme weather conditions, worsening air quality, spread of infectious diseases, food insecurity, challenges to mental health, and destruction of infrastructure and health systems, as well as other hazards.

For example, extreme heat can lead to premature death from heatstroke and exacerbation of cardiovascular and respiratory diseases. It can cause illnesses and injuries that lead to hospital admissions and emergency department visits. Extreme heat and related climate conditions also increase air pollution. Ozone formation increases with more heat and sunlight, and fine particulate matter ($PM_{2.5}$) increases due to wildfire smoke. Both ozone and $PM_{2.5}$ degrade air quality and lead to additional adverse health effects. Changing temperature and precipitation change the geographic range and season for disease-carrying mosquitoes and ticks and speed up their life cycle, which leads to faster reproduction and allows them to proliferate and infect human hosts.

These impacts of climate change on health and wellbeing exacerbate existing social inequities and are thus of greatest concern to those who are already vulnerable such as older adults, people with preexisting diseases, children, and those in low-income or disadvantaged communities.

Table 4-1 lists the selected climate impacts on human health and wellbeing along with their associated potential adaptation actions. This study quantifies and costs the items in bold.

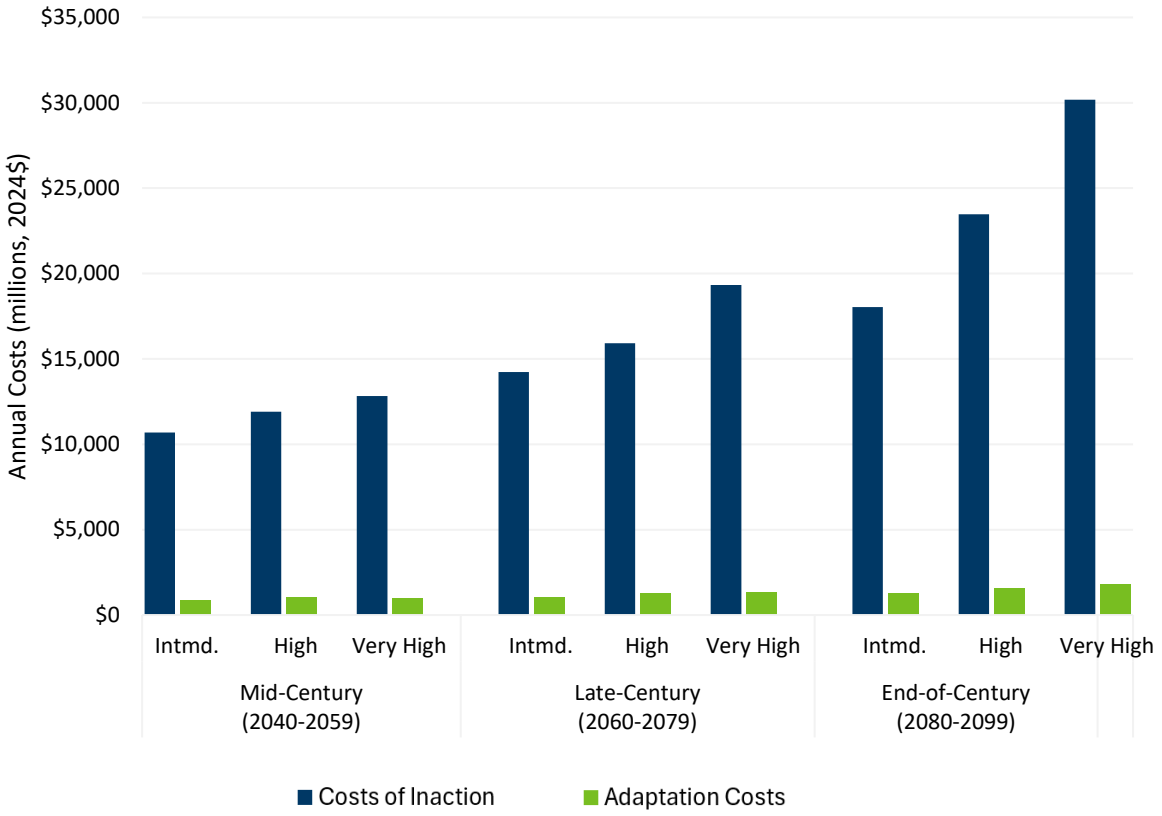
Table 4-1. Costs of Inaction (Climate Impacts) and Potential Adaptation Actions for Health and Wellbeing
Summary of costs of inaction and potential adaptation actions. Items in bold are quantified in this study.

Costs of Inaction	Potential Adaptation Actions
Increased exposure to extreme temperatures causes learning loss and **lost future earnings, lost wages among high-risk (outdoor) workers, excess mortality** (from both extreme heat and extreme cold), poor mental health, and **increased emergency department visits for heat-related illnesses.**	**Air conditioning** in homes, public buildings, and schools, **cooling centers** in urban areas, **maintaining** and expanding **tree canopies** in communities, **shade structures at playgrounds, worker protection measures** (breaks and water) decrease exposure to extreme temperatures. **Resilience planning** ensures municipalities are prepared for extreme heat events. Additional adaptation actions include installing cool roofs and pavement, as well as other urban design strategies, to reduce the urban heat island effect.
Wildfires lead to **excess mortality** through exposure to air pollution and physical hazards like **building damages,** as well as morbidity impacts including **emergency department visits for childhood asthma,** poor mental health, and **school loss days.**	**Air conditioning** in homes and public buildings has filtration systems that prevent pollutants from entering the building envelope, and **air purifiers** can be purchased for buildings with no air conditioning or air conditioning not inclusive of filtration. Increased public outreach efforts can inform the public on when to avoid outdoor activities or wear a mask.
Higher temperatures and greater precipitation lead to increased prevalence of Lyme disease and West Nile virus in ticks and mosquitoes, creating increased cases in humans and related **insurance claim costs, mortality,** and **hospital costs.**	**Mosquito control measures** (including monitoring and treating waterbodies) reduce morbidity and mortality impacts from vector borne diseases. Increased public outreach can raise awareness of vector-borne diseases and personal disease mitigation efforts such as emptying containers of water to reduce mosquito habitat and wearing protective clothing and mosquito/tick repellent when outside.

The analysis presented in this chapter quantifies costs of inaction and adaptation costs for a subset of potential costs in the health and wellbeing cost category. Figure 4-1 summarizes the quantified costs of inaction and adaptation costs. Note that the costs in this figure are not comprehensive but represent the quantifiable costs for Minnesota in this study. Annual health and wellbeing costs increase over time

and as emissions increase, with the quantified costs of inaction far outpacing the quantified costs of adaptation.

Figure 4-1. Health and Wellbeing: Quantified Annual Climate Cost Summary
Summary and comparison of cost of inaction (first set of bars, in dark blue), adaptation costs (second set of bars, in green) per year, above baseline. Costs of inaction and adaptation costs without the corresponding cost type are less than $50 million per year and not included on the graphic. Results for three time periods and three emissions scenarios (defined as Intermediate [Intmd.], High, and Very High; see section 2.2.2 for more details), averaged across six climate models. Note that given the availability of the costs of inaction, results for wildfire $PM_{2.5}$ mortality for the High emissions scenario in the Mid-Century are held constant for the Very High emissions scenario and Late- and End-of-Centuries.



The remainder of this chapter includes three main sections, addressing the three climate hazards for which the analysis quantified adaptation costs: **Heat, Air Quality,** and **Vector-borne Disease and Illness.** Within each of these three main sections, there are subsections for **Costs of inaction, Costs of adaptation,** and **Limitations and uncertainties.** Both cost subsections provide a high-level methodology description, detailed results, and further interpretation of the findings, including how costs are distributed across the state and which costs are not quantified in this study. Detailed methodological steps and specific citations to data sources, models, and peer-reviewed studies that provide a basis for estimating costs can be found in Appendix B.

4.1. Heat

4.1.1. Costs of inaction

Extreme heat can have dramatic health impacts in addition to causing loss of life. Non-fatal medical conditions include heat cramps (muscle spasms), heat edema (swelling in the ankles, feet, and hands), heat rash (red rash on skin), heat syncope (dizziness, fainting), heat tetany (respiratory and muscle

problems), heat exhaustion (profuse sweating, weakness, rapid breathing, dizziness, nausea/vomiting, muscle cramps), and heat stroke (symptoms are similar to heat exhaustion but with the addition of confusion and potential loss of consciousness; often fatal as body is unable to regulate temperature).[37] In addition to illness, heat can also increase the risk of injury through both physiological and cognitive impairment. Heat's effect on cognition has also been shown to have longer-term learning effects on children. Heat-related health and wellbeing impacts increase with the intensifying heatwaves characteristic of the changing climate.

While all populations are vulnerable to extreme heat, some populations are particularly susceptible. For instance, elderly individuals (>65 years old) are less able to regulate their body temperature and are more susceptible to the impacts of extreme heat. Similarly, younger children have physiological limitations that increase their risk of suffering heat-related illness. Extreme heat can also strain the cardiovascular and respiratory systems of pregnant people which, in addition to enhanced risk for the adult, can also lead to harm to the fetus. In addition to biological factors, some populations are heat-susceptible due to increased exposure (e.g., outdoor workers and athletes), or socioeconomic reasons like a lack of access to sufficient cooling and health services. Finally, people with certain pre-existing medical conditions (cardiovascular diseases, respiratory diseases, endocrine diseases, kidney diseases, alcoholism and substance abuse, and mental health conditions) and those taking certain medications are also more susceptible to heat-related illness.

Without further adaptation, heat associated with climate change is expected to worsen and adversely affect human health and wellbeing beyond its current impacts. The costs of inaction presented in Table 4-2 are a subset of many potential negative consequences of heat on human health and wellbeing. The quantified costs of inaction in this study include the following, each with introduced with a brief methodology description.

- The societal cost of **premature deaths from increased extreme heat events,** leveraging findings from Mills et al. (2015).[38] By the end of the century, the analysis projects an increase of 310 additional extreme heat-related deaths annually. To convert this result to monetized terms, premature deaths are valued using the U.S. EPA's VSL, which represents what society is willing to pay to reduce mortality risk.
- **Healthcare costs from heat-related emergency department visits among children,** relying on a study by Bernstein et al. (2022).[39] The projections show an additional 3,000 child emergency department visits by the end of the century attributable to heat.
- Projections of **lost future income associated with heat exposure** among high school students during the school year, applying a statistical relationship from Park et al. (2020).[40] Experiencing extreme heat impairs children's learning, which results in lower standardized test scores and reduced future earnings.

[37] Minnesota Department of Health. (2025). Minnesota Extreme Heat Toolkit, Version 2.0. Available at: https://www.health.state.mn.us/communities/environment/climate/docs/mnextremeheattoolkit.pdf
[38] Mills, D., Schwartz, J., Lee, M., Sarofim, M., Jones, R., Lawson, M., Duckworth, M. & Deck, L. (2015). Climate change impacts on extreme temperature mortality in select metropolitan areas in the United States. Climatic Change, 131(1), 83-95.
[39] Bernstein, A. S., Sun, S., Weinberger, K. R., Spangler, K. R., Sheffield, P. E., & Wellenius, G. A. (2022). Warm season and emergency department visits to US children's hospitals. Environmental health perspectives, 130(1), 017001.
[40] Park, R. J., Goodman, J., Hurwitz, M., & Smith, J. (2020). Heat and learning. American Economic Journal: Economic Policy, 12(2), 306-339. doi:10.1257/pol.20180612

- Projections of **lost income to the 659,000 weather-exposed workers** across Minnesota are based on Neidell et al. (2021).[41] Workers in weather-exposed conditions, including workers in outdoor industries (e.g., agriculture, forestry, utilities) and indoor industries that traditionally lack air conditioning (e.g., manufacturing, commercial kitchens), reduce their time spent working on high heat days to avoid the adverse health and safety effects. The reduction in work time also has the negative consequence of reducing wages among these high-risk workers, who are typically lower paid even absent heat impacts on working conditions.

Across all quantified costs of inaction related to heat impacts, annual costs are expected to increase throughout the century, particularly in the Very High emissions scenario where End-of-Century costs are more than four times the Mid-Century costs. The results are not very sensitive to climate modeling – the six climate models used in this analysis project relatively similar costs. See Appendix B for more details on methodology and limitations.

Table 4-2. Quantified Costs of Inaction (Millions per Year): Heat

Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). Costs are incremental to baseline and averaged across six climate models (range across climate models provided in parentheses). See Appendix B for more details on methodology and limitations.

		Premature Mortality	Learning Loss	Labor	Child Morbidity
		Value of a statistical life (VSL)	Lost future earnings among exposed high school students	Lost wages among high-risk workers	Emergency Department visit costs
Mid-Century (2040–2059)	Intermediate	$2,800 ($2,600 to $2,900)	$590 ($550 to $610)	$210 ($190 to $220)	$1.4 ($1.0 to $2.0)
	High	$3,000 ($2,800 to $3,200)	$620 ($590 to $650)	$220 ($210 to $240)	$1.7 ($1.2 to $2.5)
	Very High	$3,600 ($3,300 to $4,100)	$720 ($670 to $800)	$290 ($260 to $330)	$1.7 ($0.4 to $2.5)
Late-Century (2060–2079)	Intermediate	$4,800 ($4,200 to $5,500)	$740 ($660 to $840)	$380 ($310 to $460)	$1.9 ($1.3 to $2.3)
	High	$5,900 ($5,600 to $6,400)	$880 ($840 to $940)	$500 ($460 to $560)	$2.6 ($1.7 to $3.3)
	Very High	$8,200 ($7,300 to $9,000)	$1,100 ($1,000 to $1,200)	$760 ($660 to $860)	$2.8 ($0.5 to $3.9)
End-of-Century (2080–2099)	Intermediate	$7,600 ($6,500 to $9,300)	$890 ($780 to $1,000)	$650 ($530 to $840)	$2.6 ($1.9 to $3.5)
	High	$11,000 ($10,000 to $13,000)	$1,200 ($1,100 to $1,300)	$1,100 ($930 to $1,300)	$3.6 ($2.8 to $4.3)
	Very High	$16,000 ($14,000 to $19,000)	$1,600 ($1,400 to $1,800)	$1,700 ($1,400 to $2,100)	$4.5 ($3.8 to $5.8)

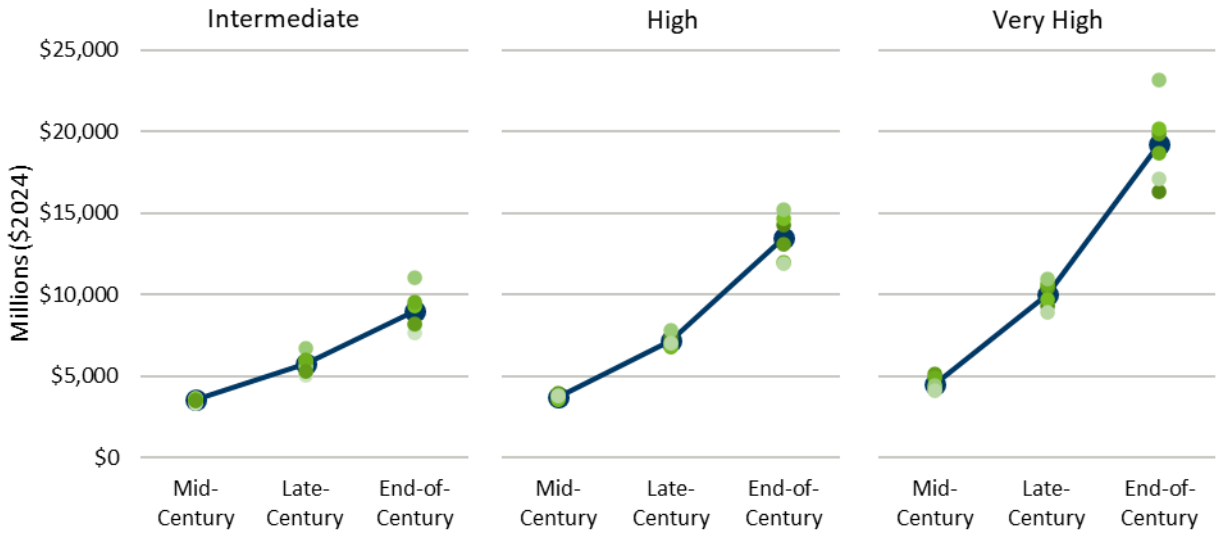
Other costs of inaction (not quantified):

- Injuries and other heat related illness costs
- Learning losses among elementary and middle school students
- Worker productivity and athlete performance
- Impacts of adverse birth outcomes (stillbirths, preterm births, low birth weight)

[41] Neidell, M., Graff-Zivin, J., Sheahan, M., Willwerth, J., Fant, C., Sarofim, M., & Martinich, J. (2021). Temperature and work: Time allocated to work under varying climate and labor market conditions. PLoS ONE 16(8): e0254224. https://doi.org/10.1371/journal.pone.0254224

Figure 4-2. Range of Quantified Annual Costs of Inaction: Heat (Premature Mortality, Learning Loss, Labor, Child Morbidity)

Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). The solid lines with blue dots represent the average across six climate models per scenario, and the green dots without lines show the results for each of the six models.



Climate impacts may have mortality benefits

In addition to increasing the number of days during which people experience extreme heat, climate change can temper days that would have been extremely cold to make them less cold. Estimates for the magnitude of the impact that climate change has on mortality due to exposure to extreme cold vary significantly based on the model employed and whether that model considers just extreme temperatures or the full range.

In considering mortality related to the top and bottom one percent of temperatures, Mills et al. (2015) find that even if climate change were to result in a decrease in the number of extremely cold days equal to the increase in the number of extremely hot days, there would still be a net mortality increase (given the greater per-degree impact extreme heat has on mortality). However, Lee and Dessler (2023) estimate temperature-related mortality across the range of temperatures and project that an increase in heat-related deaths may offset a decrease in cold-related deaths.

Applying the exposure-mortality relationship from Mills et al. (2015), this study finds climate impacts could be as large as 24 lives saved annually from exposure to extreme cold, though projections of this impact vary across analyses depending on specifics of the study design. Because this effort serves to quantify the costs of adaptation to climate change, this study does not include potential cost savings from decreased mortality from the lack of extreme cold because these benefits do not trigger significant adaptation costs.

Who bears the costs of inaction?

Section 3.2 shows areas of Minnesota that are expected to experience the greatest increase in temperatures throughout the century, which includes the west and northwestern regions of the state by Mid-Century. Because the northernmost counties have historically seen milder summer temperatures, people and infrastructure are less equipped to handle heat stress and are therefore more vulnerable to heat impacts. Historical data also reveal that households in select rural areas of Minnesota are much

less likely to have air conditioning installed (58 percent) than households in select urban areas (96 percent), which suggests rural residents may be especially vulnerable as well.[42,43] Finally, while weather-exposed workers are found throughout the state, five counties represent over half of all workers in this category: Hennepin, Ramsey, Dakota, Anoka, and Stearns.

Most Minnesotans are covered by a mix of public and private health insurance options, although a portion remain uninsured (3.8 percent in 2023).[44] Therefore, healthcare-related costs are borne by a range of entities, including insurers, employers, taxpayers, and patients. This analysis uses the VSL to monetize premature deaths, which represents an individual's willingness to pay (WTP) to reduce the risk of death. However, the financial and emotional costs associated with premature deaths are typically borne by the surviving family members, although life insurance may offset some direct lost income and out-of-pocket costs. Lost future income associated with experiencing heat during the school year is a cost to future generations. Similarly, reduced work time on high-heat days results in lower take-home wages for employees (especially for hourly workers) and potentially lower overall output for employers. Decreased earnings will also reduce taxable income, thereby limiting available funds for publicly funded initiatives and services. The distribution of costs not quantified in this study includes heat-related injuries sustained at work paid for through workers' compensation programs and patients and caregivers who experience indirect costs associated with illness and injury, including lost income to the patients and their caregivers as well as reduced quality of life.

What other costs of inaction are not quantified in this study?

The following are costs of inaction related to health and wellbeing effects of heat that are not quantified in this study.

- The non-fatal heat-related health costs of inaction, including emergency department visits for illness and injury across all age groups, hospitalizations, doctor's visits, and indirect costs such as lost productivity and reduced quality of life. Data from the Minnesota Department of Health show that older adults are hospitalized for heat-related illness at approximately 10 times the rate of children,[45] suggesting the excluded non-fatal health costs of inaction may be substantial. Beyond short-term costs, there are also long-term healthcare costs associated with sustaining heat-related illness, including damage to kidneys as well as cardiovascular, respiratory, and neurological systems.
- Beyond the high school student population examined in this chapter, other groups will experience reduced cognition associated with heat. Reduced cognition could affect learning among elementary and school age children (Roach and Whitney 2022),[46] productivity of workers, and performance of athletes. One mechanism impairing cognitive function is the deterioration of sleep quality and quantity associated with elevated temperatures. Projections

[42] U.S Census Bureau, "AHS 2013 National Public Use File," American Housing Survey (AHS), 2013, https://www.census.gov/programs-surveys/ahs/data/2013/ahs-2013-public-use-file--puf-/ahs-2013-national-public-use-file--puf-.html.
[43] Ibid.
[44] Minnesota Health Care Chartbook. Section 2: Trends and Variation in Health Insurance Coverage. Available at: https://www.health.mn.gov/data/economics/chartbook/summaries/section2summaries.html
[45] Minnesota Department of Health. "Heat Related Hospitalizations" Available at: https://data.web.health.state.mn.us/heat_hospitalizations#ageandsex. Accessed January 2026.
[46] Roach, T., & Whitney, J. (2022). Heat and learning in elementary and middle school. Education Economics, 30(1), 29-46.

of lost future sleep, such as Liao et al. (2025), indicate considerable losses due to lower sleep quality and quantity throughout the century.[47]

- Adverse birth outcomes are also linked with heat exposure to pregnant mothers. Bekkar et al. (2020) summarize the evidence showing that exposure to high temperatures increases the risk of stillbirth, preterm birth, and term low birth weight.[48] Ongoing work by Sheahan et al. suggests the increased short-term healthcare related costs associated with these cases and the economic burden of infant deaths may be on the order of $540 million in Minnesota annually at 4°C of warming (relative to conditions in 1986–2005).[49] Even this figure underestimates the total cost of this impact as it does not include the cost of childhood support services, lifetime healthcare expenses for the mother and child, or reduced future earnings.

4.1.2. Costs of adaptation

Adapting to rising temperatures requires technologies and infrastructure to maintain safe, comfortable environments for human health and wellbeing. Adaptation actions include ensuring people have access to cool indoor spaces, reducing heat exposure outdoors, and developing heat safety plans to implement best practices to address heat. This study quantifies the costs for the following adaptation actions: 1) building cooling, 2) public policy and services, and 3) shade provision.

Building cooling

This analysis finds that the highest adaptation costs across the three categories are those associated with adding air conditioning to homes, schools, and other public buildings. Research shows that air conditioning partially mitigates heat-related deaths starting at 80°F.[50] Historical data indicate that schools in Minnesota typically install cooling systems once they experience at least 15 days exceeding 80°F during the school year. For homes and other public buildings, the threshold is 15 days annually. This analysis projects purchase and installation costs for **air conditioning in homes, schools, and other public buildings** following these thresholds. Beyond installation, the analysis includes ongoing energy costs for cooling – which increase as temperatures rise – as well as system upgrades and replacements based on typical air conditioning lifespans. The analysis includes two technology scenarios: 1) the current mix of cooling technologies and 2) energy-efficient alternatives (i.e., heat pumps in homes and geothermal systems in schools). Energy-efficient cooling technologies reduce both cooling and heating costs; these cost savings are incorporated into the projections in this study.

By 2040, 650,000 homes and 580 schools that currently lack cooling technology are projected to meet the defined threshold for installing air conditioning. The energy cost burden associated with running new and existing units is also expected to grow significantly across the century. While energy-efficient technologies have higher upfront installation costs, their energy savings during both warm and cool seasons offset these additional costs over the long term. Table 4-3 presents these costs, which exceed $1 billion annually by the end of the century.

[47] Liao, J., Habre, R., Garcia, E., Eckel, S. P., Kossowsky, J., Herting, M. M., Chen, Z., Qiu, C., Yuang, Z., McConnel, R., and Gilliland, F. (2025). Impact of heat exposure on sleep health and its population vulnerability in the United States. Environment international, 109942.

[48] Bekkar, B., Pacheco, S., Basu, R., & DeNicola, N. (2020). Association of air pollution and heat exposure with preterm birth, low birth weight, and stillbirth in the US: a systematic review. *JAMA network open*, *3*(6), e208243-e208243.

[49] Sheahan, M., Basu, R., Papatheodorou, S., Fant, C., Jeweler, B., Holland, I., Neumann, J., Gould, C. "Heat, Humidity, and Adverse Birth Outcomes: Quantification of Projected Risks in the Contiguous United States." In review.

[50] Barreca, A., Clay, K., Deschenes, O., Greenstone, M., & Shapiro, J. S. (2016). Adapting to climate change: The remarkable decline in the US temperature-mortality relationship over the twentieth century. *Journal of Political Economy*, *124*(1), 105-159.

Table 4-3. Quantified Adaptation Costs (Millions per Year): Heat – Building cooling

Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). Costs are incremental to baseline and averaged across six climate models (range across climate models provided in parentheses). See Appendix B for more details on methodology and limitations.

		Household Cooling: Current Technology Mix*	Household Temperature Control: Energy Efficient Technology	Public & Commercial Building: Current Technology Mix	School Cooling: Current Technology Mix*	School Temperature Control: Energy Efficient Technology
		Cooling energy and capital costs	Energy and capital costs	Cooling energy costs	Cooling energy and capital costs	Energy and capital costs
Mid-Century (2040–2059)	Intermediate	$720 ($650 to $810)	$530 ($470 to $610)	$6.1 ($4.2 to $8.3)	$160 ($140 to $180)	$110 ($93 to $140)
	High	$780 ($670 to $920)	$590 ($480 to $710)	$7.5 ($4.6 to $11.0)	$170 ($160 to $200)	$130 ($110 to $140)
	Very High	$770 ($520 to $880)	$570 ($350 to $680)	$7.2 ($0.9 to $10.0)	$170 ($150 to $190)	$130 ($110 to $150)
Late-Century (2060–2079)	Intermediate	$810 ($700 to $880)	$620 ($510 to $680)	$8.4 ($5.4 to $10.0)	$180 ($160 to $190)	$130 ($110 to $150)
	High	$930 ($770 to $1,100)	$720 ($570 to $830)	$11.0 ($7.1 to $14)	$200 ($180 to $210)	$140 ($130 to $150)
	Very High	$960 ($540 to $1,100)	$740 ($370 to $870)	$12 ($1.4 to $15)	$200 ($170 to $210)	$140 ($140 to $150)
End-of-Century (2080–2099)	Intermediate	$920 ($810 to $1,000)	$710 ($610 to $810)	$11 ($8.1 to $14)	$200 ($180 to $210)	$140 ($140 to $150)
	High	$1,100 ($950 to $1,200)	$850 ($740 to $960)	$15 ($12 to $18)	$210 ($200 to $220)	$150 ($150 to $150)
	Very High	$1,200 ($1,100 to $1,400)	$980 ($910 to $1,200)	$18 ($16 to $23)	$230 ($200 to $250)	$150 ($150 to $150)

*Indicates an action with multiple alternatives; this alternative is not included in the annual summary.

Public policy and services

Implementing protections for weather-exposed workers and operating cooling centers during high heat events are another major cost. On high heat days, employers can protect **weather-exposed workers through various safety measures.** This analysis incorporates the cost of paid work breaks and water access using a subset of the requirements in a proposed U.S. Occupational Safety and Health Administration (OSHA) rule.[51] These per-worker costs are applied to all weather-exposed workers in Minnesota. These costs may be on the order of over $500 million annually by the end of the century.

Public spaces can serve as **cooling centers** during extreme heat events, providing critical refuge for unhoused populations and residents without adequate air conditioning. In parts of Minnesota, public libraries currently fill this role.[52] As extreme heat becomes more frequent, additional public spaces will need to be converted into temporary cooling centers or resilience hubs that can offer emergency shelter. Following an approach used in Ohio,[53] this analysis projects both the costs of establishing new

[51] U.S. Department of Labor, Occupational Safety and Health Administration (OSHA). Heat Injury and Illness Prevention in Outdoor and Indoor Work Settings [Notice of proposed rulemaking; Federal Register Document No. 2024-14824]. *Federal Register*, *89*, 70698. https://www.federalregister.gov/documents/2024/08/30/2024-14824/heat-injury-and-illness-prevention-in-outdoor-and-indoor-work-settings

[52] Ren, L. (2025). Validating the Agent-Based Model for Cooling Options Utilization During Extreme Heat Events in Hennepin County. Department of Applied Economics, University of Minnesota, https://hdl.handle.net/11299/276873.

[53] Power a Clean Future Ohio (PCFO), Ohio Environmental Council, Scioto Analysis. (2022). The Bill is Coming Due: Calculating the Financial Cost of Climate Change to Ohio's Local Governments. July 2022. https://www.poweracleanfuture.org/oh-municipal-costs-of-climate-change

cooling centers and operating existing centers. These costs are likely to be on the order of tens of millions of dollars annually by the end of the century.

Beyond investments in specific technologies and infrastructure, municipalities also incur **costs for planning and preparing for extreme heat events** and other climate-related emergencies. This analysis projects these planning costs by assuming municipalities will update their heat and resilience plans every ten years. Cost projections are based on the average size of heat and resilience planning grants funded by the MPCA between 2022 and 2025.

Table 4-4 summarizes these costs associated with public policy and services.

Table 4-4. Quantified Adaptation Costs (Millions per Year): Heat – Public Policy and Services

Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). Costs are incremental to baseline and averaged across six climate models. See Appendix B for more details on methodology and limitations.

		Worker Protections	Cooling Centers: New Centers	Cooling Centers: Existing Centers	Resilience Planning
		Cooling energy and capital costs	Cooling energy and capital costs	Cooling energy costs	Grant funding
Mid-Century (2040–2059)	Intermediate	$160 ($110 to $250)	$11 ($6.1 to $19)	$1.2 ($0.5 to $2.4)	$4.6
	High	$220 ($160 to $350)	$13 ($7.3 to $16)	$1.5 ($0.7 to $2.4)	$4.6
	Very High	$220 ($41 to $310)	$14 ($8.9 to $21)	$1.6 ($0.6 to $2.8)	$4.6
Late-Century (2060–2079)	Intermediate	$230 ($180 to $290)	$14 ($8.5 to $19)	$1.6 ($0.9 to $2.4)	$4.6
	High	$330 ($220 to $440)	$18 ($11 to $23)	$2.4 ($1.5 to $3.1)	$4.6
	Very High	$340 ($47 to $480)	$19 ($9.7 to $31)	$2.5 ($0.8 to $4.5)	$4.6
End-of-Century (2080–2099)	Intermediate	$320 ($220 to $440)	$18 ($10 to $26)	$2.4 ($1.2 to $3.6)	$4.6
	High	$440 ($340 to $540)	$25 ($17 to $30)	$3.5 ($2.4 to $4.3)	$4.6
	Very High	$530 ($410 to $700)	$30 ($19 to $43)	$4.4 ($2.9 to $6.5)	$4.6

Note: Results for resilience planning represent an average annual cost that does not change over time or across emissions scenarios.

Shade provision

The final category of quantified costs for heat-related adaptation actions is built and natural environment improvements to reduce heat exposure outdoors and reduce urban heat island effects. Table 4-5 presents these adaptation costs.

Installing shade structures at playgrounds reduces heat exposure among vulnerable children and their caregivers. The projected total investment needed to make playgrounds more conducive to safe play during hot weather is based on an estimate of the number of playgrounds statewide and shade structure costs from a Minnesota Department of Administration's published price list. The analysis finds that the costs associated with installing shade structures at playgrounds and implementing heat resilience planning are likely in the single-digit millions per year, regardless of emissions trajectory.

Trees, especially those in densely populated areas, provide shade that reduces exposure to high temperatures. Even without climate change, various efforts aim to increase the tree canopy across Minnesota, including the Minnesota Million project, with the objective of rebuilding forest lost to

logging and development. This study focuses specially on **climate-related costs associated with maintaining and protecting trees** from harms associated with increasing temperatures. These costs include: 1) increased watering expenses to protect juvenile trees from heat stress and mortality during extreme heat events and 2) replacement costs for urban ash trees lost to Emerald Ash Borer, the spread of which is accelerated by warming temperatures. This analysis is limited to trees in urban areas and other locations covered by the Minnesota Department of Natural Resources (DNR) Rapid Assessment Community Tree Reports.[54] Maintaining and replacing community trees is anticipated to result in tens of millions of dollars of increased costs annually. This cost includes replacing 1.4 million ash trees projected to be lost to Emerald Ash Borer in select communities throughout the state.

Table 4-5. Quantified Adaptation Costs (Millions per Year): Heat – Shade provision

Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). Costs are incremental to baseline and averaged across six climate models. See Appendix B for more details on methodology and limitations.

		Shade Structure Installation	Urban Trees: New Tree Maintenance	Urban Trees: Replacing Dead Ash Trees
		Capital costs	Tree maintenance costs	Replacement cost
Mid-Century (2040–2059)	Intermediate	$2.2	$1.1 ($0.6 to $1.9)	$41
	High	$2.2	$1.5 ($1.0 to $2.4)	$41
	Very High	$2.2	$1.5 ($0.4 to $2.3)	$41
Late-Century (2060–2079)	Intermediate	$2.2	$1.6 ($1.1 to $2.1)	$41
	High	$2.2	$2.3 ($1.6 to $3.0)	$41
	Very High	$2.2	$2.3 ($0.5 to $3.5)	$41
End-of-Century (2080–2099)	Intermediate	$2.2	$2.2 ($1.4 to $3.1)	$41
	High	$2.2	$3.1 ($2.4 to $3.8)	$41
	Very High	$2.2	$3.7 ($2.8 to $5.1)	$41

Note: Results for this analysis without ranges are only available for the climate model average for the emissions scenarios.

Other adaptation costs (not quantified):

- Implementing heat resilience plans
- Investments into other green infrastructure and urban planning
- Development and implementation of extreme heat early warning systems and education campaigns

What residual risks remain after adaptation?

Air conditioning can significantly reduce heat-related adverse health and wellbeing effects. Park et al. (2020) found that when air conditioning is available in both schools and homes, learning losses associated with heat exposure are eliminated.[55] This suggests that with complete adaptation through air conditioning, no residual learning losses occur. However, while Barreca et al. (2016) demonstrated that air conditioning also reduces heat-related mortality, it does not eliminate mortality impacts entirely.[56]

[54] Minnesota DNR's Rapid Assessment Community Tree Report Viewer: https://arcgis.dnr.state.mn.us/portal/apps/experiencebuilder/experience/?id=6fb3082ce97145f1ac41107d50d05a1d

[55] Park et al., "Heat and Learning."

[56] Barreca et al., "Adapting to Climate Change."

This is likely because some individuals, specifically unhoused populations, will still experience significant heat exposure even when buildings are cooled.

OSHA found that implementing a suite of worker protection measures, not all of which are monetized in this analysis, can reduce heat-related fatalities by about 95 percent and non-fatal heat-related injuries and illnesses by 65 percent.[57] In other words, while taking breaks and providing water to weather-exposed workers is found to be effective, heat risks to these individuals still remain.

Less is known about how sustaining a tree canopy or adding shade structures in playgrounds reduces health and safety risks. Moreover, research is limited concerning the remaining health and wellbeing risks once municipalities invest in planning for extreme heat events. The weight of the evidence suggests that the adaptation categories considered in this analysis can substantially reduce the adverse effects of heat on human health, but that risks will remain, especially to the most vulnerable populations.

What other effects result from adaptation?

Reliance on air conditioning can increase energy consumption and household energy costs. However, as discussed in this chapter, these impacts can be mitigated through the installation of energy-efficient cooling technologies. High-efficiency systems, particularly heat pumps and geothermal, also provide the added benefit of lowering winter heating costs. In addition, air conditioning systems offer a co-benefit of improved indoor air filtration, which can reduce adverse health impacts associated with poor air quality, as discussed in Section 4.2.

Maintaining a tree canopy in communities has many other non-health related benefits including energy cost savings, stormwater management, and carbon sequestration.

Who pays the adaptation costs?

Home air conditioning penetration is currently higher in urban areas compared with rural areas of Minnesota. Approximately 58 percent of households in select rural areas of Minnesota have air conditioning installed relative to 96 percent of households in select urban areas.[58,59] Therefore, as warming continues, rural areas are expected to incur higher air conditioning installation costs. Available data demonstrate that baseline school air conditioning coverage is higher in southern Minnesota than northern Minnesota.[60] As a result, the counties with the highest expected future costs associated with air conditioning in schools are found in northern Minnesota (see Figure 4-3).

The costs of air conditioning installation are spread across multiple entities. Several available programs in Minnesota and at the Federal level help to offset the costs of installing heat pumps in homes, particularly for low-income households. Individual school districts are likely to fund most air conditioning costs, while individual municipalities are likely to raise funds through taxpayer dollars to help fund resilience planning. Businesses in weather-exposed industries will bear the costs associated with implementing worker protections, and some businesses may pass these costs on to consumers.

[57] U.S. Department of Labor, Occupational Safety and Health Administration (OSHA). Heat Injury and Illness Prevention in Outdoor and Indoor Work Settings [Notice of proposed rulemaking; Federal Register Document No. 2024-14824]. *Federal Register*, *89*, 70698. https://www.federalregister.gov/documents/2024/08/30/2024-14824/heat-injury-and-illness-prevention-in-outdoor-and-indoor-work-settings

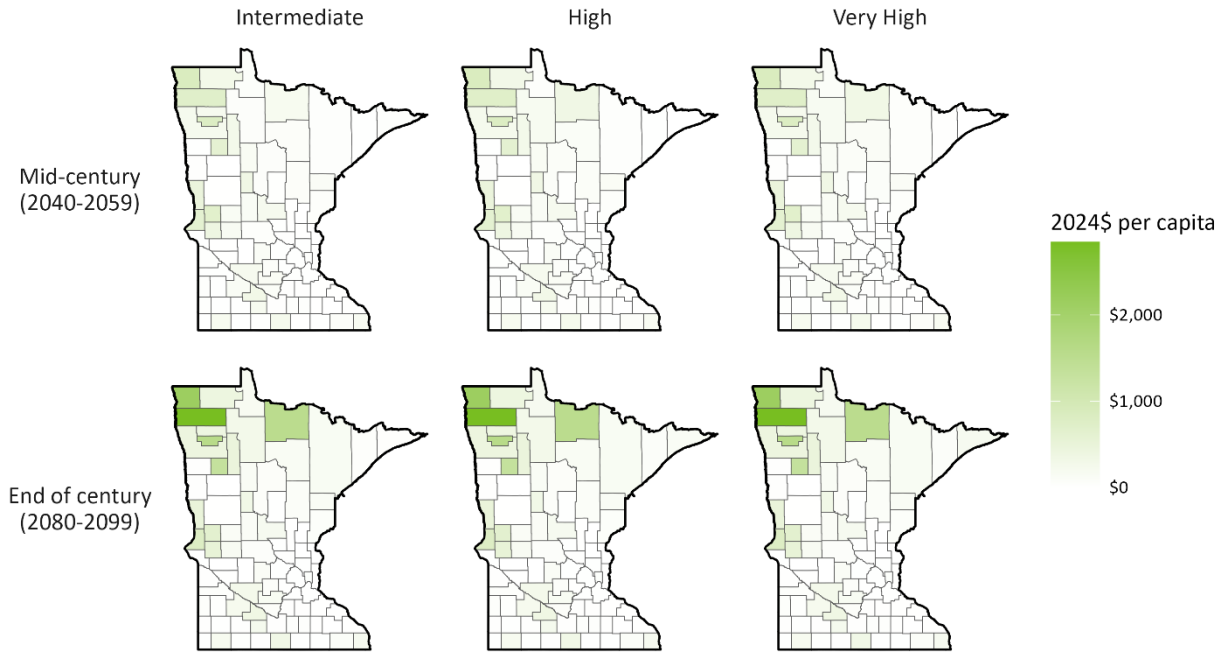
[58] U.S Census Bureau, "AHS 2013 National Public Use File."

[59] U.S Census Bureau, "AHS 2021 Metropolitan Public Use File (PUF)."

[60] Park et al., "Heat and Learning."

Figure 4-3. Distribution of energy-efficient air conditioning installation and saved energy costs in schools by county

Annual costs per capita of installation, operation, and maintenance of air conditioning in schools (2024$) by county for two time periods and three emissions scenarios (see Section 2.2.2 for more details), averaged across six climate models.



What are the other costs of adaptation not quantified in this study?

There are several other adaptation options related to health and wellbeing effects of heat not quantified in this study:

- The cost of staff implementing heat resilience plans;
- Investments in other green infrastructure and urban planning to facilitate cooling (green roofs, cool pavement); and
- The cost to develop and implement extreme heat early warning systems. In Hennepin County alone, the Climate Resilience and Adaptation Program requires seven staff members to implement this work under current conditions.[61] Throughout the state, hundreds of additional staff may be required to implement resilience plans.

4.1.3. Limitations and uncertainties

The quantified adaptation costs presented in this study are illustrative of the magnitude of costs required, though they do not cover all potential reactive and proactive responses to climate change. Key limitations to the analysis are described below; see Appendix B for a full discussion of limitations and uncertainties:

- Energy-efficient technologies in this analysis include heat pumps for households and geothermal for schools, but other technologies exist.
- Capital and energy costs may vary significantly from the current average costs, particularly as energy prices shift and technologies advance. Limited information is available on the cost of geothermal installation and operation in schools.

[61] Personal communication with a representative of Hennepin County.

- Cooling costs are calculated for the current building inventory and therefore do not include potential growth, which may be particularly important for household cooling.
- Worker protections are defined using the work break and water requirements on high temperature days from a proposed OSHA rule. However, it is unknown whether these requirements are sufficient to limit worker health and safety risk.
- Resilience planning costs were estimated using historical data from the MPCA Resilient Communities grant program. The funding provided by this program represents only a subset of the total costs municipalities incur to develop and implement a plan, typically excluding staffing costs. Other sources of funds for resilience planning include other State programs and utilities.

4.2. Air Quality

4.2.1. Costs of inaction

Climate change contributes to poor air quality through increased prevalence of extreme heat, wildfires, aeroallergens, and other related impacts on pollution. Extreme temperatures create conditions that are conducive to the generation of tropospheric ozone, a health-harming criteria pollutant. Increasingly frequent and intense wildfires generate smoke that contains particulate matter (including $PM_{2.5}$)[62] and other harmful gases, further degrading air quality. In addition, climate change has increased concentrations of aeroallergens due to the longer spring and summer seasons, extending human exposure to pollen and other allergens.

Minnesota is already experiencing poor air quality from wildfire activity

In Minnesota, the summers of 2023 and 2025 saw poor air quality from wildfires burning across Canada. In addition to smoke and particulate matter, wildfire emissions contributed volatile organic compounds that are precursors of ozone formation, thus increasing ozone (or air quality) action days. In 2023, the MPCA issued 22 alerts over 52 days, with 14 of those alerts being more severe.

Poor air quality creates adverse human health impacts that range from premature mortality to morbidity effects like respiratory and cardiovascular diseases, asthma exacerbation, and shortness of breath. The costs of inaction for addressing poor air quality associated with climate change are monetized through willingness to pay (e.g., VSL) and cost of illness metrics (e.g., cost per emergency department visit).

The quantified costs of inaction in this study include the following, each with introduced with a brief methodology description.

- The costs of **premature mortality associated with exposure to $PM_{2.5}$** (from wildfires) and **premature mortality associated with exposure to ozone** (from wildfires and other non-wildfire ozone concentrations). The wildfire-driven premature mortality analysis employs county-level projections of premature mortality from Qiu et al. (2025).[63] Qiu et al. derive relationships between smoke-related $PM_{2.5}$ exposure and premature mortality to project a 73 percent increase in average annual excess deaths compared to the 2011–2020 average by 2050, nationally. Because of limitations in the time periods and emission scenarios analyzed by Qiu et

[62] Fine particulate matter, or $PM_{2.5}$, refers to particles in the atmosphere that are 2.5 micrometers or less. $PM_{2.5}$ is dangerous to human health because the microscopic particles can get deep into the lungs and move systemically throughout the body, creating impacts to many different body systems. See EPA's $PM_{2.5}$ and health primer for more details: https://www.epa.gov/pm-pollution/particulate-matter-pm-basics.

[63] Qiu, M., Li, J., Gould, C. F., Jing, R., Kelp, M., Childs, M. L., ... & Burke, M. (2025). Wildfire smoke exposure and mortality burden in the USA under climate change. *Nature*, *647*(8091), 935-943.

al. (2025), this analysis only values premature mortality associated with $PM_{2.5}$ from wildfires in the Mid-Century for the Intermediate and High emissions scenarios. Both premature mortality results are quantified using the VSL.

- Three measures of the costs of increased **childhood asthma.** This analysis uses a WTP metric for a statistical case of childhood asthma (VSC)[64] and cost of illness metrics to capture the caregiver costs for school loss days and the costs per visit for childhood asthma emergency department visits. Morbidity air quality-related costs increase over time and across emissions scenarios.

Additional details on the methods for air quality-related health valuation can be found in Appendix B.

Table 4-6. Quantified Costs of Inaction (Millions per Year): Air Quality

Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). Costs are incremental to baseline and averaged across six climate models (range across climate models provided in parentheses). See Appendix B for more details on methodology and limitations.

		Wildfire $PM_{2.5}$ Premature Mortality	Ozone Premature Mortality	New Childhood Asthma	School Loss Days	Childhood Asthma ED Visits
		Value of a statistical life (VSL)	Value of a statistical life (VSL)	Value of a statistical case of childhood asthma (VSC)	Caregiver costs	Cost per visit
Mid-Century (2040–2059)	Intermediate	$6,100 (-$3,800 to $11,000)	$440 ($430 to $440)	$470 ($460 to $470)	$37 ($36 to $37)	$0.06 ($0.06 to $0.06)
	High	$7,100 ($4,400 to $13,000)	$450 ($440 to $460)	$470 ($460 to $470)	$37 ($37 to $37)	$0.06 ($0.06 to $0.06)
	Very High	-	$510 ($480 to $560)	$510 ($480 to $540)	$40 ($38 to $43)	$0.06 ($0.06 to $0.07)
Late-Century (2060–2079)	Intermediate	-	$660 ($600 to $750)	$510 ($470 to $560)	$52 ($48 to $57)	$0.06 ($0.06 to $0.07)
	High	-	$820 ($770 to $890)	$610 ($570 to $660)	$62 ($58 to $67)	$0.07 ($0.07 to $0.08)
	Very High	-	$1,100 ($1,000 to $1,200)	$830 ($750 to $900)	$85 ($76 to $92)	$0.10 ($0.09 to $0.11)
End-of-Century (2080–2099)	Intermediate	-	$1,100 ($900 to $1,300)	$620 ($540 to $770)	$79 ($68 to $97)	$0.08 ($0.06 to $0.09)
	High	-	$1,600 ($1,400 to $1,800)	$910 ($820 to $1,000)	$120 ($100 to $130)	$0.11 ($0.10 to $0.12)
	Very High	-	$2,200 ($1,900 to $2,600)	$1,200 ($1,100 to $1,500)	$160 ($140 to $180)	$0.15 ($0.13 to $0.18)

Note: Wildfire PM results are only available for Mid-Century Intermediate and High emissions scenarios via Qiu et al. (2025).

Other costs of inaction (not quantified):

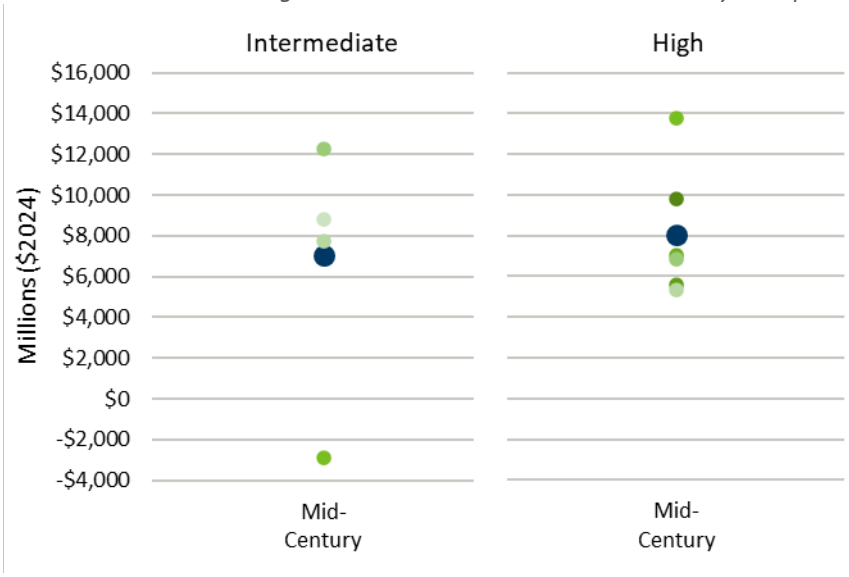
- Adverse maternal health and birth outcomes
- Long-term susceptibility of illness caused by onset of changes in air quality
- Non-medical long-term impacts

Figure 4-4 provides the range of quantified annual costs of inaction for air quality for premature mortality from wildfire $PM_{2.5}$ exposure, ozone mortality, new childhood asthma cases, school loss days, and childhood asthma ED visits. The models are generally in agreement about the expected magnitude of damages, but under the Intermediate emissions scenario, one model projects reductions in premature mortality from wildfire $PM_{2.5}$ compared to the baseline.

[64] A 2024 OECD survey asked parents what they are willing to pay to reduce the severity of asthma of their youngest asthmatic child and what they are willing to pay to reduce the risk that their youngest non-asthmatic child get asthma.
OECD (2024). Insights on "Attitudes towards chemicals" from the surveys on willingness-to-pay to avoid negative chemicals-related health impacts (SWACHE) project, OECD series on risk management of chemicals, OECD Publishing, Paris.

Figure 4-4. Range of Quantified Annual Costs of Inaction: Air Quality (Wildfire Mortality, Air Quality Mortality, New Childhood Asthma Cases, School Loss Days, Childhood Asthma ED Visits)

Annual costs (in millions, 2024$) for the Mid-Century time period and two of the three emissions scenarios (see Section 2.2.2 for more details). The blue dots represent the average across six climate models per scenario, and the green dots show the results for each of the six models. Given the availability of wildfire mortality results, the figure below is limited to the Intermediate and High emissions scenarios in the Mid-Century time period.



Who bears the costs of inaction?

The costs of inaction are primarily borne by the individuals who experience adverse health effects associated with air pollution exacerbated by climate change. Healthcare-related costs are borne by a range of entities, including insurers, employers, taxpayers, and patients.

Certain individuals are more vulnerable and susceptible to air quality-related adverse health effects, including young children whose bodies are still developing and older adults who may not be as resilient to health problems. People with underlying chronic conditions like diabetes, heart disease, or asthma are more susceptible to the impacts of $PM_{2.5}$ and ozone exposure. Beyond those who are already sick, people who live in communities with other physical, social, and emotional stressors are more vulnerable to air pollution impacts. They may live in poor-quality homes that allow outdoor pollution inside or in neighborhoods near major emissions sources like high-traffic roadways or industrial equipment. Air pollution and related healthcare costs often disproportionately burden those who are poor, uninsured, are living with a disability, or are people of color.[65]

What other costs of inaction are not quantified in this study?

This quantified costs of inaction in this study are limited in three ways. First, the analysis only covers a subset of the potential ways climate change impacts human health through changes in air quality:

- Evidence supports that experiencing poor air quality during pregnancy increases the risk of maternal complications (gestational diabetes, preeclampsia/eclampsia) and adverse birth outcomes (preterm birth, term low birth weight, and stillbirth). In progress work by Holland et al. projects these outcomes stemming from exposure to $PM_{2.5}$ and O_3 associated with changes in temperature and precipitation patterns as well as $PM_{2.5}$ associated with wildfire smoke, finding

[65] Minnesota Pollution Control Agency. (2025). The air we breathe: The state of Minnesota's air quality. Available at: http://pca.state.mn.us/sites/default/files/lraq-1sy25.pdf

that the economic cost of these outcomes could increase by over $35 million annually in Minnesota at 4°C of warming (relative to 1986–2005 conditions).[66]

- This study also does not quantify the vulnerability or susceptibility caused by the onset of respiratory, cardiovascular, and other systemic illnesses. Individuals who acquire new onset asthma from exposure to wildfire smoke will be more susceptible to health effects from other environmental pollutants. Qiu et al. (2025) indicate that the mortality impacts of smoke-related $PM_{2.5}$ last up to three years after exposure.[67] This analysis does not capture other short-term healthcare costs associated with non-fatal illnesses, including mental health effects.
- Beyond the direct impacts of climate change on air quality, extreme heat requires increased energy use to support the proliferation of air conditioning in homes, businesses, and schools. Severe weather and natural disasters degrade infrastructure, which also contributes to a need for increased energy usage. In many cases, energy generation requires burning fossil fuels, contributing further to air pollution and worsening climate change through combustion-related emissions which are not quantified in this study.

Second, the valuation methods applied do not capture the full impact associated with the analyzed outcomes. While this analysis captures the pain and suffering associated with premature mortality and childhood asthma through the WTP valuation, it does not include the non-medical costs associated with childhood emergency department visits for asthma or for school loss days.

- For example, the study captures caregiver costs for school loss days when children are not able to be in school because they are sick, but it does not capture the long-term impacts that the children may bear if they frequently miss school due to air pollution-related illnesses. Long-term, missing school leads to lost future earnings.
- Quantified childhood asthma emergency department visit costs include what families pay for an emergency department visit but do not include the costs of adult caregivers missing work, needing to find care for other dependents, over-the-counter medications, or any costs that would occur prior to or after the visit.

Finally, the quantified costs do not include impacts to all age groups based on the scopes of the underlying studies.

- This study quantifies $PM_{2.5}$-attributable mortality for those age 30 and older, thus underestimating the total risk of premature mortality. The study also does not capture any costs related to adult-onset asthma, including adult emergency department visits.
- This study quantifies school loss days for parents with children aged five through 18, underestimating impacts of parents with children under age five.

4.2.2. Costs of adaptation

Adaptation to poor air quality from climate change requires providing clean air both indoors and outdoors for people to breathe. This analysis evaluates the costs of adapting to poor ambient air quality that people are exposed to indoors. The quantified adaptation costs reflect the costs required to reduce air pollution from wildfires that travels through the building envelope into the indoor environment. Current technologies allow cleaning of indoor air through purification and filtration methods that can be obtained through air conditioning and other separate air purifiers. This analysis captures the costs of

[66] Holland, I., I., Neumann, J.E., Papatheodorou, S.I., Basu, R., Sheahan, M. (in preparation). Adverse pregnancy and birth outcomes associated with projected air quality changes in the contiguous United States.
[67] Qiu, M., Li, J., Gould, C.F. et al. Wildfire smoke exposure and mortality burden in the USA under climate change. Nature 647, 935–943 (2025). https://doi.org/10.1038/s41586-025-09611-w

non-air conditioning air purifier investment and operation, as air conditioning is analyzed to capture the costs of adaptation in Section 4.1.2.

To calculate the adaptation **costs of air purifiers,** this analysis estimates ambient $PM_{2.5}$ exposure based on historical trends to determine the time at which households will purchase air purifiers to ensure that the air traveling through the building envelope from outdoors into the home has been cleaned. It assumes that when wildfire $PM_{2.5}$ exposure increases ambient concentrations to above the annual National Ambient Air Quality Standard (NAAQS), all households that do not use central or heat pump air conditioning units (which often provide air filtration) will purchase air purifiers.[68] The analysis includes three options of potential adaptation that reflect different mixes of future A/C technology adoption, consistent with the options used in the air conditioning analysis. Consistent with Yang (2022), this analysis reflects the annualized purchase price across 53 air purifier units assuming a ten-year lifespan.[69] Once households have invested in adaptation, they generally operate air purifier units to mitigate the effects of aeroallergens like pollen.[70] Using a statistical relationship between temperature and pollen season length from Ziska et al. 2019, this analysis estimates changes in future pollen season length when air purifier operation is assumed necessary.[71] Operating costs are adapted from Yang 2022 to better reflect energy costs in Minnesota.[72]

Additional detail on the methods to estimate air quality-related adaptation costs can be found in Appendix B. Table 4-7 provides the adaptation costs of responding to poor air quality created by climate change.

Table 4-7. Quantified Adaptation Costs (Millions per Year): Air quality

Annual costs (in millions, 2024$) for three time periods and two emissions scenarios (see Section 2.2.2 for more details). Costs are incremental to baseline and averaged across six climate models (range across climate models provided in parentheses). See Appendix B for more details on methodology and limitations.

		Air Purifiers: Current Technology Mix*	Air Purifiers: Energy Efficient Technology	Air Purifiers: No A/C*
		Capital and energy costs	Capital and energy costs	Capital and energy costs
Air Quality impacts are also addressed through air conditioning. See adaptation actions addressed in Table 4-3.				
Mid-Century (2040–2059)	Intermediate	$10 ($3 to $24)	$6 ($3 to $8)	$29 ($3 to $65)
	High	$18 ($3 to $42)	$8 ($3 to $13)	$48 ($3 to $110)
Late-Century (2060–2079)	Intermediate	$18 ($4.2 to $58)	$8.4 ($4 to $18)	$49 ($4 to $150)
	High	$26 ($5.7 to $62)	$12 ($5.7 to $21)	$69 ($5.7 to $160)
End-of-Century (2080–2099)	Intermediate	$20 ($6.2 to $63)	$10 ($6 to $22)	$52 ($6.2 to $160)
	High	$30 ($8.7 to $69)	$15 ($8.7 to $26)	$74 ($8.7 to $170)

Note: Air Purifier results are not available for the Very High emissions scenario.
*Indicates an action with multiple alternatives; this alternative is not included in the annual summary.

[68] The National Ambient Air Quality Standard for annual $PM_{2.5}$ concentration is 9.0 µg/m³. NAAQS serve to protect human health.
[69] Yang, A. (2022). The cost of clean air: a price analysis of air filtration technology. arXiv preprint arXiv:2208.06041.
[70] Evergreen Economics *Air Purifiers National Consumer Survey (1)*, Regulations.gov, https://www.regulations.gov/comment/EERE-2021-BT-STD-0035-0009.
[71] Ziska, L. H., Makra, L., Harry, S. K., Bruffaerts, N., Hendrickx, M., Coates, F., ... & Crimmins, A. R. (2019). Temperature-related changes in airborne allergenic pollen abundance and seasonality across the northern hemisphere: a retrospective data analysis. The Lancet Planetary Health, 3(3), e124-e131.
[72] Yang, "The Cost of Clean Air: A Price Analysis of Air Filtration Technology."

	Air Purifiers: Current Technology Mix*	Air Purifiers: Energy Efficient Technology	Air Purifiers: No A/C*
	Capital and energy costs	Capital and energy costs	Capital and energy costs
Other adaptation costs (not quantified):			
• Ambient air quality policy and emissions reductions efforts			

What residual risks remain after adaptation?

Installation of air purifying filters significantly reduces indoor exposure to $PM_{2.5}$. Air purifiers include a series of components to remove different pollutants and ensure the air they deliver is clean. Most home air purifiers boast 85 percent effectiveness at removing particles when installed correctly and maintained appropriately.[73]

Because this analysis does not consider the adaptation costs associated with policy and technology measures required to reduce emissions from wildfires (or wildfire intensity and frequency), the risk of exposure to poor air quality and high concentrations of $PM_{2.5}$ and other wildfire emissions remains. Those who spend significant time outdoors, including outdoor workers, children playing, or people exercising, will continue to face the deleterious consequences of exposure to increased ambient air pollution.

What other effects result from adaptation?

Air purifiers serve to remove $PM_{2.5}$ from the air that enters an indoor environment. While this study analyzes the adaptation costs for reducing $PM_{2.5}$ from wildfires, air purifiers remove $PM_{2.5}$ emitted or generated from any source. Because particulate matter is defined based on its size rather than its composition, filtration of $PM_{2.5}$ also includes filtration of many aeroallergens like pollen and dust. Thus, this adaptation measure has the added benefit of reducing indoor concentrations of $PM_{2.5}$ beyond what is emitted from wildfires. Air purifiers also can remove volatile organic compounds (VOCs) from the air through inclusion of activated charcoal to neutralize the chemicals.

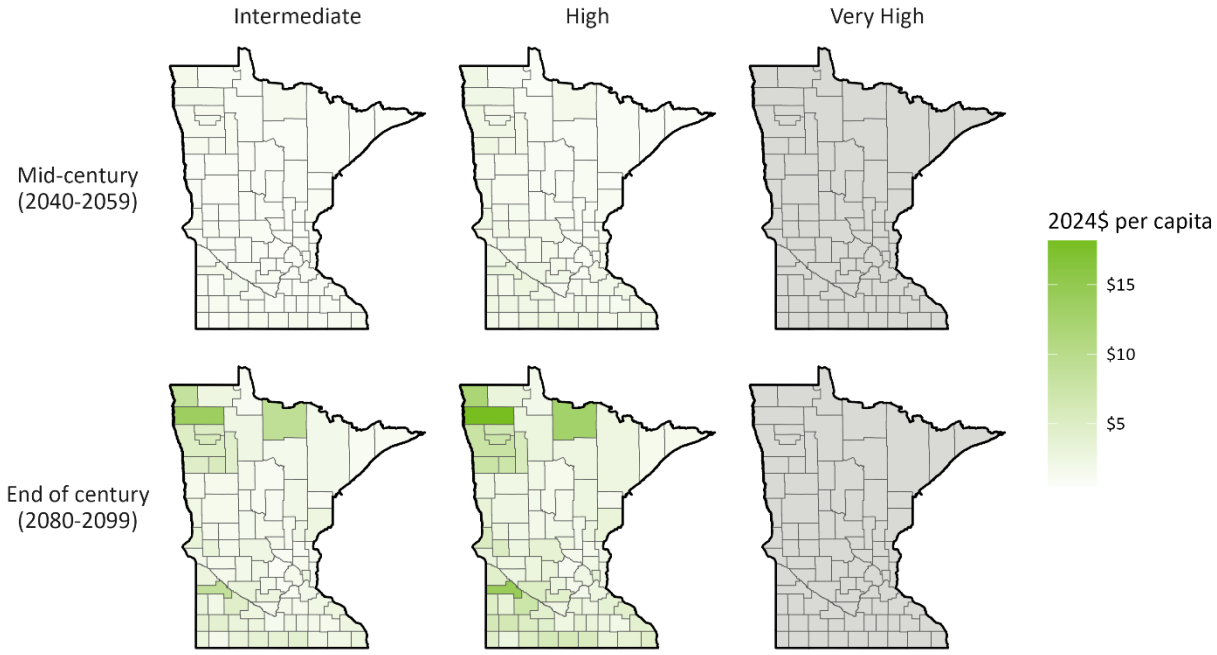
Who pays the adaptation costs?

The air quality-related adaptation cost of purchasing air purifying units is borne by Minnesota's approximately 2.2 million individual households. The estimates assume households with window air conditioning units will purchase air purifiers when ambient air quality exceeds NAAQS, while households with central or heat pump systems use the air purification within these systems to mitigate poor air quality. Estimates of air conditioning penetration are specific to urban and rural counties.[74] By the End-of-Century period, in both the Intermediate and High emissions scenarios, 71 and 20 percent of households in rural and urban counties respectively will operate window units under the Current Technology Mix adoption scenario. Under the Energy Efficient Technology scenario, 42 and 19 percent of households respectively will operate window units.

[73] Yang, "The Cost of Clean Air: A Price Analysis of Air Filtration Technology."
[74] Counties are classified using Census Bureau definitions. Ramsey and Hennepin County are considered urban counties, while all other counties are considered rural.

Figure 4-5. Distribution of energy efficient air purifier costs per capita by county

Annual capital and energy costs per capita of air purifiers in schools (2024$) by county for two time periods and two emissions scenarios (see Section 2.2.2 for more details), averaged across six climate models. Note that results are not available for the Very High emissions scenario.



What are the other costs of adaptation not quantified in this study?

Additional adaptation actions not costed in this study include pollution reduction and individual protection strategies:

- To improve ambient (outdoor) air quality (that does not have a chance to travel indoors), adaptation measures require reductions in pollutant emissions and ambient aeroallergens. In this case, reductions in wildfire emissions require a decrease in their frequency, intensity, and duration. This analysis does not capture costs associated with preventative or other adaptation measures for reducing wildfires primarily because the majority of wildfire-driven air quality issues stem from wildfires occurring outside of Minnesota (namely in Canada), where Minnesota decision makers have limited ability to enact action. The state could make efforts to reduce energy usage and reduce concentrations of ozone precursors that allow for ozone formation in the presence of increased heat and sunlight.
- To otherwise adapt to increased air pollution due to climate change requires personal use of masks or respirators. Masks and respirators that filter small particles (similar to those used during the COVID-19 pandemic) are often single-use and cost between $0.60 and $2.50 per mask, depending on how many are purchased at one time.

4.2.3. Limitations and uncertainties

The quantified adaptation costs presented in this study are illustrative of the magnitude of costs required, though they do not cover all potential reactive and proactive responses to climate change. Key limitations to the analysis are described below; see Appendix B for a full discussion of limitations and uncertainties:

- Morbidity endpoints may not capture the full extent of potential health impacts both in terms of the endpoints analyzed and the full costs of health issues. Additionally, the morbidity cost of illness values applied represent a central estimate, but depending on individual's access to health insurance, high-quality healthcare, time off from work, reliable childcare, and other circumstances, actual individual costs may vary.
- Data from Qiu et al. (2025) only provide information applicable to the Mid-Century and do not include SSP5-8.5. Thus, additional research is needed to fully inform the range of time frames and emissions scenarios.
- Because empirical evidence does not provide information on when homes should purchase air purifiers, this analysis relies on exceeding NAAQS standards to establish a threshold for purchase. If household air purifier investments are inconsistent with this assumption, this analysis may overestimate or underestimate these adaptation costs.

4.3. Vector-borne Disease and Illness

4.3.1. Costs of inaction

Vector-borne diseases such as Lyme disease and West Nile Neuroinvasive disease are dependent on vectors (ticks and mosquitoes, respectively) for the transmission of a disease agent (a bacterium and a virus, respectively) to humans exposed to infected vectors. The ecology of the relevant ticks and mosquitos can be complex, but in Minnesota climate change can result in more favorable overwintering survival and higher activity levels for the deer ticks that carry the Lyme disease bacterium, and more favorable mosquito reproductive conditions and higher abundance in hotter and wetter weather.

Costs of inaction result from human infections from these vectors. The quantified costs of inaction assume these diseases are treated in a hospital setting. Even with treatment, both forms of disease examined here can lead to premature death, though death resulting from Lyme disease is rare. The estimated costs of inaction therefore include two broad categories: direct medical costs of treatment (either insurance claims or estimated hospital costs) and the willingness to pay to avoid the risk of premature mortality associated with a West Nile virus infection.

Estimating changes in the incidence rate of these vector-borne diseases involves consideration of climate-induced changes in the ecology of the vectors themselves, as well as the frequency of outdoor exposure by humans. Both diseases have a high degree of seasonality as well, and because they are related to climate conditions that fluctuate, rates of incidence can vary considerably from year to year and season to season. For West Nile virus, this analysis adapts results from a national-scale study by Belova et al. (2017) that projects incidence by state under multiple future emissions scenarios.[75,76] The Lyme disease analysis similarly relies on a national-scale study with state-level detail (Yang et al. 2024).[77] Additional information on the methods is provided in Appendix B.

The trend in West Nile virus infection costs in Table 4-8 shows an increase over time, as an increased infection rate is mostly influenced by increasing temperatures over time. Costs of inaction for West Nile

[75] 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. https://doi.org/10.4236/ajcc.2017.61010

[76] Belova et al. study does not provide estimates compatible with the High emissions scenario analyzed in this study.

[77] Yang. H., C.A. Gould, R. Jones, A. St Juliana, M. Sarofim, M. Rissing, M. B. Hahn (2024). By-degree Health and Economic Impacts of Lyme Disease, Eastern and Midwestern United States. *Ecohealth*. 21(1), 56-70, doi:10.1007/s10393-024-01676-9. Available online at https://pubmed.ncbi.nlm.nih.gov/38478199/

virus are also dominated by the risk of premature mortality; according to a literature review conducted for Belova et al. (2017), approximately 6.5 percent of the more serious West Nile virus infections that lead to West Nile Neuroinvasive disease result in death.

The trend in costs in Table 4-8 and Figure 4-6 for Lyme disease cases, however, shows an increase above the current incidence in Minnesota through Mid-Century, and then a decline in those cases in the Late-Century and End-of-Century periods. This trend for Lyme disease, reflects the complex interactions in the ecology of deer ticks, their non-human host species, and human activity that leads to exposure. Yang et al. (2024) consider all three of these factors at county scale to estimate a probability of Lyme disease infections. The highest joint probability of infection, where all three of these factors line up, occurs in Minnesota at a point that is roughly two degrees Celsius higher than the baseline global temperature – which corresponds roughly to the Mid-Century period depicted in Figure 4-6. At higher levels of global warming, the probability of infection declines somewhat from that peak level but remains above the baseline human infection probability.

Table 4-8. Quantified Costs of Inaction (Millions per Year): Vector-borne Disease and Illness

Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). Costs are incremental to baseline and averaged across six climate models (range across climate models provided in parentheses). See Appendix B for more details on methodology and limitations.

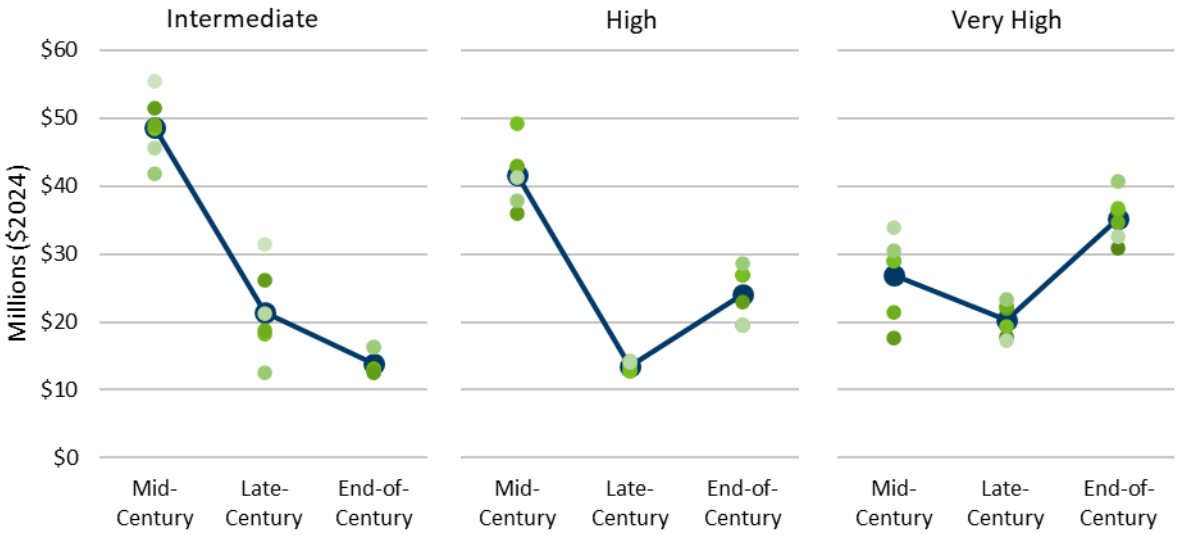
		Lyme Disease Morbidity	West Nile Virus Mortality	West Nile Virus Morbidity
		Insurance claim costs	Value of a statistical life (VSL)	Hospital costs
Mid-Century (2040–2059)	Intermediate	$49 ($42 to $55)	$13	$0.7
	High	$42 ($36 to $49)	-	-
	Very High	$27 ($18 to $34)	$16	$0.9
Late-Century (2060–2079)	Intermediate	$21 ($13 to $31)	$21	$1.2
	High	$13 ($13 to $14)	-	-
	Very High	$20 ($17 to $23)	$44	$2.5
End-of-Century (2080–2099)	Intermediate	$14 ($12 to $16)	$33	$1.9
	High	$24 ($19 to $29)	-	-
	Very High	$35 ($31 to $41)	$87	$5.0

Note: West Nile virus results are only available for the climate model average for the Intermediate and Very High emissions scenarios.

Other costs of inaction (not quantified):

- Other tick and mosquito-borne infections

Figure 4-6. Range of Quantified Annual Costs of Inaction: Vector-borne Disease and Illness (Lyme Disease)
Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). The solid lines with blue dots represent the average across six climate models per scenario, and the green dots without lines show the results for each of the six models. Note that West Nile virus mortality and morbidity only have results for an average across climate models, so they are not included in this figure.



Who bears the costs of inaction?

The morbidity and mortality risks are borne by Minnesota's population, and in particular, by those whose outdoor activity patterns are more likely to bring them in contact with the relevant tick and mosquito vectors during their most active periods. This includes individuals who work and recreate outdoors during the peak exposure summer months. However, both types of exposures also occur in settings where any resident could be exposed, including suburban backyards and urban parks. The economic burden of morbidity is moderated to some extent by health insurance, but over time higher risks of incidence will be passed on to the broader population by increasing health insurance premiums.

What other costs of inaction are not quantified in this study?

Ticks and mosquitos also cause other types of disease that are not quantified in this study. For example, the range of lone star ticks, which are currently present in Minnesota but only rarely found, could expand northward and increase the risk of potentially life-threatening alpha-gal syndrome (red meat allergy), although this is not currently a well-studied topic.[78] Other mosquito-borne viral infections common in tropical and subtropical regions or other parts of the U.S., such as eastern equine encephalitis, dengue fever, and Zika, have serious consequences but have either not been encountered in Minnesota or are exceedingly rare.

4.3.2. Costs of adaptation

The quantified costs of adaptation to address the risks of vector-borne disease reflect the costs of increased mosquito control activities in the area managed by the Metropolitan Mosquito Control District (MMCD).

[78] See the Minnesota Department of Health information on alpha-gal syndrome here: https://www.health.state.mn.us/diseases/alphagal/index.html and the Metropolitan Mosquito Control District information on mosquito and tick-borne diseases here: https://mmcd.org/diseases-to-know/

Mosquito control activities ramp up in response to elevated levels of reported West Nile virus infections (based on conversations with Minnesota experts on this topic). The analysis compares 10 years of budget data for the MMCD with U.S. Centers for Disease Control and Prevention (CDC) data on reported West Nile virus infections to find that operating costs are higher in years with high infection rates.[79] The estimate of the potential increase in the costs of mosquito control activities is calculated using the projected increases in West Nile virus infection (described above, under the costs of inaction).

A more detailed explanation of methods can be found in Appendix B. The results shown in Table 4-9 below indicate that mosquito control costs are less than the costs of inaction, but that these costs are likely to increase in the future as the risk of infection grows.

Table 4-9. Quantified Adaptation Costs (Millions per Year): Vector-borne Disease and Illness

Annual costs (in millions, 2024$) for three time periods and two emissions scenarios (see Section 2.2.2 more details). Costs are incremental to baseline and averaged across six climate models (range across climate models provided in parentheses). See Appendix B for more details on methodology and limitations.

		Mosquito Control: Treatment
		Operating costs
Mid-Century (2040–2059)	Intermediate	$1.9
	Very High	$2.3
Late-Century (2060–2079)	Intermediate	$2.4
	Very High	$5.1
End-of-Century (2080–2099)	Intermediate	$3.0
	Very High	$7.9
Note: Results for this analysis are only available for the climate model average for the emissions scenarios. Results are not available for the High emissions scenario.		
Other adaptation costs (not quantified): • Investment into education to diagnose and limit exposure and adverse health effects • Health surveillance		

What residual risks remain after adaptation?

Residual risks are likely to be concentrated in rural areas outside of the MMCD operational area, where typical mosquito control practices (e.g., spraying and standing water treatment) are not practical.

What other effects result from adaptation?

In the absence of an effective vaccination for humans, vector control remains the primary method for preventing and containing West Nile virus outbreaks. An integrated vector management strategy utilizes a combination of vector surveillance tools to guide vector control interventions at the right time and place, in response to elevated risk.[80] The treatment of water bodies for mosquito control may have

[79] According to conversations with Minnesota experts, higher adaptation action could also be linked to years with higher rainfall, when standing water that fosters mosquito reproduction is more common, but rainfall data proved to be a less reliable indicator of adaptation activity in the data analysis conducted for this study.

[80] European Centre for Disease Prevention and Control. Vector control practices and strategies against West Nile virus. Stockholm: ECDC; 2020; and Centers for Disease Control (2024), West Nile Virus Surveillance and Control Guidelines, available at: https://www.cdc.gov/west-nile-virus/media/pdfs/2024/08/WestNileVirus-SurveillanceControlGuidelines_508-h.pdf

unintended consequences for ecosystems and, perhaps rarely, for human health. Modern treatments and spraying techniques (for example, strategic timing of spraying) are designed to minimize these effects, and the CDC concludes that the health risks from mosquito-borne viruses demonstrably exceed the risks from mosquito control practices (CDC 2024).[81]

Who pays the adaptation costs?

The mosquito control adaptation costs estimated here are incurred by the MMCD, whose budget is funded by property tax collected from the seven participating counties: Ramsey, Hennepin, Anoka, Washington, Dakota, Scott, and Carver Counties.

What are the other costs of adaptation not quantified in this study?

Other adaptation actions have been conducted historically and likely will be needed, and perhaps expanded, in the future, including the following:

- Additional limitation of individual exposure to vectors through use of insect repellants and avoidance behavior.
- Additional or expanded education campaigns to ensure both exposure avoidance and quick diagnosis of Lyme disease to limit adverse health effects.
- The potential need for additional health surveillance for both vectors and infection, which is a critical element in triggering vector control activities.

This study does not quantify any increase in these types of costs beyond current costs.

4.3.3. Limitations and uncertainties

The quantified adaptation costs presented in this study are illustrative of the magnitude of costs required, though they do not cover all potential reactive and proactive responses to climate change. Key limitations to the analysis are described below; see Appendix B for a full discussion of limitations and uncertainties:

- The costs of inaction are driven by the expectation of a substantial increase in the need for Lyme disease treatment in Mid-Century and by End-of-Century by anticipated mortality from West Nile virus infections, which are monetized using the VSL. Climate change-attributed West Nile virus mortality reaches <5 deaths per year by End-of-Century. Technological advances in diagnosis and treatment, however, could reduce the need for or costs of treatment over time. For example, vaccines for both Lyme disease and West Nile virus have been under development for many years and could be effective means of prevention of serious impacts from infection.
- The outdoor recreation analyses presented in this study suggest that people will spend more time outside recreating under warmer climate conditions which could result in additional risk of vector-borne disease and illness that are not captured in this analysis.
- The quantified adaptation costs do not include any actions addressing tick-borne diseases, but the expected rapid rise in Lyme disease infection rates in Minnesota through Mid-Century may increase the need for new vector control and educational campaigns to limit exposures.

[81] Centers for Disease Control. (2024). West Nile Virus Surveillance and Control Guidelines, available at: https://www.cdc.gov/west-nile-virus/media/pdfs/2024/08/WestNileVirus-SurveillanceControlGuidelines_508-h.pdf

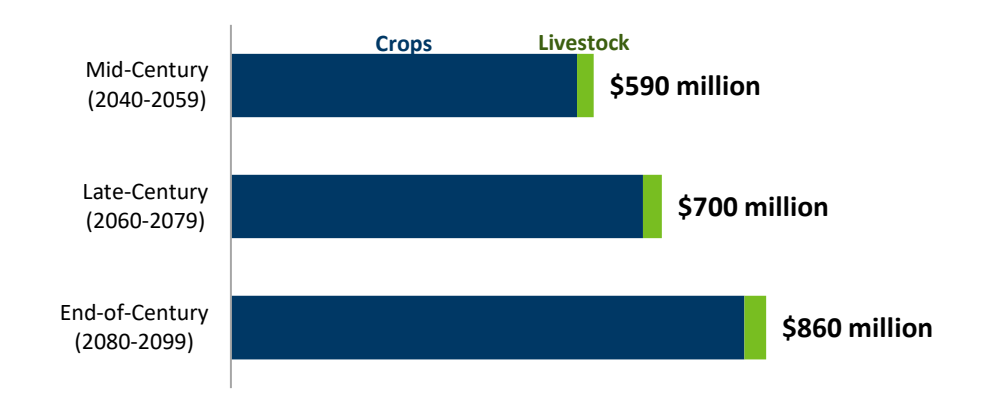
5. Cost of climate change: Agriculture and Livestock

Key takeaways: Agriculture and Livestock

- Changing temperature and precipitation patterns will very likely impact agricultural productivity in Minnesota. This study quantifies adaptation costs for climate impacts on select **crops** and **livestock.**
- A portion of the anticipated lost crop productivity may be alleviated by an expansion of irrigated capacity. Assuming no water curtailment or limited groundwater availability, an investment of $700 million annually in irrigation for corn, soybean, and wheat by the end of the century could prevent $3.1 billion in productivity losses annually under the High emissions scenario.
- Other adaptation investments quantified in this analysis include increased use of in-field tile drainage as well as retention ponds to hold drainage outflows and barn cooling costs for livestock.
- Additional adaptation needs not quantified in this analysis include actions such as switching crop types, employing soil conservation methods, and implementing pest and disease management strategies.

Quantified Annual Adaptation Costs by Period (High Emissions Scenario)

These costs are incremental of baseline adaptation costs and only include the quantified adaptation actions.



Agriculture is a critical part of Minnesota's economy. About half of the state is farmland, and primary agricultural revenue in Minnesota totals $26 billion per year, of which 61 percent are from crops and 39 percent are from livestock. The combined agricultural production, processing, and support industries make up over 15 percent of Minnesota's economic activity and over 10 percent of jobs.[82]

[82] Minnesota Department of Agriculture. (2023). Minnesota Agricultural Facts and Stats. https://www.mda.state.mn.us/sites/default/files/inline-files/MNAgFactsStats2023.pdf

Climate change is expected to affect agriculture in many ways, including through the selected impacts listed below, along with their associated potential adaptation actions.[83] This study quantifies and costs the items in bold.

Table 5-1. Costs of Inaction (Climate Impacts) and Potential Adaptation Actions for Agriculture and Livestock
Summary of costs of inaction and potential adaptation actions. Items in bold are quantified in this study.

Costs of Inaction	Potential Adaptation Actions
Higher temperatures cause **crops to require more water** as they grow. Changes in rainfall amounts and seasonality can further affect yields.	**Increased irrigation,** use of cover crops, reduced tillage, switching to drought-tolerant varieties, adjusting planting timing, enhanced on-farm water storage.
Higher temperatures also **reduce livestock productivity,** including dairy and poultry.	**Install and operate barn cooling,** adopt more heat-tolerant species in stocking choices, modify feed and pest management practices.
Higher soil moisture makes it **difficult for machinery to work the fields** during critical planting seasons.	**Install drainage systems and water storage systems,** shift timing of planting season.
Changing suitability zones increase threats from pests, diseases, and animal pathogens.	Increased monitoring, pest-resistant crop selection.

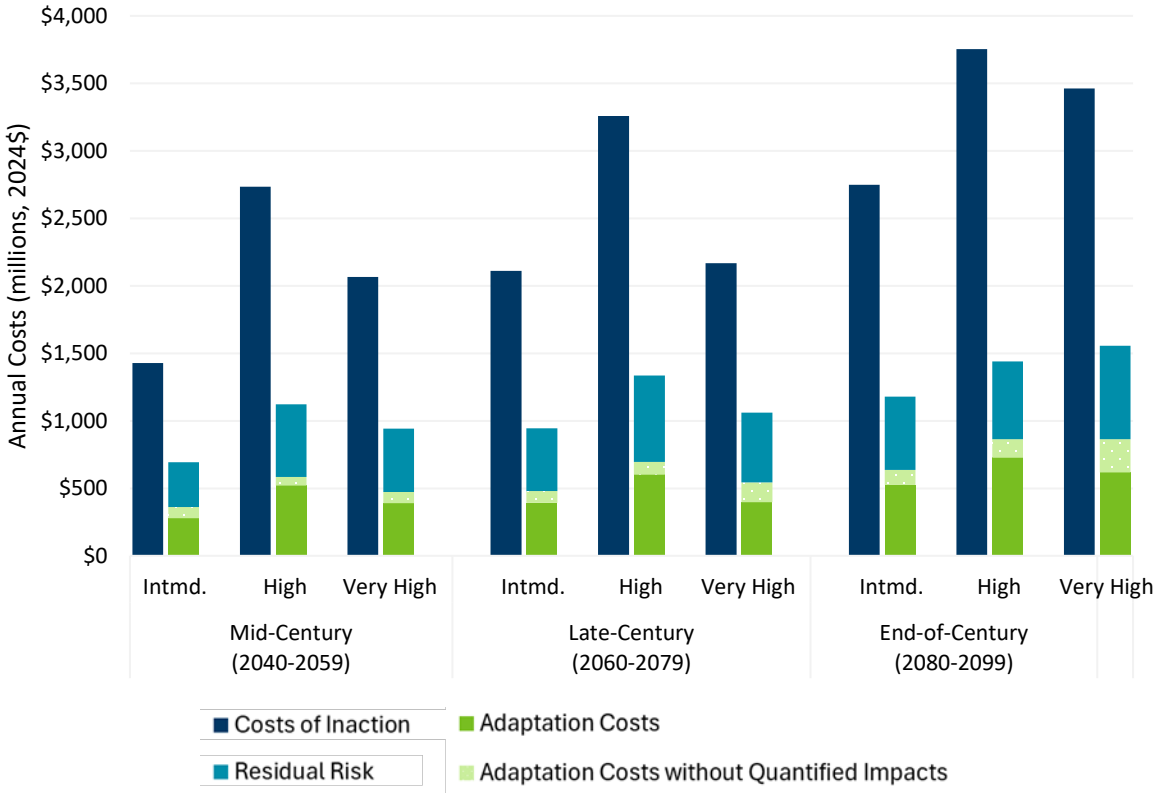
In Minnesota, the agriculture sector is already dealing with the effects of a more variable climate. Loss ratios, which represent the ratio of insurance losses to premium and are a good indicator of droughts and commodity crop productivity over time, have risen since 2015, with 10-year peaks in 2019 and 2024.[84, 85] Since 2020, a period of variable precipitation has resulted in substantial increases in agricultural irrigation.[86] In 2021, one of the worst droughts in recent memory resulted in nearly 3,000 applications for the Agricultural Drought Relief Program, requesting assistance for a total of $19 million in eligible expenses.[87]

This analysis quantifies costs of inaction, adaptation costs, and residual risk for a subset of potential costs to the agricultural sector, focusing on corn, soy, and wheat (hereafter referred to as crops), dairy, and turkey production.[88] The figure below summarizes the quantified costs of inaction, adaptation costs, and residual risk (meaning, the damages that persist with adaptation – See Section 1.2.6 for more information on residual risks) related to agriculture. Note that the costs in this figure are not comprehensive but rather represent the quantifiable costs in this study.

[83] Roop, H. A., Meyer, N., Klinger, G., Blumenfeld, K., Liess, S., Farris, A., Boulay, P., Baule, W., Andresen, J., Bendorf, J., Wilson, A. B., Nowatzke, L., Todey, D., & Ontl, T. (2024). Climate Change Impacts on Minnesota Agriculture. United States Department of Agriculture Climate Hubs, University of Minnesota Climate Adaptation Partnership and Great Lakes Research Integrated Science Assessment. https://www.climatehubs.usda.gov/sites/default/files/Climate%20Change%20Impacts%20on%20Minnesota%20Agriculture.pdf
[84] US Department of Agriculture Risk Management Agency, "State/County/Crop Summary of Business," n.d., accessed December 19, 2025, https://www.rma.usda.gov/tools-reports/summary-of-business/state-county-crop-summary-business.
[85] US Department of Agriculture Risk Management Agency, Minnesota State Profile - 2019 (n.d.), https://www.rma.usda.gov/about-crop-insurance/fact-sheets/minnesota-state-profile-2019.
[86] Minnesota Department of Natural Resources. (2025). Water Availability and Assessment Report 2025 https://www.eqb.state.mn.us/sites/eqb/files/appendix_c.pdf
[87] MDA. 2021 Agricultural Drought Relieve Program. https://www.mda.state.mn.us/droughtrelief
[88] Note that forestry impacts are discussed in the Ecosystems chapter and impacts to agricultural workers are discussed in the Health and Wellbeing chapter.

Figure 5-1. Agriculture and Livestock: Quantified Annual Climate Cost Summary

Summary and comparison of cost of inaction (first set of bars, in dark blue), adaptation costs (base of the second set of bars, in green; where light green represents adaptation costs without quantified impacts), and residual risk (top of second set of bars, in light blue) per year, above baseline. Results for three time periods and three emissions scenarios (see Section 2.2.2 for more details), averaged across six climate models.



The remainder of this chapter includes two main sections, addressing the two main categories of agricultural production with quantified adaptation costs: **Crops** and **Livestock.** Within each of these two main sections, there are subsections for **Costs of inaction, Costs of adaptation,** and **Limitations and uncertainties.** Both cost subsections provide a high-level methodology description, detailed results, and further interpretation of the findings, including how costs are distributed across the state and which costs are not quantified in this study. Step-by-step detail on methods and specific citations to data sources, models, and peer-reviewed studies that provide a basis for estimating costs can be found in Appendix B.

5.1. Crops

5.1.1. Costs of inaction

Without further adaptation, climate change will continue to impact crop yields. The costs of inaction presented in Table 5-2 reflect modeled changes in yield for three crops (corn, soybean, and wheat) due to changes in temperature and rainfall (both magnitude and seasonality). The analysis first calculates monthly crop evapotranspiration requirements and available water supply from precipitation for each crop in each county, which are then used to calculate annual water deficits. These are then converted to yield deficit using yield response coefficients, which are compared against a historical baseline to calculate yield changes. Of the three modeled crops, corn is expected to see the highest percent yield declines because it has the highest sensitivity to water stress, as well as the highest absolute monetary

losses due to its large share of the market. The largest impacts are anticipated in the High emissions scenario, which is projected to see the largest declines in precipitation across the state.

See Appendix B for more details on methodology and limitations.

Table 5-2. Quantified Costs of Inaction (Millions per Year): Crops

Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). Costs are incremental to baseline and averaged across six climate models (range across climate models provided in parentheses). See Appendix B for more details on methodology and limitations.

		Corn	Soybean	Wheat
		Lost production value	Lost production value	Lost production value
Mid-Century (2040–2059)	Intermediate	$1,000 (-$440 to $3,300)	$330 (-$130 to $1,000)	$45 (-$88 to $190)
	High	$1,900 ($780 to $3,300)	$650 ($260 to $1,100)	$110 ($22 to $260)
	Very High	$1,500 (-$1,100 to $3,700)	$480 (-$390 to $1,300)	$100 (-$59 to $240)
Late-Century (2060–2079)	Intermediate	$1,500 (-$370 to $3,400)	$470 (-$120 to $1,100)	$82 (-$31 to $230)
	High	$2,300 ($970 to $4,300)	$770 ($370 to $1,400)	$170 ($89 to $320)
	Very High	$1,500 (-$1,300 to $4,600)	$510 (-$400 to $1,500)	$95 (-$100 to $280)
End-of-Century (2080–2099)	Intermediate	$1,900 (-$940 to $3,400)	$650 (-$280 to $1,100)	$120 ($17 to $270)
	High	$2,700 ($2,000 to $3,500)	$860 ($580 to $1,100)	$160 ($65 to $230)
	Very High	$2,400 (-$120 to $3,700)	$790 (-$47 to $1,200)	$140 (-$1 to $190)

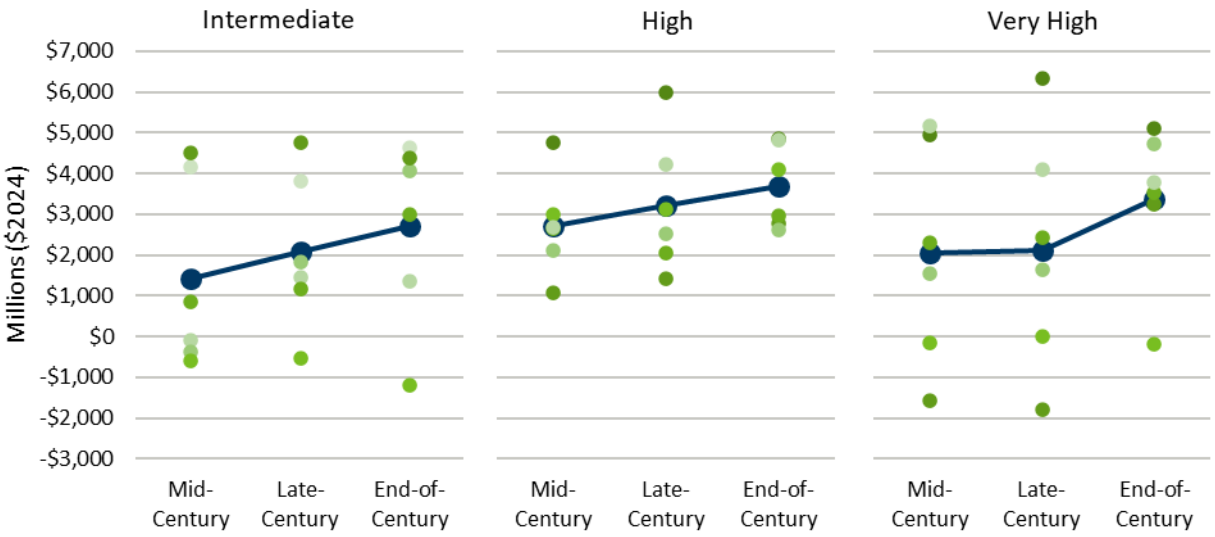
Other costs of inaction (not quantified):

- Impacts to other commodity and specialty crops beyond corn, soybean, and wheat
- Heat stress on crops' sensitive growth stages
- Impacts of changes in soil moisture on crop yields and field trafficability
- Impacts of floods on crop yields, including topsoil erosion, timing of planting and harvest, and soil contamination
- Effects of pests, wildfires, air quality, and other climate stressors

While projections on average show losses for all three crops for nearly all scenarios and time horizons, the range of projected impacts spans from possible declines in yields to increases in yields. Projected crop production impacts vary significantly across climate models due to differences in projected precipitation. Some of the projected impacts are in the form of increased yields where precipitation is expected to increase during the growing season, but most models show declines, reflecting lower projected rainfall in key months.[89]

[89] Note that the analysis assumes the growing season does not change, though farmers do have some flexibility to start earlier or later and avoid some of these losses.

Figure 5-2. Range of Quantified Annual Costs of Inaction: Crops (Corn, Soybean, Wheat)
Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). The solid lines with blue dots represent the average across six climate models per scenario, and the green dots without lines show the results for each of the six models. Negative costs reflect projected improvements in yields relative to the baseline.



Who bears the costs of inaction?

These costs of inaction are primarily borne by farmers (individuals and corporations), mostly in rural areas in the south and west of the state. Note that at least some of these projected costs of inaction may be compensable under the Federal Crop Insurance Program, shifting the burden to the program and/or to program premium payers nationwide. The program has seen an increase in indemnified losses associated with drought and high temperature, however,[90] which might not be sustainable over time and could lead to increases in insurance premiums paid by Minnesota farmers. Changes in crop production may also have indirect effects on food processing and retail markets. Uncertainties in the assessment of the costs of inaction include the water sensitivity of the specific crop varieties used in Minnesota and farmers' ability to adjust the crop season to reflect changes in seasonal precipitation.

What other costs of inaction are not quantified in this study?

Other important costs of inaction to crops, not quantified above, include:

- Impacts to other economically important crops, such as sugar beets and potatoes, as well as impacts to hay. The three modeled crops account for 79 percent of cropland, but the combined impact across all other crops may also be significant.[91]
- Heat stress on crop yields due to increased temperatures and heat waves. Corn is a generally heat-tolerant crop. Other crops may be significantly affected by heat stress. Globally, the literature suggests these effects can be consequential, potentially leading to crop failure during extreme heat years.
- Flooding damages to crops due to periods of increased precipitation.

[90] See the USDA Economic Research Service "Risk Management - Crop Insurance at a Glance" summary at: https://www.ers.usda.gov/topics/farm-practices-management/risk-management/crop-insurance-at-a-glance
[91] USDA. (2024). Quick Stats. Census of Agriculture, 2022. https://quickstats.nass.usda.gov/.

- Increased soil erosion and nutrient loss from periods of increased precipitation.
- Increased threat of pests, diseases, and invasive species due to shifting suitability zones. For example, analysis of Natural Resource Canada's Insect and Disease Risk Maps shows the suitable range for soybean aphids could approximately double by Mid-Century under both the Intermediate and Very High scenarios. By End-of-Century, suitable area declines in both scenarios, even decreasing below the current extent in the Very High scenario.[92]
- Flood or other climate-driven impacts to transportation infrastructure used to bring agricultural products to market.[93]
- Indirect economic impacts to the food processing industry and related employment opportunities.

5.1.2. Costs of adaptation

Farmers may choose to take any number of actions to avoid the impacts of climate change described above. Costs for two of those potential actions, namely expanding irrigation use and installing on-field drainage and drainage outflow storage systems, are presented below in Table 5-3.

- To estimate the adaptation costs associated with **increased irrigation,** farmers are assumed to install irrigation infrastructure when the benefits exceed the costs by a ratio of 2:1, based on the cost of inaction analysis described above. The model utilizes a ratio of two to account for inefficiencies not captured by the model, such as suboptimal investment due to farm characteristics or nutrient leaching. The analysis is done at the county level, such that all farms within a county make the same adaptation decisions each time period.[94] Irrigation costs include capital costs[95] (to install equipment) and operations and maintenance costs, including electricity and labor costs.
- To estimate the adaptation costs associated with the **increased need for field drainage** due to changes in soil moisture, the analysis computes the Design Drainage Rate[96] for each county and soil type under historical climate conditions and under the different emissions scenarios and time periods. The change in the Design Drainage Rate under altered climate conditions drives changes in the optimum drain spacing, from which the investment costs associated with additional tile drainage are estimated using unit costs from Ghane et al. (2021).[97]
- As increased tile drainage can introduce more runoff into the system, potentially exacerbating flooding, and is associated with water quality concerns and other impacts downstream, the costed adaptation actions also include the costs of **retention ponds to hold field drainage outflows.** Retention ponds are sized so as to be able to hold two days' worth of drainage water when the drains are operating at their peak discharge rate (i.e., their Design Drainage Rate), with unit costs from EPA (2015).[98] Both the tile drainage and retention pond cost estimates are

[92] NRCan. (2020). Forest Insect and Disease Risk Maps. https://cfs.cloud.nrcan.gc.ca/bmfid/bmfid.php?lang=e
[93] See Transportation and Electricity Infrastructure chapter for a general discussion on infrastructure impacts and adaptation costs.
[94] The decision to irrigate is made once per time period and emissions scenario based on the average outcome across climate models. Based on that decision, the residual risk, or the remaining lost yields are calculated per climate model.
[95] Capital cost inputs were annualized over the lifespan of the equipment, reflecting depreciation and interest.
[96] Ghane, E., Askar, M. H., & Skaggs, R. W. (2021). Design drainage rates to optimize crop production for subsurface-drained fields. Agricultural Water Management, 257, 107045.
[97] Ibid.
[98] EPA. (2015). Low Impact Development Stormwater Control Cost Estimation Analysis. https://pasteur.epa.gov/uploads/10.23719/1510483/documents/LID%20Cost%20Analysis_Report_National%20SWC_2015.pdf

conducted for individual soil types, with costs aggregated to the county and state level depending on the number of hectares of each soil type per county.

Table 5-3. Quantified Adaptation Costs (Millions per Year): Crops

Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). Costs are incremental to baseline and averaged across six climate models (range across climate models provided in parentheses). See Appendix B for more details on methodology and limitations.

		Corn Irrigation	Soybean Irrigation	Wheat Irrigation	Tile Drainage System	On-site Retention Ponds
		Irrigation Cost	Irrigation Cost	Irrigation Cost	Capital installation cost	Capital installation cost
Mid-Century (2040–2059)	Intermediate	$240	$0	$14	$15 ($0.9 to $33)	$65 ($3.3 to $140)
	High	$400	$50	$45	$13 ($0 to $51)	$47 ($0 to $200)
	Very High	$320	$0	$41	$16 ($0 to $43)	$63 ($0 to $170)
Late-Century (2060–2079)	Intermediate	$330	$0	$34	$17 ($0 to $32)	$67 ($0 to $130)
	High	$450	$61	$63	$19 ($0 to $52)	$69 ($0 to $200)
	Very High	$330	$0	$38	$28 ($1.6 to $51)	$110 ($8.3 to $210)
End-of-Century (2080–2099)	Intermediate	$400	$51	$48	$22 ($0 to $42)	$84 ($0 to $160)
	High	$500	$140	$61	$27 ($5.0 to $98)	$100 ($23 to $330)
	Very High	$480	$60	$53	$57 ($2.3 to $140)	$180 ($11 to $410)

Note: The decision to irrigate is modeled each time period based on the average outcome across climate models, therefore there is no range. The $0 results for soybeans reflect time period-scenario combinations where irrigation may not make financial sense; see residual risks discussion.

Other unquantified adaptation costs:

- Switching to more resilient crops
- Switching to heat- or drought-tolerant varieties
- Use cover crops
- Conservation tillage (reduced or no till)
- Pest and disease management
- Precision agriculture

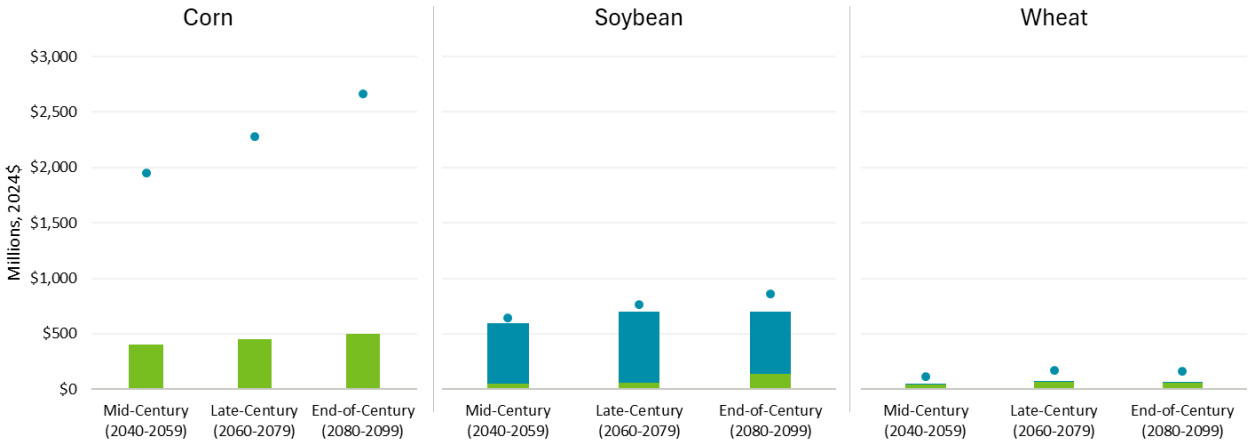
What residual risks remain after adaptation?

Irrigation can nearly eliminate yield reductions from water stress. However, it is unlikely that all farms will fully implement irrigation given that in some cases, the cost of irrigation will be higher than the projected losses associated with water stress from climate change. The remaining impacts to crop yields, after irrigation decisions are made, are characterized as residual risks. The analysis of residual risk is done at the county level, such that all farms within a county install irrigation when the benefits exceed the costs by a ratio of 2:1. Residual risks associated with field trafficability are not able to be modeled.

Figure 5-3 shows how the costs of inaction (production losses), adaptation costs (irrigation costs), and residual risks (production losses remaining after irrigation investments) compare by crop and time period. Importantly, the modeled soybean irrigation costs are relatively low compared to the costs for corn, but the lower investment in irrigation means that significant production losses persist. In all cases, the irrigation costs plus residual risks are less than the costs of inaction.

Figure 5-3. Quantified Adaptation Costs and Residual Risks versus Costs of Inaction, by Crop

Annual costs (in millions, 2024$) for irrigation (green bar segments) and the yield losses that remain with the implemented irrigation (blue bar segments). Costs of inaction (blue dots) are shown for reference – adaptation plus residual risks are always less than the costs of inaction. Results reflect the High emissions scenario, though similar patterns persist across all modeled emissions scenarios.



What other effects result from adaptation?

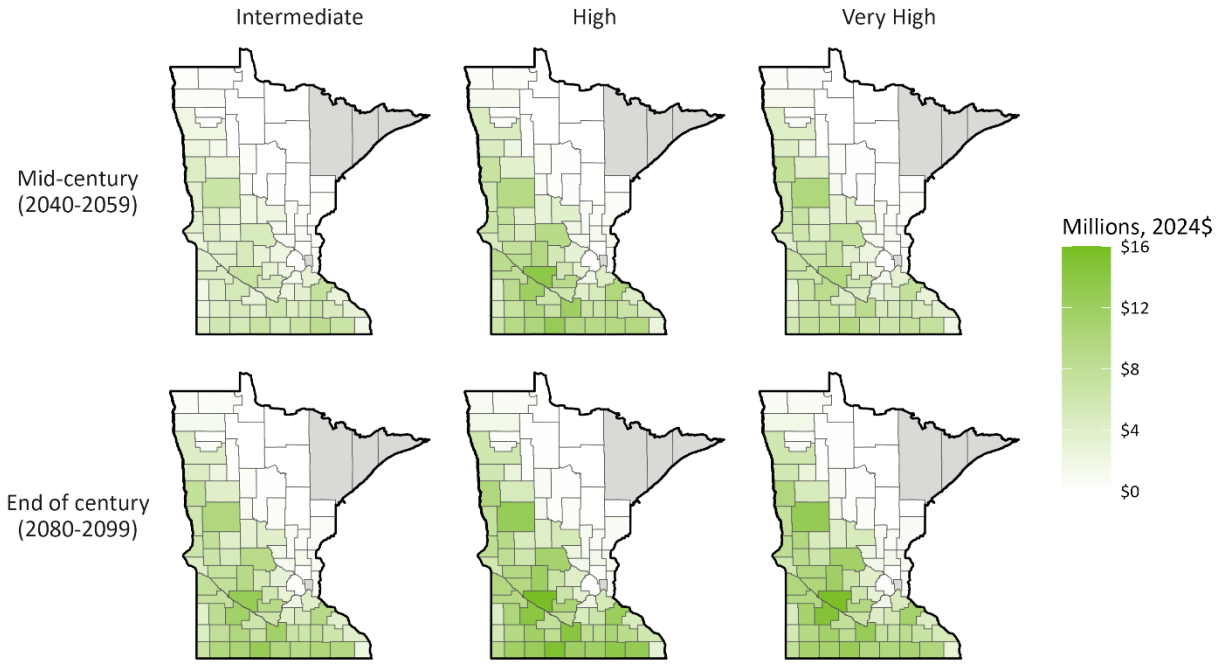
In addition to improving crop yields, investing in adaptation can bring about additional benefits such as the ability to grow higher-value, more water-sensitive crops that need consistent water supply. In addition, as introduced above, changes in soil moisture and field trafficability may drive increased reliance on tile drainage in fields, which can be associated with flooding and downstream water quality issues. To mitigate this downstream issue, the assessment of adaptation costs for field drainage includes costs associated with retention ponds to store drainage water.

Who pays the adaptation costs?

Looking in more detail at the spatial distribution of irrigation costs across the state, projected costs mainly follow the pattern of harvested area. Figure 5-4 below shows the distribution of irrigation costs for growing corn as an example. These projects would be implemented by farmers in rural parts of the state, and absent funding from other sources they would bear the costs.

Figure 5-4. Distribution of Corn Irrigation Costs by County

Annual costs of increased irrigation need (millions, 2024$) by county for two time periods and three emissions scenarios (see Section 2.2.2 for more details), averaged across six climate models. Counties in gray do not have significant farmland area.



What are the other costs of adaptation not quantified in this study?

The costs reported above do not reflect a comprehensive estimate of costs of adaptation, quantifying only a subset of the costs. Other, potentially important adaptation costs include:

- Switching to more resilient crops in areas where yield impacts to corn, a crop with high water requirements and sensitivity, make its production prohibitive compared to other grains;
- Increasing adoption of heat- or drought-tolerant varieties of currently produced crops;
- Utilizing cover crops to improve moisture and nutrient retention;
- Expanding reduced or no-till agriculture to improve moisture and nutrient retention;
- Pest and disease management to decrease effects from increased heat; and
- Implementing precision agriculture techniques using GPS or automation to plant seeds and monitor growth, which can increase yields and reduce irrigation needs, with potential for indirect benefits of reducing excessive fertilizer runoff.

5.1.3. Limitations and uncertainties

The quantified adaptation costs presented in this study are illustrative of the magnitude of costs required, though they do not cover all potential reactive and proactive responses to climate change. Crop yields and water availability are complex systems, and adaptation decisions are made by individual farmers, not uniformly across entire counties. Key limitations to the analysis are described below; see Appendix B for a full discussion of limitations and uncertainties:

- The crop yield results presented here capture the impacts of water stress on crops but do not capture additional climate stressors such as extreme temperature stress or pests.

- Corn, soybean, and wheat account for most of the total acres planted and production value, however the combined impact across all other crops that are not modeled may also be significant.
- Irrigation water is assumed to be groundwater, and the analysis does not account for any potential limits on groundwater supply. Irrigation operating costs could increase in the future if groundwater table lowers. Groundwater use for agricultural irrigation has grown substantially since 2020 due to a period of variable precipitation. In some areas, groundwater levels have decreased due to growing demand and seasonally intensive use.[99] Increased groundwater take may also negatively impact nearby well owners. See Section 8.2 for a further discussion of future water availability.

5.2. Livestock

5.2.1. Costs of inaction

Livestock, including dairy cattle and poultry, are vulnerable to changing climate conditions that can reduce productivity and increase the risk of mortality. This study quantifies the costs of inaction in terms of the effect of heat and humidity stress on cattle milk yields, shown in Table 5-4. Dairy cattle operations in Minnesota typically do not currently have the equipment necessary to mitigate the risks of high temperatures, so on very hot days, milk production will decrease without further investments. Losses increase later in the century due to more significant temperature increases, with more instances of daily temperatures crossing heat stress thresholds. Across all emissions scenarios and models, projected dairy livestock production is projected see consistent losses through the end of the century. The modeled losses capture lost production value, but do not account for the indirect impacts of these losses on industries that rely on dairy products.

See Appendix B for more details on methodology and limitations.

Table 5-4. Quantified Costs of Inaction (Millions per Year): Livestock

Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). Costs are incremental to baseline and averaged across six climate models (range across climate models provided in parentheses). See Appendix B for more details on methodology and limitations.

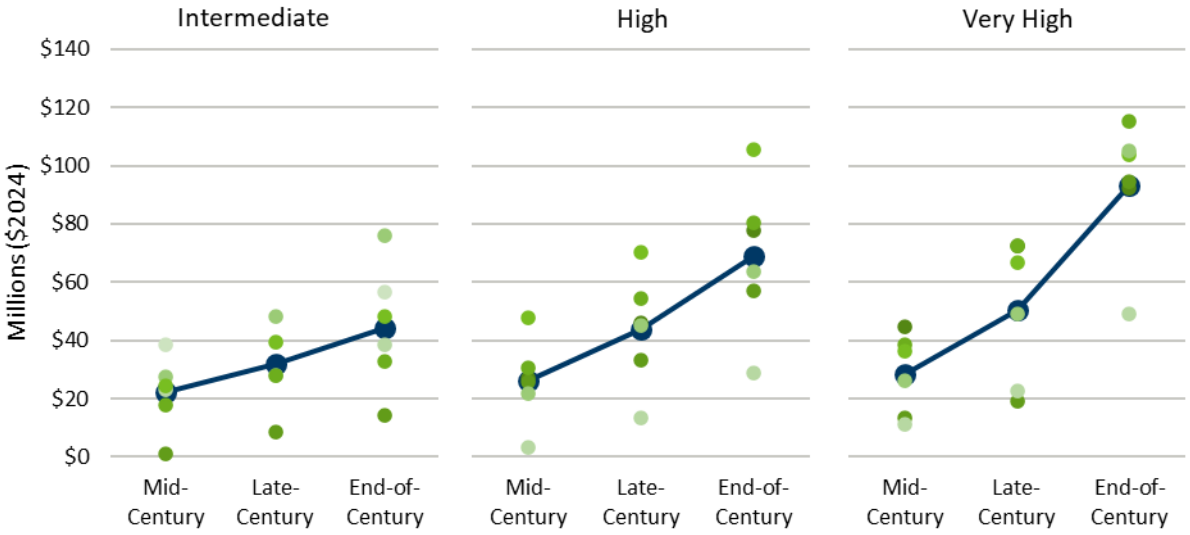
		Dairy Milk
		Lost production value
Mid-Century (2040–2059)	Intermediate	$1,000 (-$440 to $3,300)
	High	$1,900 ($780 to $3,300)
	Very High	$1,500 (-$1,100 to $3,700)
Late-Century (2060–2079)	Intermediate	$1,500 (-$370 to $3,400)
	High	$2,300 ($970 to $4,300)
	Very High	$1,500 (-$1,300 to $4,600)
End-of-Century (2080–2099)	Intermediate	$1,900 (-$940 to $3,400)
	High	$2,700 ($2,000 to $3,500)

[99] *Water Availability and Assessment Report 2025*.

	Dairy Milk
	Lost production value
Very High	$2,400 (-$120 to $3,700)
Other costs of inaction (not quantified): • Heat stress on other livestock products • Climate impacts on pasture and other feeds • Pest and diseases on livestock due to increased heat	

Figure 5-5. Range of Quantified Annual Costs of Inaction: Livestock

Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). The solid lines with blue dots represent the average across six climate models per scenario, and the green dots without lines show the results for each of the six models.



Who bears the costs of inaction?

These costs are primarily borne by livestock producers (individuals and corporations), mostly in rural parts of the state, with significant production in central and southeastern Minnesota. Impacts to cattle milk yields may have indirect economic effects in feed, processing, and retail markets. Uncertainties of these estimates include temperature tolerance thresholds of specific animal varieties produced in Minnesota, as well as the current degree of adoption of heat abatement measures, such as ventilation or fans.

What other costs of inaction are not quantified in this study?

Other important costs of inaction to livestock, not quantified above, include:

- Heat stress on other livestock products. For example, hogs, which are the highest producing livestock in Minnesota ($3.6 billion per year),[100] are vulnerable to heat stress as well, particularly

[100] MDA. (2023). 2023 Minnesota Agricultural Facts and Stats. https://www.mda.state.mn.us/sites/default/files/inline-files/MNAgFactsStats2023.pdf

because their bodies have limited means of regulating heat. Heat stress results in impacts to the breeding herd and reduced weight gain on growing-finishing pigs.[101]

- Climate impacts on pasture and other feed, which in turn affect livestock productivity.
- Increased pests and disease risk to livestock due to increased heat and reduced winter die offs. For example, turkeys have a frail immune system, and culling populations in the event of an outbreak represents a significant loss to producers.

5.2.2. Costs of adaptation

Reducing the impact of climate change on livestock may involve a variety of actions including infrastructure investments and energy costs (particularly for cooling and ventilation), adjustments to livestock management systems and breeding strategies, and increased pest and disease monitoring.[102] The quantified adaptation costs in this study include investments in heat abatement measures for dairy farms and energy costs for the heating and cooling of turkey barns,[103] shown in Table 5-5.

- For **dairy farms,** quantified adaptation costs include the costs to install cooling equipment[104] and the annual operating costs in the form of energy expenditures. Three different levels of abatement equipment are estimated that each have a heat-stress function that predicts variations in heat stress from the corresponding temperature humidity index: moderate (fans or forced ventilation), high (fans and sprinklers), and intense (high-pressure evaporative cooling system). Farmers are assumed to install adaptation measures when the benefits exceed the costs, based on the cost of inaction analysis described above. The dairy analysis is done at the county level, such that all farms within a county make the same adaptation decision in each time period.
- For **turkey farms,** the analysis estimates the changes in cooling and heating costs from baseline levels. The turkey analysis is also conducted at the county level and assumes farmers pay the required energy costs to continue operating existing systems.

See Appendix B for more details on methodology and limitations.

[101] Schieck-Boelke, S. (2024). Heat stress in swine affects production. UMN Extension. https://extension.umn.edu/swine-production-management/heat-stress-swine-affects-production

[102] Rojas-Downing, M. M., Nejadhashemi, A. P., Harrigan, T., & Woznicki, S. A. (2017). Climate change and livestock: Impacts, adaptation, and mitigation. Climate risk management, 16, 145-163.

[103] Energy costs for turkey barns are quantified as adaptation costs, though the parallel costs of inaction (the production losses associated with not increasing cooling) are not quantified. This is because most turkey barns are assumed to already be equipped for cooling, and therefore in the baseline scenario, farmers are already using cooling systems to minimize losses. This response is therefore also the default action under future climates.

[104] Capital costs are annualized over the lifespan of the equipment.

Table 5-5. Quantified Adaptation Costs (Millions per Year): Livestock

Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). Costs are incremental to baseline and averaged across six climate models (range across climate models provided in parentheses). See Appendix B for more details on methodology and limitations.

		Dairy Barn cooling	Turkey Barn Cooling	Turkey Barn Heating
		Cooling cost	Cooling cost	Heating Cost
Mid-Century (2040–2059)	Intermediate	$23 ($22 to $24)	$2.8 ($2.1 to $4.5)	-$5.7 (-$7.6 to -$3.8)
	High	$23 ($22 to $25)	$3.5 ($2.2 to $5.1)	-$7.0 (-$9.9 to -$4.4)
	Very High	$23 ($21 to $25)	$3.7 ($1.2 to $5.6)	-$6.4 (-$10 to $0.9)
Late-Century (2060–2079)	Intermediate	$24 ($23 to $25)	$4.0 ($3.2 to $5.0)	-$7.7 (-$9.0 to -$6.1)
	High	$25 ($23 to $26)	$5.6 ($4.0 to $7.0)	-$10 (-$13 to -$8.2)
	Very High	$25 ($21 to $27)	$6.1 ($1.7 to $8.8)	-$10 (-$15 to $1.2)
End-of-Century (2080–2099)	Intermediate	$25 ($24 to $26)	$5.5 ($4.1 to $7.5)	-$10 (-$11 to -$8.0)
	High	$27 ($26 to $28)	$7.9 ($6.4 to $9.7)	-$13 (-$16 to -$7.7)
	Very High	$28 ($27 to $30)	$10 ($8.4 to $14)	-$16 (-$19 to -$14)

Note: The majority of turkey barns are assumed to already have both heating and cooling infrastructure, therefore the incremental costs only address operating costs (i.e., energy costs). Dairy barns are assumed to currently incur limited heating costs, therefore heat saving are expected to be minimal and therefore are not quantified.

Other unquantified adaptation costs:

- Cooling costs for all other vulnerable livestock
- Pest and pathogen monitoring and surveillance
- Diversified feed stock

What residual risks remain after adaptation?

Adaptation costs for dairy barn cooling only slightly vary throughout the century because it is often cost-effective to invest in cooling under all scenarios, so the variation is only due to differences in energy costs (driven by differences in cooling degree days). On average, the modeled heat abatement measures are sufficient to mitigate the increased heat stress risk above baseline. Therefore, the investment results in slightly higher milk yields than in the baseline at the statewide level.

On net, turkey farms are projected to experience a decrease in energy expenditures due to the offsetting savings from reduced heating costs, despite increased cooling costs. Even with the net benefit, farmers will have to plan for the shifting temporal pattern of costs. The turkey analysis also does not include residual risk because the model assumes farmers pay the full costs of increased cooling to operate existing barn systems. Furthermore, even though total energy expenditures are expected to decrease, the increased use of cooling systems is expected to lead to more frequent repair, maintenance, and replacement of the equipment. These costs are not considered in this study.

What other effects result from adaptation?

Importantly, energy use for heat abatement can increase greenhouse gas emissions, depending on the technology and energy mix used. In a warmer future, energy demand will shift from colder to warmer months. Generally, heating energy demands are supplied by on-farm combustion of propane, whereas cooling energy demand relies on grid electricity where there is no local generation. Increased use of

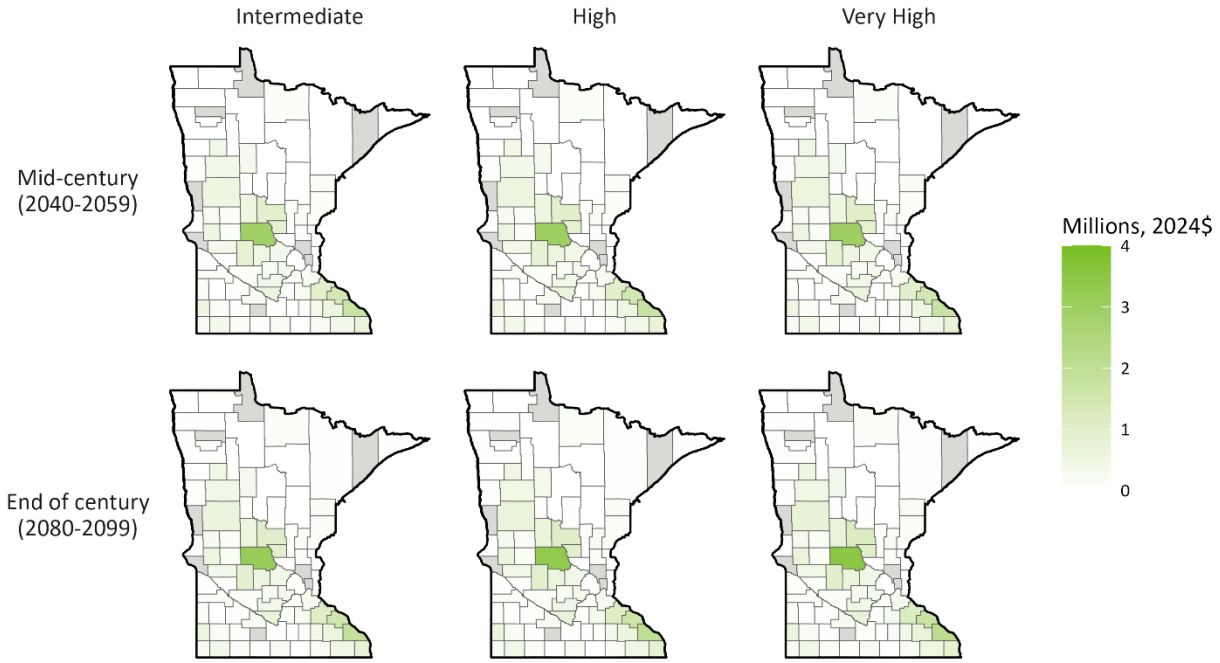
cooling systems will require a more reliable grid, as other users also increase their demand, particularly during heat waves.

Who pays the adaptation costs?

Figure 5-6 shows the distribution of cooling costs associated with dairy heat abatement by county, which follows the pattern of cattle milk production across the state. These improvements would be implemented and paid for by cattle farmers across the state, absent outside funding sources. The total cooling costs are expected to be highest in Stearns County, which has the largest share of cattle milk farms (i.e., 17 percent of the state total) as well as cattle milk production and revenues (i.e., 12 percent of the state total).

Figure 5-6. Distribution of Dairy Barn Cooling Costs by County

Annual costs of increased cooling costs (millions, 2024$) by county for two time periods and three emissions scenarios (see Section 2.2.2 for more details), averaged across six climate models. Counties in gray are excluded due to low number of farms.



What are the other costs of adaptation not quantified in this study?

The costs reported above do not reflect a comprehensive estimate of costs of adaptation, quantifying only a subset of the costs. Other potentially important adaptation costs include:

- Cooling for beef cattle, hogs, boilers, and other livestock. For example, all poultry producers will likely experience similar changes in heating and cooling costs as quantified here for turkey producers. Turkey farm area makes up approximately 60 percent of Minnesota's poultry farm area, suggesting the total net energy savings for poultry farms could be as much as 1.6 times the cost quantified in this study.
- Diversified sources of feed if climate change has a significant impact on the production of key feed products (i.e., hay, fodder crops, pastures).
- Monitoring and surveillance for pests, disease, and animal pathogens.

5.2.3. Limitations and uncertainties

The quantified adaptation costs presented in this study are illustrative of the magnitude of costs required, though they do not cover all potential reactive and proactive responses to climate change. Climate change affects livestock species in unique ways, and producers have options for how they prepare and respond to these challenges, which are not captured in the quantified costs. Key limitations to the analysis are described below; see Appendix B for a full discussion of limitations and uncertainties:

- The analysis does not quantify costs for other livestock, such as boilers or hogs, and only addresses heat stress impacts.
- Based on limited information available, the analysis assumes dairy barns do not currently have cooling systems and therefore will require capital investment, while turkey barns do already have cooling systems, and therefore costs are limited to energy usage.
- Net energy usage costs for turkey barns are negative, meaning heating cost savings outweigh increased cooling costs. Dairy cattle require limited heating in the baseline due to a higher cold-weather tolerance; therefore, the estimates do not include heating cost savings.

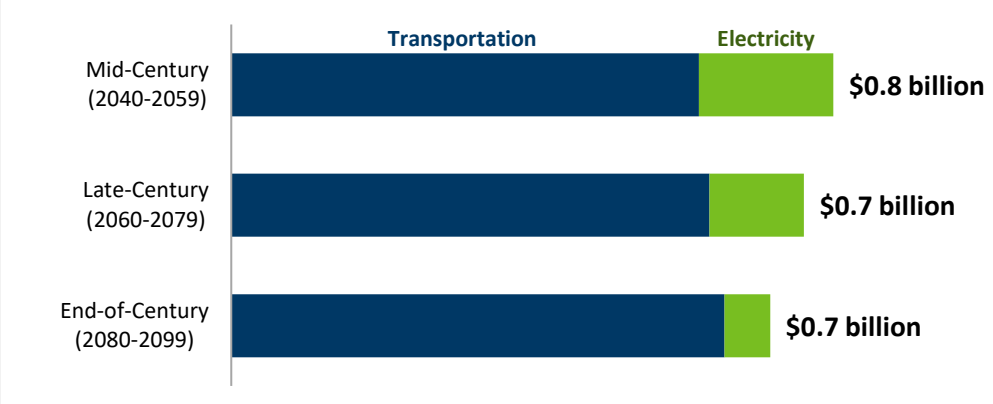
6. Cost of climate change: Transportation and Electricity Infrastructure

Key takeaways: Transportation and Electricity Infrastructure

- A wide range of Minnesota's transportation and electric power infrastructure is vulnerable to damage from climatic hazards. Effects quantified in this study include impacts to **roads** (primarily but not exclusively from heat and extreme rainfall events); **rail** (primarily from extreme heat); and **culverts** (from extreme rainfall events) in the transportation sector – and to **transmission and distribution infrastructure** (from extreme heat and other hazards) in the electricity sector.
- Proactive adaptation actions, which mainly involve investments to upgrade infrastructure and materials, timed for when it might otherwise wear out and require replacement or major rehabilitation, have been shown to be cost-effective in avoiding the worst effects and minimizing infrastructure outages, closures, and delays. An incremental investment of $0.8 billion annually for **roads, rail, culverts,** and **electric infrastructure** by Mid-Century could prevent over $4.3 billion in annual repair and delay costs projected in the absence of adaptation under the High emissions scenario.
- Additional adaptation needs not quantified in this analysis include actions such as resealing and strategically upgrading road materials to minimize freeze-thaw damage; elevating or armoring vulnerable coastal roads near Lake Superior; protecting rail and light rail corridors from flood risks; adding electric generating capacity to meet increasing summer peak load demand for air conditioning; and addressing electric distribution vulnerabilities to ice storms and other extreme events.

Quantified Annual Adaptation Costs by Period (High Emissions Scenario)

These costs are incremental of baseline adaptation costs and only include the quantified adaptation actions.



High temperature and increased precipitation events due to climate change can damage roadways and rail infrastructure throughout Minnesota. Impacts to roads result from increased rutting, cracks, and surface roughness after high heat and extreme precipitation events, or from a higher frequency of freeze-thaw cycles. This leads to a need for road repair or, if repairs are not completed, a reduction in vehicle speed to navigate damaged roadways and increased vehicle operating costs (e.g., damage from potholes and lower fuel economy) from driving on damaged roads. Unpaved roads are susceptible to

washout during high rainfall events.[105] Culverts, which allow water to flow under roads, are vulnerable to high precipitation and extreme weather events, which increase the chance of culvert failure. Impacts to rail transportation include track buckling from high heat and flood damage, both of which can delay service and require expensive repairs of the rails or rail bed. In the most extreme cases, track buckling can lead to derailment.

Effects on electric transmission and distribution infrastructure include failure of transformers under high heat conditions, reduced wire transmission capacity at higher temperatures, susceptibility to ice storms, and damage to wood poles from increased risk of decay in warmer and wetter conditions. Recent historical damage to the electric grid in Minnesota provides a guide to the need for adaptation. For example, among "The 10 worst power outages in the central United States since 2020," according to the Union of Concerned Scientists, two of these events affected Minnesota.[106] The first was a series of summer derechos (severe wind storms) in 2020 and 2021, and the second was a set of intense thunderstorms in December of 2021, which included a tornado in southeastern Minnesota, the first ever recorded in that month by the (NOAA) in the state. NOAA concluded that record heat in the far north played a factor in the December 2021 storm. Estimates of the damage of these events to the power grid in Minnesota are not available, but the August 2021 derecho was estimated to have caused at least $11.5 billion in direct and indirect damages across the central United States.[107]

There is a relatively robust literature on climate vulnerabilities and adaptation costs for transportation and electric infrastructure. Quantified adaptation costs in this chapter include changes in asphalt binders to increase the resilience of roads to temperature stress; upgraded culverts to reduce the risk of floods damaging roadways; unpaved road regrading or in the most extreme cases, paving to avoid washouts; speed controls and temperature sensors to limit the effects of high heat on rails; and upgraded transformer, wire, and pole infrastructure to improve the resilience of the electric transmission and distribution network.

Results are available from a single model for cost of inaction, reactive response, and proactive adaptation scenarios. In general, reactive responses address needed repairs in real-time but do not include forward-looking upgrades in materials and infrastructure, and proactive adaptation considers future conditions to optimize investments in material and infrastructure upgrades. The relevant literature concludes that proactive adaptation has a lower net life-cycle cost than reactive responses, but proactive adaptation requires larger and earlier investments in adaptation, which decline over time as the capital stock turns over and is gradually converted to more resilient construction. The details of the adaptation scenarios are described in the two main sections of this chapter, in Neumann et al. (2021), and in Fant et al. (2020).

Transportation and electricity infrastructure are vulnerable to several climate-driven hazards, including through the selected impacts listed below, along with their associated potential adaptation actions. This study quantifies and costs the items in bold.

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[105] 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 at: https://link.springer.com/article/10.1007/s10584-021-03179-w; Fant, C., B. Boehlert, K. Strzepek, P. Larsen, A. White, S. Gulati, Y. Li, and J. Martinich (2020). Climate change impacts and costs to U.S. electricity transmission and distribution infrastructure. Energy, **195**, 116899, doi:10.1016/j.energy.2020.116899. Available online at https://www.sciencedirect.com/science/article/pii/S0360544220300062

[106] See blog post of January 8, 2026, by Dr. Susanne Moser, "The 10 Worst Power Outages in the Central United States Since 2020—And How We Build Back Better."

[107] See Moser, 2026.

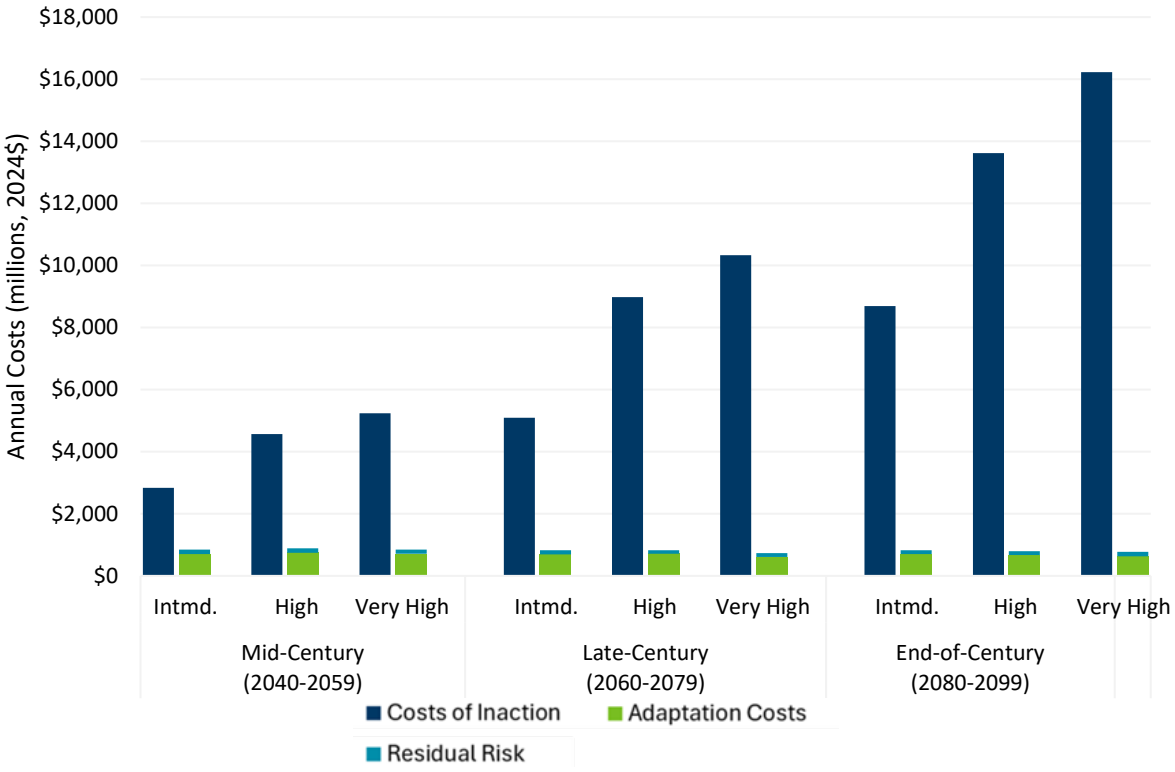
Table 6-1. Costs of Inaction (Climate Impacts) and Potential Adaptation Actions for Transportation and Electricity Infrastructure

Summary of costs of inaction and potential adaptation actions. Items in bold are quantified in this study.

Costs of Inaction	Potential Adaptation Actions
Higher temperatures cause **paved road surfaces to soften and develop ruts.**	**Changes in asphalt binders** can provide increased resilience to high temperature stress, if strategically incorporated during periodic road resurfacing cycles.
Extreme **rain and floods can lead to overwhelmed culverts,** leading to road washouts and delays.	**Upgraded culvert capacity** can avoid these events and be a cost-effective upgrade during road maintenance activities.
Extreme **rain can wash out unpaved roads.**	**Unpaved roads can be regraded, culverts upgraded, or in the case of frequent washouts, they can be paved.**
Road surfaces are affected by repeated freeze-thaw cycles, causing increasingly large cracks and ruts across multiple events.	Actions to counteract freeze-thaw events include resealing to reduce permeability and deicing. Proactive concrete design can also be implemented.
High temperatures deform rails, leading to delays and the need for rail repairs or replacement.	Reactive actions include **speed controls to reduce risks of rail kinks.** Proactive action includes **use of rail temperature sensors.**
Extreme **heat reduces the useful life of power transformers.**	**Accelerated replacement and/or upgrades to more resilient transformers at the end of service life.**
Heat decreases the ampacity (carrying capacity) of electric wires.	**Upgrade wiring.**
Hot and humid conditions accelerate **decay of electricity distribution poles,** many of which are also used for communications infrastructure.	**Steel reinforcement of poles** maintains their structural integrity.
Extreme rainfall and flooding can affect water supply and wastewater treatment infrastructure.	Enhanced drainage, floodwater retention ponds/areas, pumping, and flood barrier construction.

This analysis quantifies costs of inaction, adaptation costs, and residual risk for a subset of potential costs related to transportation and electricity infrastructure, focusing on roads, rail, culverts, and electricity infrastructure. The figure below summarizes the quantified costs of inaction, adaptation costs, and residual risk (meaning, the damages that persist after adaptation is implemented) to transportation and electricity infrastructure. Note that the costs in this figure are not comprehensive but rather represent the quantifiable costs in this study.

Figure 6-1. Transportation and Electricity Infrastructure: Quantified Annual Climate Cost Summary
Summary and comparison of cost of inaction (first set of bars, in dark blue), adaptation costs (base of the second set of bars, in green), and residual risk (top of second set of bars, in light blue) per year, above baseline. Results for three time periods and three emissions scenarios (see Section 2.2.2 for more details), averaged across six climate models.



The remainder of this chapter includes two sections, addressing the two main categories of infrastructure with quantified adaptation costs: **Transportation** and **Electricity.** Within each of these two main sections, there are subsections for **Costs of inaction, Costs of adaptation,** and **Limitations and uncertainties.** Both cost subsections provide a high-level methodology description, detailed results, and further interpretation of the findings, including how costs are distributed across the state and which costs are not quantified in this study. Step-by-step detail on methods and specific citations to data sources, models, and peer-reviewed studies that provide a basis for estimating costs can be found in Appendix B.

6.1. Transportation

6.1.1. Costs of inaction

This analysis quantifies the costs of inaction for two categories of transportation impacts: roads (including culverts) and rail. Specifically, the analysis estimates the economic impact of temperature changes and precipitation events on roads and rail based on Neumann et al. (2021).[108]

Roads can deteriorate in response to temperature and rainfall extremes. For example, rut depth increases over the life span of the road, but it may increase faster due to temperature changes

[108] Neumann et al., "Climate Effects on US Infrastructure: The Economics of Adaptation for Rail, Roads, and Coastal Development."

associated with climate change.[109] Additionally, in extreme heat and precipitation conditions, the flexible pavement that makes up the modern road system can expand and crack. Rutting, cracks, and general deterioration contribute to higher international roughness index (IRI) values, a measure of how rough or smooth a surface is. Roads with high IRI may require frequent repairs and cause high vehicle operating costs for drivers (e.g., the need for more frequent vehicle repair, increased fuel costs, and external social costs associated with higher vehicle air pollutant emissions) and more delays due to repair schedules and speed reductions. In addition, high rainfall can wash out unpaved roads.

Culverts are water passages that allow flows to pass under roadways and are designed to prevent overtopping or road washout during flood events but are vulnerable to changes in the frequency and intensity of floods. These flood events may change significantly over this century due to climate change, with events larger than the floods these culverts were designed to withstand. Beyond damaging the culvert, failure also damages the road around the culvert and leads to road closures until the damage can be repaired.

The quantified costs of inaction for roads are based on changes to repair activities at the time that a climate stressor causes damages to the infrastructure, where costs accrue to entities responsible for road maintenance and repair, as well as delays associated with speed reduction, where costs accrue to road users for passenger or freight travel.

Temperature changes due to climate change can affect the structural integrity of railroad tracks throughout Minnesota. The impacts result from thermal expansion of rails during high heat events, which in cases of moderate heat stress leads to a reduction in train speeds to avoid further and potentially damaging heating of the rails. In more extreme cases, heat stress can cause deformation of rails, which requires repair, without which the risk of derailment may increase to unacceptably high levels.

Steel tracks are designed to operate in a narrow range that is based on the temperature in which they are originally laid, known as the Design Neutral Temperature. When this temperature is exceeded, the ability of the steel rails to support rail traffic begins to degrade. Under extreme heat conditions, the continuously welded rail tracks that make up the modern rail system will buckle due to expanding metal. For example, a typical welded length of 1,800 feet of rail can expand up to one inch per 10 degrees of temperature increase (Wolf, 2005).[110] In extreme heat conditions where temperature increases can be several times that, expansion and offset can quickly exceed several inches, which will lead to derailment if undetected. These expansion conditions are known as “sun kinks” and will lead to failure if rail traffic is not reduced until temperatures decline.

The quantified costs of inaction for rail represent the cost of passenger and freight delays associated with the speed warnings triggered by high ambient heat, which are implemented in an effort to avoid derailments, but which tend to have large margins of safety, meaning delays are longer than if specific information were available on actual rail temperature. These delays make up most of the cost of inaction for rail. In addition, absent specific information on rail temperature, rails may be traversed in some cases where it is inadvisable, and the use of the rails increases their temperature, raising the likelihood that a costly repair will be needed. The costs of inaction are therefore a mix of delays (which fall on passengers and freight customers) and repairs (which fall on the rail operators).

[109] Qiao, Y., Flintsch, G., Dawson, A., Parry ,T. (2013). Examining effects of climatic factors on flexible pavement performance and service life. Transportation Research Record. Journal of the Transportation Research Board 2349:100–107. https://doi.org/10.3141/2349-12

[110] Wolf, G. (2005). Preventing Track Buckles. Interface. 10 March 2005. Available at: https://interfacejournal.com/archives/644

As shown in Table 6-2, costs of inaction for road and rail increase sharply over time for all three emissions scenarios, but most sharply for the Very High emissions scenario, which has the highest temperature increases over time. Figure 6-2 shows that the variation in costs over the six climate models is broad, as much as a factor of three to eight times, mainly associated with differences in rainfall projections. The figure shows the sum of costs across road and rail categories, but about 95 percent of the costs are associated with impacts to road resources, which also includes costs of delay due to culverts.

Table 6-2. Quantified Costs of Inaction (Millions per Year): Transportation

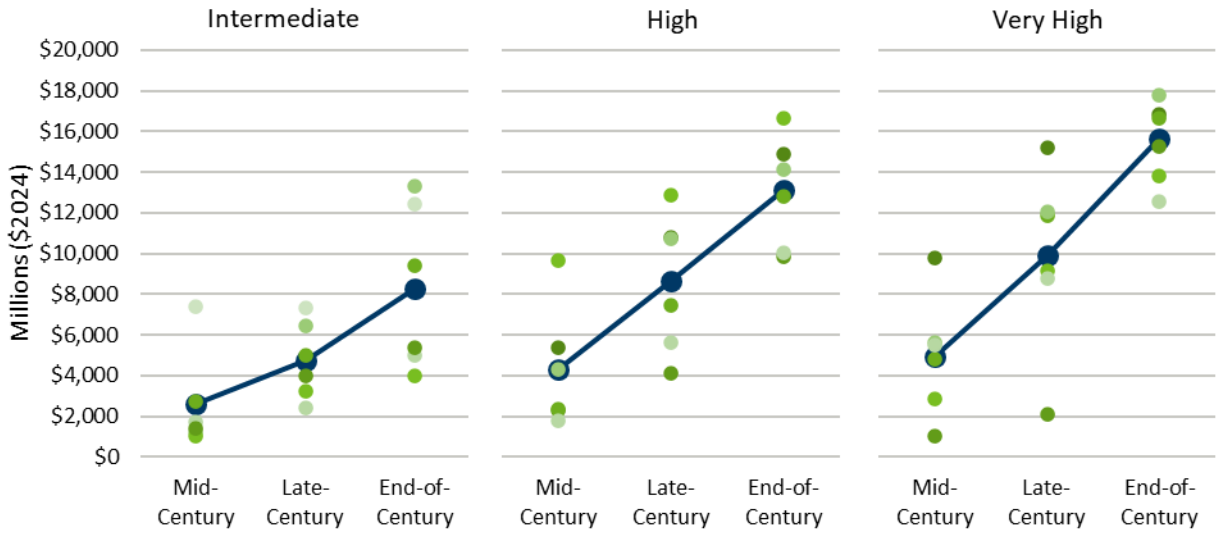
Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). Costs are incremental to baseline and averaged across six climate models (range across climate models provided in parentheses). See Appendix B for more details on methodology and limitations.

		Roads (Including Culverts)	Rail
		Delay and vehicle operating costs (VOC)	Delay and repair costs
Mid-Century (2040–2059)	Intermediate	$2,500 ($920 to $7,300)	$89 ($85 to $91)
	High	$4,200 ($1,800 to $9,600)	$92 ($89 to $96)
	Very High	$4,800 ($910 to $9,700)	$120 ($100 to $140)
Late-Century (2060–2079)	Intermediate	$4,600 ($2,300 to $7,200)	$160 ($130 to $200)
	High	$8,400 ($3,900 to $13,000)	$240 ($210 to $280)
	Very High	$9,500 ($1,700 to $15,000)	$400 ($340 to $470)
End-of-Century (2080–2099)	Intermediate	$8,000 ($3,700 to $13,000)	$320 ($240 to $450)
	High	$13,000 ($9,300 to $16,000)	$610 ($510 to $740)
	Very High	$15,000 ($13,000 to $16,000)	$1,100 ($830 to $1,500)

Other costs of inaction (not quantified):

- Costs related to bridge scouring and overtopping associated with extreme precipitation
- Freeze-thaw cycle impacts and long-term effects of frequent flooding on roads
- Slope instability (e.g., erosion and landslides) adjacent to roadways

Figure 6-2. Range of Quantified Annual Costs of Inaction: Transportation (Roads, Culverts, Rail)
Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). The solid lines with blue dots represent the average across six climate models per scenario, and the green dots without lines show the results for each of the six models.



Who bears the costs of inaction?

Costs of inaction include road and rail repair cost, and delays for road and rail users. The repair costs are borne by local, state, and federal road and highway maintenance agencies, or by rail owners. Delays affect passenger and freight users of the roads and railroads, and these users also bear road vehicle operating costs.

What other costs of inaction are not quantified in this study?

Additional costs of inaction related to transportation infrastructure that are not quantified in this study include:

- Impacts on roads from additional climate stressors. A potentially important additional cause of pavement deterioration results from freeze-thaw cycles – that is, the expansion of water as it freezes, followed by infiltration of water during thaw, with repeating cycles.[111] A few recently available analyses examine the impacts of this phenomenon (Jiang et al. 2025), but it is not part of the estimates presented above. In addition, the above estimates include the impact of high precipitation but exclude the effects of more extreme flood risks to roads and all flood risks to railbeds.
- The impact of climate change on bridges. Bridges over waterways can be subject to damage such as scouring of the bridge supports and footings,[112] and in extreme cases, overtopping of the deck, but due to time and resource constraints it was not possible to assess bridge vulnerabilities for this study.
- The impact of slope instability on roads. Risk of instability is caused by a multitude of factors including slope, terrain curvature, proximity to rivers, and proximity to bedrock outcrops.

[111] Jiang, Y., Ullah, S., Zapata, C., & Yu, X. (2025). Assessment of the impacts of climate change on cold region pavement design and operation. Journal of Infrastructure Preservation and Resilience, 6(1), 20. https://doi.org/10.1186/s43065-025-00126-2
[112] Wright, L., Chinowsky, P., Strzepek, K., Jones, R., Streeter, R., Smith, J. B., ... & Perkins, W. (2012). Estimated effects of climate change on flood vulnerability of US bridges. Mitigation and Adaptation Strategies for Global Change, 17(8), 939-955.

Instability allows for increased erosion and landslides which may result in increased repair costs for the roadway, or even sinkholes and vertical soil collapses in extreme cases.[113]

6.1.2. Costs of adaptation

The quantified costs of adaptation for transportation infrastructure reflect the costs of proactively improving the ability of the infrastructure to withstand projected climate stressors rather than waiting to replace failed infrastructure.

- Quantifying the costs of adaptation for **roads** under a reactive and proactive scenario incorporates two components: determining the potential increases in repairs due to climate change-related damage and estimating road delays associated with the adaptation action (Note: road delays are minimized but not eliminated under the planned repairs activated under a proactive scenario, and are higher under a reactive approach where repairs are triggered by heat or high rainfall events). A reactive scenario implies that repair budgets could be increased to react to climate-induced damage, while a proactive scenario involves a forward-looking approach that incorporates upgraded asphalt binders and more resilient unpaved road regrading with an eye toward building resilience to future climatic changes. To reduce costs and improve cost-effectiveness, proactive upgrades to asphalt binders and road drainage are implemented at the time of scheduled rehabilitation, leaving some time periods when the road deteriorates, which results in residual risk. The details of the adaptation scenarios are described in Appendix B and in Neumann et al. (2021).[114]
- **Culvert upsizing and replacement costs,** to improve the ability of the infrastructure to withstand future precipitation events, are based on a customized methodology building on a method previously developed and applied for the State of Delaware and use MNDOT culvert infrastructure data. Costs include the upsized culvert itself, repair/installation costs, and road delays associated with the construction activity. The culvert analysis does not consider life cycle optimization but is more consistent with a preliminary screening analysis of the costs of continuing a program of strategic upgrading of culvert capacity during road maintenance activity. This type of program is already being practiced by MNDOT[115] and many local governments.
- For **rail repair costs,** the proactive scenario results involve the installation of rail temperature sensors, which allow rail operators to keep trains off rails that are too hot and might be damaged by train traffic, while also providing real-time information on rail temperature to minimize train speed controls (see Neumann et al. 2021 for details). Some delays persist even with this repair, but they are minimal compared to the repair costs. Unfortunately, the proactive scenario modeling in the underlying study did not separate out the residual risk of delay from the infrastructure upgrade costs, so this study is unable to calculate the residual risk.

[113] Muehlbach, P. (2019). MnDOT Slope Vulnerability Assessments. March 2019, https://mdl.mndot.gov/items/201912
[114] Neumann et al., "Climate Effects on US Infrastructure: The Economics of Adaptation for Rail, Roads, and Coastal Development."
[115] See the 2022 MNDOT Transportation Asset management Plan: https://www.dot.state.mn.us/assetmanagement/tamp.html and 2015 Maintenance Culvert Cost Data Analysis: http://www.dot.state.mn.us/bridge/hydraulics/culvertcost/2015%20Drainage%20Maintenance%20Data%20Summary%20-%20Final%20Version.pdf

Table 6-3. Quantified Adaptation Costs (Millions per Year): Transportation

Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). Costs are incremental to baseline and averaged across six climate models (range across climate models provided in parentheses). See Appendix B for more details on methodology and limitations.

		Roads: Proactive Adaptation	Roads: Reactive Adaptation*	Culverts: Proactive Adaptation	Rail: Proactive Adaptation	Rail: Reactive Adaptation*
		Repair and upgrade costs	Repair and upgrade costs	Culvert and road replacement and delay costs	Damage and delay costs	Damage and delay costs
Mid-Century (2040–2059)	Intermediate	$480 ($410 to $570)	$1,300 ($1,200 to $1,500)	$110 ($41 to $150)	$7.8 ($6.8 to $8.4)	$89 ($87 to $91)
	High	$520 ($450 to $620)	$1,300 ($1,300 to $1,400)	$130 ($49 to $170)	$8.8 ($7.9 to $9.8)	$91 ($90 to $94)
	Very High	$490 ($440 to $530)	$1,400 ($1,300 to $1,600)	$140 ($9 to $200)	$14 ($11 to $17)	$110 ($100 to $130)
Late-Century (2060–2079)	Intermediate	$460 ($370 to $510)	$1,400 ($1,300 to $1,500)	$120 ($21 to $230)	$19 ($14 to $25)	$150 ($130 to $190)
	High	$510 ($400 to $630)	$1,500 ($1,400 to $1,600)	$120 ($21 to $280)	$29 ($26 to $34)	$210 ($190 to $240)
	Very High	$450 ($350 to $560)	$1,600 ($1,200 to $1,900)	$130 ($21 to $330)	$47 ($41 to $54)	$350 ($300 to $410)
End-of-Century (2080–2099)	Intermediate	$480 ($400 to $550)	$1,500 ($1,300 to $1,700)	$120 ($10 to $300)	$39 ($29 to $55)	$290 ($220 to $390)
	High	$480 ($330 to $580)	$1,700 ($1,500 to $2,000)	$150 ($18 to $300)	$70 ($60 to $82)	$520 ($440 to $630)
	Very High	$380 ($280 to $500)	$1,900 ($1,400 to $2,100)	$180 ($27 to $390)	$110 ($89 to $140)	$930 ($700 to $1,300)

*Indicates an action with multiple alternatives; this alternative is not included in the annual summary.

Other unquantified adaptation costs:

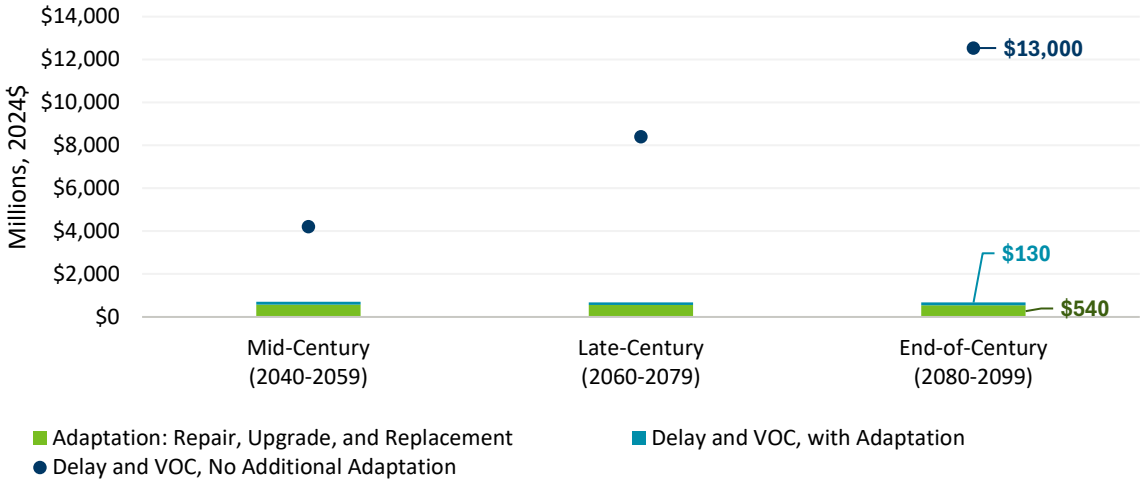
- Upgrading bridge design
- Costs to develop resilient design standards to support infrastructure upgrades

It is important to note that the proactive road adaptation costs decline over time, even though the costs of inaction increase over time as climate hazards worsen. Adaptation costs decline because investments in resilient roads in earlier periods are effective in limiting the need for repairs and reducing costs in later periods. Road surfaces last longer, through the end of their scheduled rehabilitation cycles, and are in better condition than they would be without these investments.

What residual risks remain after adaptation?

Proactive repair and upgrade of roads does result in some road delays, because it is most cost-effective to implement upgrades at the time roads are rehabilitated. As a result, a short period may remain in the repair cycle between the time when climatic stresses first affect the system and when the rehabilitation (and upgrade) is complete. Nonetheless, because upgrades are planned in advance, remaining delays are minimized, and they are less than road (and rail) delays associated with the costs of inaction. These road delays are quantified in this analysis – the remaining road delays are about 20 to 30 percent of the repair costs, while proactive adaptation eliminates most rail delays in the Mid-Century and Late-Century periods, though they return in the End-of-Century period as temperatures warm to the point where the benefits of optimized heat sensor technology diminish.

Figure 6-3. Quantified Adaptation Costs and Residual Risks versus Costs of Inaction for Roads and Culverts
Annual costs (in millions, 2024$) for proactive road and culvert upgrades (green bar segments) and the delays that remain with the proactive adaptation (blue bar segments). Costs of inaction (blue dots) are shown for reference – adaptation plus residual risks are always less than the costs of inaction. Results reflect the High emissions scenario though similar patterns persist across all modeled emissions scenarios. "VOC" refers to vehicle operator costs, meaning wear and tear on vehicles from driving on damaged roads.



What other effects result from adaptation?

There are substantial, unquantified co-benefits of road and rail adaptation associated with minimizing the indirect costs of delays. Fewer delays can improve overall productivity of the economy as passengers, workers, and freight move more quickly to desired destinations.

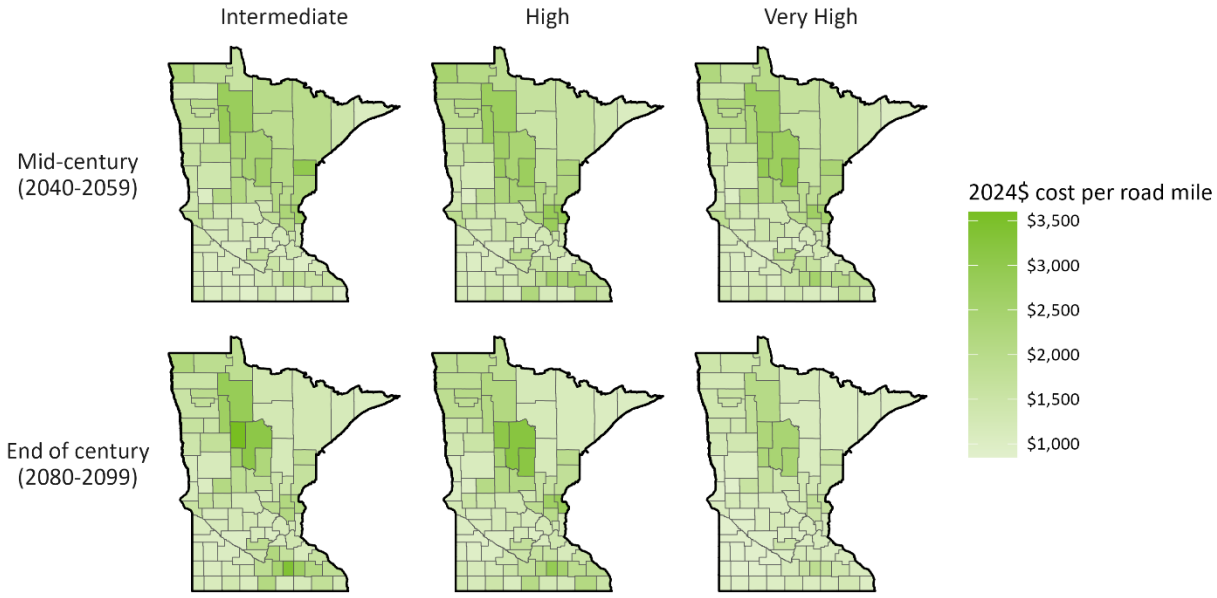
Who pays the adaptation costs?

Road and culvert adaptation costs are paid almost entirely by Federal, state, local, and tribal road maintenance authorities, which are in turn funded by taxpayers. At least some of the rail costs are borne by the private sector freight rail operators that own and maintain the rail corridors, while other rail adaptation costs are borne by public transit or other passenger rail operators.

On a geographic basis, per lane mile road adaptation costs are distributed widely across Minnesota, as shown in Figure 6-4 below. Although absolute costs are highest in counties with the densest road networks (in the Twin Cities) or the largest geographic counties (such as St. Louis County), the costs per lane road mile are highest in the mid-central and south-central areas of Minnesota. This result is consistent with those areas expected to see the highest intensities of precipitation in the future.

Figure 6-4. Distribution of Damage and Maintenance Costs Per Lane Mile for Proactive Road Adaptation by County

Annual per lane mile costs of increased damage and maintenance costs (millions,2024$) by county for two time periods and three emissions scenarios (see Section 2.2.2 for more details), averaged across six climate models.



What are the other costs of adaptation not quantified in this study?

The costs reported above do not reflect a comprehensive estimate of costs of adaptation, quantifying only a subset of the costs. Other, potentially important adaptation costs include:

- Costs for adapting bridges over waterways to harden supports and footings against an increased risk of scour.
- Adaptation costs to address the long-term effects of flood ponding on road surfaces, which can reduce the time required between rehabilitation cycles. The quantified costs do, however, include culvert upgrades, which addresses one of the major causes of flood risk to roads (i.e., undersized culverts).
- Costs to stabilize slopes or otherwise protect roads from blockage or incursion associated with erosion of nearby slopes, which could increase with more intense precipitation.
- Costs for state and local government agencies to redefine resilient design standards for both road and rail, which may include requirements throughout the state for better drainage, nature-based solutions, and enhanced material selection.

6.1.3. Limitations and uncertainties

The quantified adaptation costs presented in this study are illustrative of the magnitude of costs required, though they do not cover all potential reactive and proactive responses to climate change. Key limitations to the analysis are described below; see Appendix B for a full discussion of limitations and uncertainties.

- Costs of inaction for roads reflect continued repair activity consistent with baseline actions and current maintenance budgets, meaning all incremental costs presented here are to road users from deteriorating road conditions. This assumption (holding current maintenance budgets

constant) may not be consistent with the preferred response of all road maintenance authorities at all levels of government.

- Rail costs reflect delay and repair but assume delays are implemented with existing safety procedures and speed orders to avoid derailments.
- Estimates shown here reflect costs for cost-effective proactive adaptation. Some residual risks remain for roads and rail involving user delays, mostly from repair activities.
- Incremental adaptation costs for roads decline over time as inventory is gradually upgraded during planned rehabilitation or replacement to incorporate resilience to the projected future climate.

6.2. Electricity

6.2.1. Costs of inaction

Costs to repair electric transmission and distribution infrastructure failure and incremental damage are associated with heat stress, precipitation, and extreme events. Changes in climate contribute to alterations in the regular maintenance costs and period of performance of electric distribution and transmission infrastructure. Climate stressors also cause power outages resulting from grid infrastructure failure, which have potentially large direct and indirect costs. This section focuses on three components of the transmission and distribution network that are vulnerable to climate stressors: 1) Changes in air temperature cause changes in the lifespan and capacity of large power transformers, with higher temperatures associated with a reduction in transformer lifespan and capacity (both substation and distribution transformers); 2) High temperatures cause a reduction in transmission-line ampacity; and 3) Changes in precipitation and temperature alter the rate of decay at the base of the wood poles.

The costs of inaction and the costs of adaptation are based on a previous study (Fant et al. 2020) that considers the effect of a range of climate drivers (extreme temperature, extreme storms, lightning, vegetation growth, and wildfire activity) on these three electrical grid components.[116] The costs of inaction are based on changes to repair activities at the time that a climate stressor causes damage to the infrastructure. Details of the methodology are provided in Appendix B.

The estimated costs of inaction, shown in Table 6-4 and Figure 6-5 below, generally increase over time, primarily because the largest share of costs is associated with transformer vulnerability, which is based on temperature increases. Costs are also relatively consistent across climate models, as shown in Figure 6-5.

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

Table 6-4. Quantified Costs of Inaction (Millions per Year): Electricity

Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). Costs are incremental to baseline and averaged across six climate models (range across climate models provided in parentheses). See Appendix B for more details on methodology and limitations.

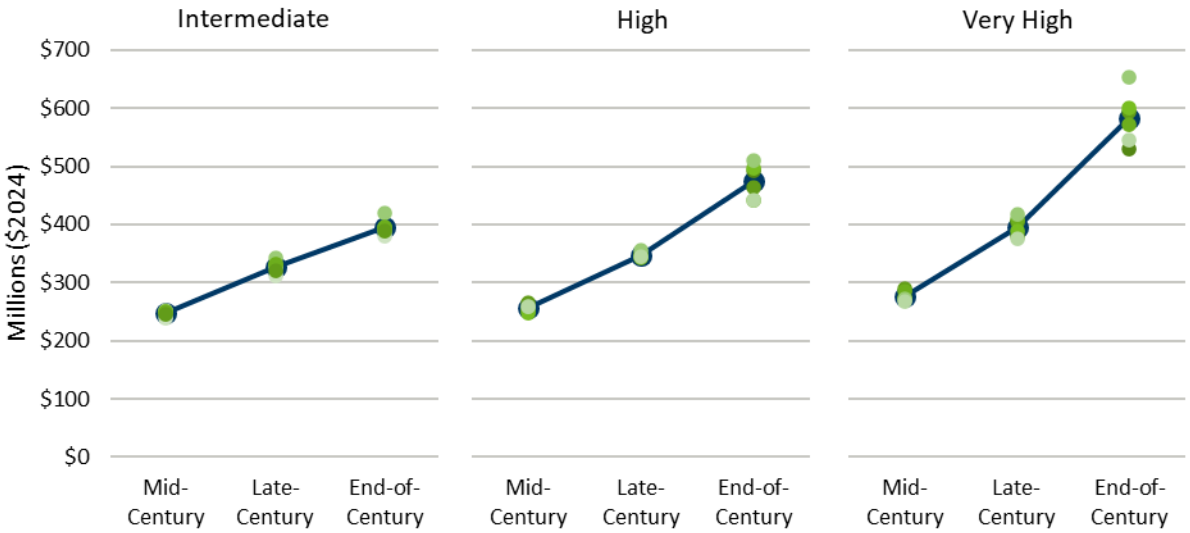
		Electricity Transmission and Distribution
		Damage and repair costs
Mid-Century (2040–2059)	Intermediate	$250 ($240 to $250)
	High	$260 ($250 to $260)
	Very High	$280 ($270 to $290)
Late-Century (2060–2079)	Intermediate	$330 ($310 to $340)
	High	$350 ($340 to $360)
	Very High	$400 ($380 to $420)
End-of-Century (2080–2099)	Intermediate	$390 ($380 to $420)
	High	$470 ($440 to $510)
	Very High	$580 ($530 to $650)

Other costs of inaction (not quantified):

- Power outages that could result from elevated electricity demand during heat events
- Service reliability and damage during ice storms

Figure 6-5. Range of Quantified Annual Costs of Inaction: Electricity Transmission and Distribution

Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). The solid lines with blue dots represent the average across six climate models per scenario, and the green dots without lines show the results for each of the six models.



Who bears the costs of inaction?

The costs of inaction are initially borne by electric utilities, which generally pass the costs of maintaining the transmission and distribution system on to their residential and commercial ratepayers.

What other costs of inaction are not quantified in this study?

Additional costs of inaction related to electricity infrastructure that are not quantified in this study include:

- Costs (to residents and businesses) of power outages caused by damaged lines and elevated electricity demand during heat events.
- Potential damage and interruption in service that might result from an increased frequency of ice storms, which can cause power line outages. The authors of the Fant et al. (2020) study contemplated an analysis connecting climate forecasts with the likelihood of ice storm conditions, but the state of climate science at that time was not developed to a point where the connections were considered reliable. Climate science has advanced since the publication of that work. An analysis of ice storm impacts on wires might be possible by relying on these recent advancements.

6.2.2. Costs of adaptation

Reactive and proactive adaptation for this cost category involves differing perspectives on climate change from utility infrastructure managers. While the cost of inaction estimates presented in the previous section above assume that utility infrastructure managers replace worn out transformers with new transformers of the same model as currently used (that is, to be consistent with baseline climate expectations), under the reactive response scenario utility managers update their expectations to consider the most recent 20 years of experience with climate change as they set specifications for their replacement transformers. For proactive adaptation, managers instead look forward and set specifications consistent with the average temperature profile that could be expected for the next 20 years of climate model forecasts. The same perspective applies for wire upgrades to account for transmission and distribution line ampacity decrements attributable to temperature increases, and for the need for steel reinforcement of wood distribution poles. Additional detail on these methods is provided in Appendix B and in Fant et al. (2020).

The results in Table 6-5 below indicate gradually increasing costs over time for the reactive response scenario, but with consistently higher costs than for the proactive adaptation scenario. In addition, proactive adaptation costs decline over time, as the process of replacing less resilient capital stock proceeds and the overall infrastructure inventory gradually is converted to a more resilient state.

Table 6-5. Quantified Adaptation Costs (Millions per Year): Electricity

Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). Costs are incremental to baseline and averaged across six climate models (range across climate models provided in parentheses). See Appendix B for more details on methodology and limitations.

		Electricity T&D: Reactive Response*	Electricity T&D: Proactive Adaptation
		Damage and repair costs	Damage and repair costs
Mid-Century (2040–2059)	Intermediate	$250 ($240 to $250)	$170 ($160 to $170)
	High	$250 ($250 to $260)	$170 ($160 to $170)
	Very High	$260 ($250 to $260)	$140 ($120 to $160)

		Electricity T&D: Reactive Response*	Electricity T&D: Proactive Adaptation
		Damage and repair costs	Damage and repair costs
Late-Century (2060–2079)	Intermediate	$300 ($300 to $310)	$170 ($140 to $190)
	High	$290 ($280 to $300)	$120 ($98 to $130)
	Very High	$250 ($240 to $260)	$58 ($50 to $75)
End-of-Century (2080–2099)	Intermediate	$320 ($290 to $340)	$130 ($71 to $170)
	High	$270 ($250 to $280)	$57 ($49 to $69)
	Very High	$240 ($220 to $250)	$57 ($51 to $67)

*Indicates an action with multiple alternatives; this alternative is not included in the annual summary.

Other unquantified adaptation costs:

- Costs of power outages
- Power line pole replacement
- Impacts of supply chain bottlenecks for transformers which might lead to service outages if upgraded replacements are delayed
- Grid undergrounding
- Generators and microgrids for critical facilities

What residual risks remain after adaptation?

Utilities closely monitor the condition of transformers to avoid power outages, and transformer replacement, line upgrade, and pole reinforcement are usually relatively routine operations. As a result, residual risks can be expected to be minimal.

Transformer upgrades, however, can be delayed by supply chain bottlenecks if national utility demand on transformer suppliers is elevated. For example, after the devastating effects of Hurricane Helene in North Carolina in 2024, many transformer replacements around the country were delayed as most of the available supply of transformers was allocated to restore power in that location. A similar supply chain bottleneck in the future, anywhere in the country, can delay adaptation actions and result in residual risks from foregone upgrades that are not estimated in this analysis.

What other effects result from adaptation?

Actions to reduce the likelihood of grid infrastructure failure are designed to make the provision of electric power more reliable. Enhancements to grid reliability in turn have multiple co-benefits not quantified here, including minimizing losses from power disruption for businesses, residences, and individuals who depend on reliable power for medical devices.

Who pays the adaptation costs?

Similar to the costs of inaction, adaptation costs are initially borne by electric utilities, which generally pass the costs of maintaining the transmission and distribution system on to their residential and commercial ratepayers.

What are the other costs of adaptation not quantified in this study?

The costs reported above do not reflect a comprehensive estimate of costs of adaptation, quantifying only a subset of the costs. Other, potentially important adaptation costs include:

- Costs of burying power lines and other equipment underground to prevent damage from increased hazardous weather events (wind and ice storms are two of the most common), trees, and other collisions are also not a quantified adaptation action but may increase grid resilience and reliability.
- Costs of pole replacement (and associated outages). While transformer and line performance is closely monitored by utility managers, and replacement usually occurs in advance of infrastructure failure, pole decay is not always monitored as closely.
- Costs to ensure that critical facilities and households that rely on power for medical devices have access to reliable energy through the creation of microgrids or supplying generators. These types of action may become more important as infrastructure becomes increasingly digitized. Rural areas specifically would benefit from improved connectedness to telehealth and other critical infrastructure connectedness.

6.2.3. Limitations and uncertainties

The quantified adaptation costs presented in this study are illustrative of the magnitude of costs required, though they do not cover all potential reactive and proactive responses to climate change. Key limitations to the analysis are described below; see Appendix B for a full discussion of limitations and uncertainties.

- Roughly half of the costs for electricity infrastructure are for early transformer replacement, and another large component is avoiding decrements in line carrying capacity (ampacity) reduced below baseline by extreme heat. Other costs of adaptation could be incurred for other elements of the transmission and distribution system, such as flooded substation components or wires and towers affected by ice storms, that are not estimated here.
- Costs of power outages are not included in this study. High electricity demand events associated with extended periods of extreme heat could put stress on the power system that could result in outages. No study was identified to estimate this impact for Minnesota, but some past national-scale studies have suggested that the potential impacts of power interruptions associated with climate change could be large.[117]

[117] 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. Available online at https://doi.org/10.1016/j.energy.2017.12.081

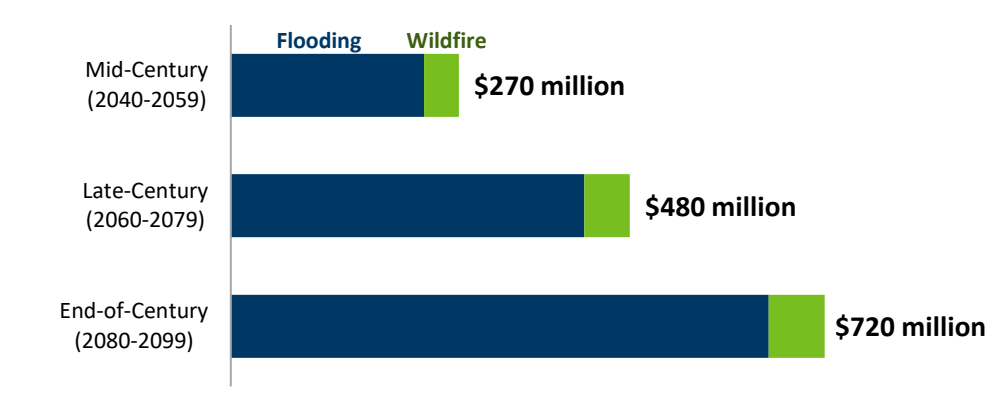
7. Cost of climate change: Buildings

Key Takeaways: Buildings

- Changing precipitation patterns and the occurrence of natural hazards are expected to result in damage to buildings in Minnesota. This study quantifies adaptation costs for climate impacts on buildings from **flooding** and **wildfires.**
- Riverine and rainfall flood risks are projected to worsen as precipitation events intensify. An investment of $650 million annually in building-level floodproofing by the end of the century, however, could reduce flood damage by over $6 billion under the High emissions scenario.
- Other adaptation investments quantified in this analysis include sump pumps, drainage systems, or foundation waterproofing to limit the damage caused by basement flooding.
- Additional flood risk adaptation needs not quantified in this analysis include actions such community-level measures to reduce flood risk over broader spatial areas, such as river levees, stormwater drainage upgrades, and nature-based solutions such as wetland enhancements.
- Other natural hazards that damage buildings include hail, windstorms, and **wildfires.** Damaging hail and windstorms have been documented in Minnesota, but changes in those risks are less reliably linked to climate change. Wildfire risk to buildings is a growing risk but of lower magnitude than flood risk. An investment of $70 million annually in wildfire hardening and fire pre-suppression by the end of the century could reduce direct structure damage and fire suppression costs of a similar order of magnitude under the High emissions scenario, with substantial co-benefits for forest health.

Quantified Annual Adaptation Costs by Period (High Emissions Scenario)

These costs are incremental of baseline adaptation costs and only include the quantified adaptation actions.



Buildings are vulnerable to many climate-driven hazards including floods, high winds, wildfires, and hail. Flooding is typically the most significant risk to buildings and livelihoods, causing damage through prolonged moisture, hydrostatic pressure, and erosion of the foundation, sometimes causing structural instability or failure but more commonly necessitating the need for repair and replacement of contents. Severe convective storms, including hail, can result in widespread damage to roofs and other exterior equipment causing leaks into the building. Wildfires present an additional hazard, particularly in wildland-urban interface areas where extreme heat, embers, and smoke can cause the destruction of buildings or contamination of interior spaces. Collectively these hazards increase repair and replacement costs of buildings and cause major disruptions to economic activity and livelihoods. Climate change is expected to increase the risk of extreme events, particularly flooding and wildfires.

There have been numerous recent flooding events in Minnesota that illustrate the risks of river flooding and high rainfall. The 1997 Red River flood in northwest Minnesota, an example of riverine (fluvial) flood risk, caused a total of $3.5 billion in damages throughout the basin in the U.S. and Canada. The city of East Grand Forks, Minnesota suffered severe damage, later working with the Federal Emergency Management Agency (FEMA) and the State government to prohibit future housing or businesses in the floodplain and creating a greenway corridor to help absorb floodwaters, and dikes in the more densely populated areas.[118] More recently, in June and July of 2025, there were multiple instances of rainfall amounts in excess of five inches in just a few hours, leading to pluvial flooding. During one of these events, the mayor of Marshall, Minnesota declared a state of emergency, citing basement and street flooding and noting, "This is not a river flooding issue – the issues we have are stemming from heavy rainfall."[119]

Minnesota often experiences over 1,000 wildfires a year, and the number of wildfires in the state has been increasing since the state started tracking them in 1992.[120] Multiple recent wildfires in northeastern Minnesota have resulted in structural losses. For example, the Camp House Fire in 2025 consumed more than 12,000 acres and destroyed more than 140 structures, including homes.[121] In 2024, the Snake Trail and Doran WMA wildfires caused over $200,000 in damage.[122]

In summary, buildings are vulnerable to numerous climate-driven hazards, including through the selected impacts listed below, with associated potential adaptation actions also shown. This study quantifies and estimates the costs of only those entries shown in bold.

Table 7-1. Costs of Inaction (Climate Impacts) and Potential Adaptation Actions for Buildings
Summary of costs of inaction and potential adaptation actions. Items in bold are quantified in this study.

Costs of Inaction	Potential Adaptation Actions
Increased precipitation leads to **more frequent and intense riverine floods (fluvial flooding) and overwhelms local drainage capacity (pluvial flooding).** Both types of flood damage structures and contents.	**Structure-level floodproofing** prevents above-ground water infiltration for many of the most frequent floods, though it cannot eliminate risk from the most damaging, but less frequent, events. Community-scale investments to reduce flood risk include land use planning to reduce building exposure in floodplains, levees, stormwater retention measures, and nature-based solutions such as wetland construction or enhancement.
Changes in precipitation volume and intensity **affect soil moisture,** which can result in increased basement flooding.	**Sump pump installation, interior or exterior drainage, exterior foundation waterproofing,** regrading, under-slab drainage systems.
Wildfires cause damage to building structures and contents, as well as to vehicles. **Fire suppression costs** are also incurred once a wildfire is ignited.	**Structures can be hardened and nearby vegetation can be managed** to substantially reduce fire risks. **Prescribed burning and forest thinning** also reduce wildfire risks and the need for suppression, with co-benefits for forest health. Land use planning could reduce building activity in high fire risk areas.

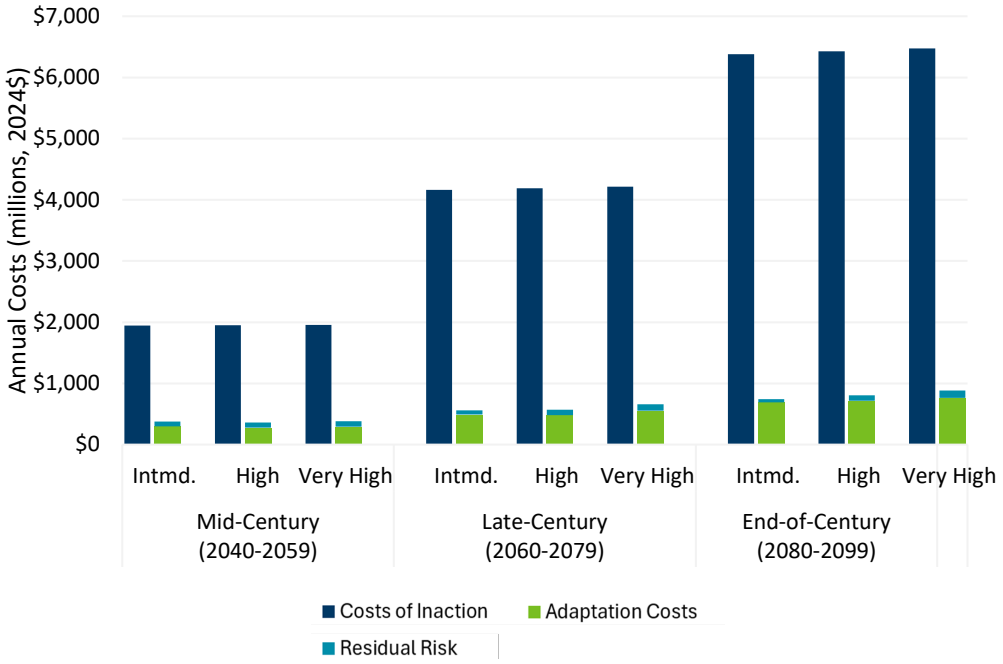
[118] See 1997 Red River flood and Greater Grand Forks Greenway.
[119] Gau, D. (2025). Marshall declares emergency after Friday flash floods. Marshall Independent, July 19, 2025. Available at: https://www.marshallindependent.com/news/local-news/2025/07/marshall-declares-emergency-after-friday-flash-floods/
[120] National Interagency Fire center. https://data-nifc.opendata.arcgis.com
[121] Galloway, A. (2025). Three wildfires are raging in Minnesota - Here's where and how much they've burned. 14 May 2025. Minnesota Now, https://minnesotanow.net.
[122] National Interagency Fire Center (2024). "WFIGS 2024 Interagency Fire Perimeters to Date" (Interactive map and database). https://data-nifc.opendata.arcgis.com. National Interagency Fire Center.

Costs of Inaction	Potential Adaptation Actions
Hailstorms can damage roofs, break windows, and damage vehicles.	Installing impact-resistant roof shingles, metal roofing, and other impact-resistant building materials substantially reduces the risk of hail damage.
Windstorms can directly damage roofs and walls or make nearby debris airborne, causing further damage.	Hardening of walls, windows, and roofs can reduce the risk of wind damage.
Climate impacts on building materials can lead to faster deterioration. Heavy precipitation, humidity, and sometimes heat accelerate building material wear and tear.	Building materials can be upgraded to reduce the rate of deterioration from climate hazards. Interior upgrades to ventilation and air quality systems can reduce damage from high humidity.

This chapter discusses the quantified costs and risks that can most reliably be associated with future climate changes (i.e., costs of inaction) and then provides a set of adaptation actions which could potentially mitigate those risks. This analysis quantifies costs of inaction, adaptation costs, and residual risk for a subset of potential costs to buildings sector, focusing on surface and subsurface flooding and wildfire risk. Figure 7-1 summarizes the quantified costs of inaction, adaptation costs, and residual risk (meaning, the damages that persist with adaptation – see Section 1.2.6 for more information on residual risks) related to buildings. Note that the costs in this figure are not comprehensive but rather represent the quantifiable costs in this study.

Figure 7-1. Buildings: Quantified Annual Climate Cost Summary

Summary and comparison of cost of inaction (first set of bars, in dark blue), adaptation costs (base of the second set of bars, in green), and residual risk (top of second set of bars, in light blue) per year, above baseline. Results for three time periods and three emissions scenarios (see Section 2.2.2 for more details), averaged across six climate models.



The remainder of this chapter includes two main sections, addressing the two climate hazards that trigger quantified adaptation costs: **Flooding** and **Wildfire and Other Natural Hazards.** Within each of these two main sections, there are subsections for **Costs of inaction, Costs of adaptation,** and **Limitations and uncertainties.** Both cost subsections provide a high-level methodology description, detailed results, and further interpretation of the findings, including how costs are distributed across the

state and which costs are not quantified in this study. Step-by-step detail on methods and specific citations to data sources, models, and peer-reviewed studies that provide a basis for estimating costs can be found in Appendix B.

7.1. Flooding

7.1.1. Costs of inaction

Flooding primarily causes damage to buildings and building content that necessitates repair or replacement. While flooding has historically been a potential threat to structures, the extreme precipitation events that cause floods are expected to worsen under a warmer future climate due to an accelerated hydrologic cycle with increased variability. Since most existing building-level flood protection is designed using knowledge of the intensity of past flood events, existing protection may prove less effective in the future against more severe flood events unless additional adaptation is implemented.

Flood types considered in this Study

This study addresses three main types of floods:

- **Fluvial,** meaning floods along riverbanks and other flow-driven events – sometimes also called riverine floods.
- **Pluvial,** meaning floods caused by intense precipitation. These often occur when stormwater systems are overwhelmed during intense precipitation but can also result in damage to areas without man-made drainage infrastructure.
- **Subsurface,** meaning floods caused by seepage, high soil moisture, and rising groundwater tables, often causing damage to basements.

The estimated costs of these **changes in flood events to building damages** rely on flood surfaces from the 2025 Fathom U.S. Flood Maps[123] that include both fluvial (i.e., riverine or flow-driven) and pluvial (i.e., precipitation-driven) flood effects. Flood depths are overlayed on a building inventory developed from datasets of building footprints and parcel maps, which includes important characteristics that affect repair costs such as the existence of basements and structure value. After overlaying flood depths on the building inventory, costs are calculated using depth-damage functions to estimate repair costs. More details on the methods, including data sources, can be found in Appendix B.

Table 7-2 shows the costs of inaction for flooding for two emissions scenarios and time periods for both pluvial and fluvial flood events. Pluvial flood damage is consistently slightly higher than fluvial damage, although they both reach almost $1 billion annually each by Mid-Century. This is roughly 25 percent higher than current flood damages if additional adaptation is not implemented. While the higher emissions scenario does result in higher damage costs, the difference is relatively small. By the end of the century, costs relative to current damages increase to over $6 billion per year in total across the two surface flood types, suggesting that increases in flood damage for the state accelerate in the latter half of the century to almost double the current costs of flooding. This analysis does not quantify the uncertainty across climate models due to the way the flood depths are generated by Fathom, but there is likely significant uncertainty in the central estimates presented here and actual flood damage costs in the future.

[123] https://www.fathom.global/product/global-flood-map/us-flood-map/

Table 7-2. Quantified Costs of Inaction (Millions per Year): Flooding

Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). Costs are incremental to baseline and averaged across six climate models (range across climate models provided in parentheses). See Appendix B for more details on methodology and limitations.

		Pluvial Flooding	Fluvial Flooding
		Damage costs	Damage costs
Mid-Century (2040–2059)	Intermediate	$980	$950
	Very High	$990	$950
End-of-Century (2080–2099)	Intermediate	$3,200	$3,100
	Very High	$3,300	$3,100

Note: Results for this analysis are only available for Mid- and End-of-Century and for the climate model average for the Intermediate and Very High emissions scenarios.

Other costs of inaction (not quantified):

- Sub-surface floods
- Direct and indirect business interruptions
- Tax revenue losses to local governments related to destroyed and damaged homes

Who bears the costs of inaction?

Generally, flood repair costs are either paid by the owner of the building or through insurance claims. However, Minnesota has one of the lowest rates of flood insurance coverage in the country with only about 0.3 percent of homes covered.[124] FEMA has offered disaster relief from flood events in the past, including nearly $17 million in individual assistance for the recent 2024 floods.[125]

The analysis suggests flood damage will increase in all counties in Minnesota, but some counties will bear more of the costs than others. Increases vary from about 25 percent to 55 percent by Mid-Century and from 90 to 250 percent by End-of-Century. Not surprisingly, the largest increase in total damage is expected around the Twin Cities, but some of the largest increases relative to historical damage are expected in the southwestern areas of the state. The northeastern areas, including Duluth, are also expected to have substantial increases in flooding.

What other costs of inaction are not quantified in this study?

This analysis of the costs of inaction is limited to costs to repair building damage due to surface floods, though additional flood-related costs of inaction are likely to occur. Additional costs of inaction related to flooding that are not quantified in this study include:

- Sub-surface floods can cause damage to basements or other subsurface infrastructure, resulting in flood damage. Note that this effect is discussed in the following section on adaptation costs.
- Flood events can also cause costly disruptions to economic activity. For example, commercial or industrial buildings may need to temporarily close to repair flood damage before resuming business. In some extreme cases, businesses may permanently close from flood damage or prolonged downtime. Flooding of critical infrastructure, such as water treatment plants or health care facilities, can have even larger indirect impacts not captured here.

[124] Minnesota Commerce Department. (2024). Flood insurance fact sheet summer 2024. https://mn.gov/commerce-stat/pdfs/2021_fact_sheet_floodIns_Owners_B_1.pdf

[125] FEMA. (2026). Minnesota Severe Storms and Flooding. https://www.fema.gov/disaster/4797#funding-obligations

- Residents who have flood damage may need to temporarily or permanently relocate, causing disruptions to their work.
- The damage estimates produced here focus on buildings and therefore omit flood damage to vehicles or other mobile assets, as well as flood damages to other types of infrastructure, such as shoreline recreation infrastructure (e.g. parks, boardwalks, boat ramps). Note that impacts to transportation and electricity infrastructure are discussed in Chapter 6.

7.1.2. Costs of adaptation

Adaptation options evaluated here include dry floodproofing and elevating buildings to adapt to surface flooding, and basement waterproofing intended to limit subsurface flood damage.

- **Dry floodproofing** is a flood mitigation method intended to prevent the entry of floodwater into a building by making the building watertight below a designated flood protection elevation. This technique relies on sealing all potential points of water ingress – walls, openings, and service penetrations – so that exterior floodwaters do not enter the interior space. Typically, dry floodproofing is implemented up to the bottom of windows, or about three feet. **Elevating an existing structure** is a structural retrofit measure intended to reduce the risk of flood damage in areas subject to flood hazards by raising the lowest habitable floor above a designated flood protection elevation.[126] The elevation process involves lifting the building from its existing foundation and supporting it on new or extended structural elements such as piers, columns, posts, or continuous foundation walls, thereby increasing the vertical separation between anticipated floodwater and the building's usable space. This analysis uses set thresholds of benefit-to-cost ratios to determine when adaptation will occur at the building level, and which of the two adaptation options (e.g., dry floodproofing or building elevation) would be implemented based on the risk of surface (pluvial and fluvial) floods. The benefit-cost ratio compares the expected damage avoided with adaptation to the cost of implementing the specified adaptation action. The moderate and high adaptation options presented reflect two different benefit-cost ratio thresholds triggering adaptation.[127]
- To limit damage caused by basement flooding, **basement waterproofing** options considered include the installation of a sump pump, interior or exterior drainage system, and exterior foundation waterproofing. A sump pump reduces basement flooding by actively removing any soil moisture that accumulates beneath or around the foundation of a building, by pumping it away from the building via a sump pit. Interior and exterior drainage systems reduce basement flooding by intercepting and redirecting subsurface water before it builds pressure against foundation walls or floors. Exterior foundation waterproofing prevents basement flooding by creating a continuous barrier that blocks water from penetrating foundation walls. The analysis first characterizes soil types in urban areas using data on land use and soil types from the U.S. Department of Agriculture (USDA), [128,129] and then estimates increases in soil moisture resulting

[126] The cost analysis for the elevation option considers whether the structure has a basement or is built on a crawl space or slab, using parcel level data from Minnesota IT Services: Geospatial Information Office, "Land Ownership: Parcels," n.d., https://www.mngeo.state.mn.us/chouse/land_own_property.html. Where parcel level data is not available, the average basement occurrence percentage from counties with data is assigned. See Appendix B for more details on the methods.
[127] In the Moderate adaptation scenario, a property owner invests when the flood protection benefits are at least six times the adaptation cost, and in the High adaptation scenario, investments occur when the benefits are 4.1 times the adaptation cost. The selection of 4.1 in the High adaptation scenario is designed to reduce residual risk (i.e., difference of historical to future) to near zero.
[128] USDA National Agricultural Statistics Service. (2025). Cropland Data Layer. https://www.nass.usda.gov/Research_and_Science/Cropland/Release/index.php
[129] USDA Natural Resources Conservation Service. (n.d.). Web Soil Survey. Accessed November 15, 2025, https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx

from changes in peak monthly precipitation under the different scenarios considered. The projected costs represent the investment costs associated with basement waterproofing measures necessary based on soil-specific investment thresholds.

More details on both methodologies are available in Appendix B.

The need for building flood protection measures more than doubles between Mid- and End-of-Century, though the differences between emissions scenarios are relatively minor. The basement protection costs are steadier through the End-of-Century, though the variability in the results across climate models is significant.

Table 7-3. Quantified Adaptation Costs (Millions per Year): Flooding

Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). Costs are incremental to baseline and averaged across six climate models (range across climate models provided in parentheses). See Appendix B for more details on methodology and limitations.

		Building Flooding Protection: Moderate Adaptation*	Building Flooding Protection: High Adaptation	Floodproofing Basement: Proactive Adaptation
		Protection cost due to pluvial and fluvial flooding	Protection cost due to pluvial and fluvial flooding	Floodproofing cost
Mid-Century (2040–2059)	Intermediate	$40	$180	$77 ($1.1 to $120)
	High	-	-	$51 ($13 to $120)
	Very High	$41	$180	$63 ($2.5 to $140)
Late-Century (2060–2079)	Intermediate	-	-	$72 ($4.7 to $140)
	High	-	-	$49 ($0.5 to $120)
	Very High	-	-	$110 ($6.9 to $150)
End-of-Century (2080–2099)	Intermediate	$200	$570	$72 ($4.3 to $130)
	High	-	-	$77 ($9.2 to $140)
	Very High	$200	$570	$100 ($7.7 to $150)

Note: Results for this analysis without a range are only available for the climate model average for the emissions scenarios.
*Indicates an action with multiple alternatives; this alternative is not included in the annual summary.

Other adaptation costs (not quantified):

- Stormwater system upgrades
- Business relocation
- Sump pump and drainage inspection and energy costs
- Emergency plans
- Retention ponds or pervious paving alternatives in developed areas
- Changes in land cover to reduce surface flow velocities
- Managed retreat from high-risk areas that are difficult to protect with other means
- Levees or other large-scale flood barriers

What residual risks remain after adaptation?

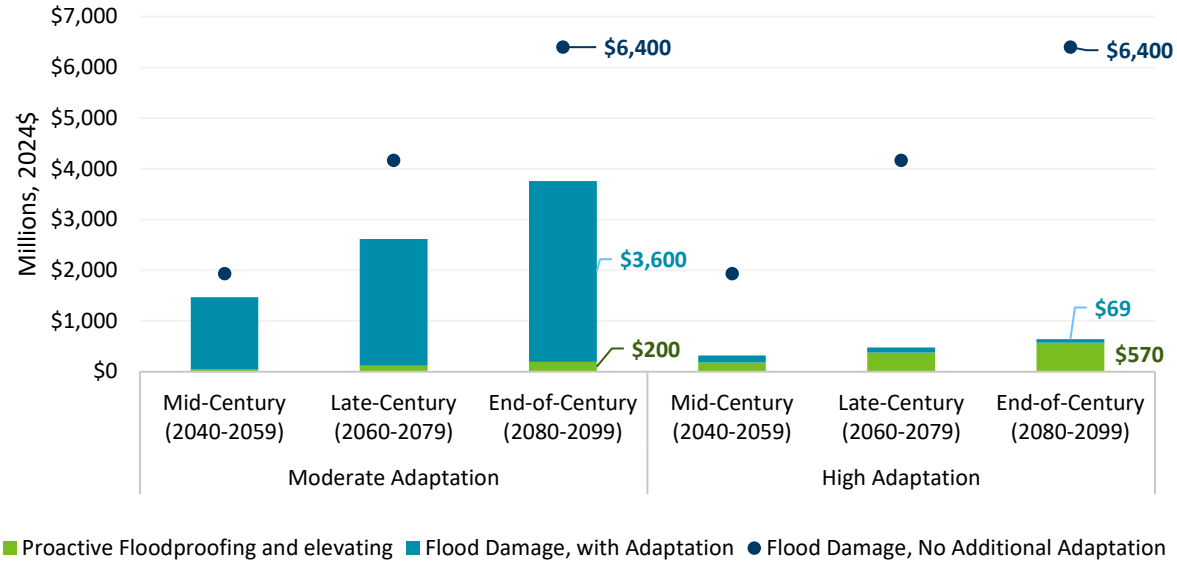
Flood risk is effectively never eliminated. The remaining impacts to buildings, after floodproofing decisions are made, are characterized as residual risk. Buildings that are vulnerable to flood damage but do not adapt based on the model decision rules do not reduce their future risk, and even homes with flood protection can incur damage, particularly for low-probability, extreme events with flood depths

that exceed the existing level of protection. For example, if a home with dry floodproofing experiences flood depths that exceed three feet above the first floor elevation, flood damage will occur.

As shown in Figure 7-2, under both the Moderate and High Adaptation scenarios, the costs of adaptation plus the remaining risk after adaptation are less than the expected damages without additional adaptation. However, higher adaptation investment avoids significant residual risks compared to the Moderate Adaptation scenario – a $140 million increase in annual adaptation spending in the Mid-Century avoids $1.3 billion of annual flood damage over the same time period.

Figure 7-2. Quantified Adaptation Costs and Residual Risks versus Costs of Inaction for Flooding

Annual costs (in millions, 2024$) for floodproofing and elevation (green bar segments) and the flood damages that remain with the proactive adaptation (blue bar segments). Costs of inaction (blue dots) are shown for reference – adaptation plus residual risks are always less than the costs of inaction. Results reflect the High emissions scenario though similar patterns persist across all modeled emissions scenarios.



Certain communities in Minnesota are disproportionately impacted by environmental issues and are referred to as environmental justice areas.[130] When considering the environmental justice communities experiencing severe flooding risk, many communities in the northern part of the state experience higher impacts and costs from flooding, as do census tracts within Minneapolis–St. Paul. Since model simulations determine flood protection using economic viability, homes with lower values tend to be left without protection.[131]

What other effects result from adaptation?

In addition to reducing direct flood damage, investing in flood adaptation can bring about a range of additional effects. For example, elevating buildings or installing flood barriers can improve the long-term usability of certain areas, allowing for more stable economic activity and reducing disruption to households and businesses. At the same time, such adaptations can alter local hydrology, potentially

[130] According to the Minnesota Pollution Control Agency, environmental justice communities are defined as census tracts where the estimated percentage of the population that identify as people of color is 40% or greater, the estimated percentage of economically disadvantaged community members is 35% or greater, and the estimated percentage of the population that has limited English proficiency is 40% of greater. Economic disadvantage is defined as an income threshold at two times the federal poverty threshold (for family size). Additional information can be found here: https://resources.gisdata.mn.gov/pub/gdrs/data/pub/us_mn_state_pca/env_ej_mpca_census/metadata/ej_mpca_census.html

[131] Residual risks associated with basement flooding are not quantified in this analysis.

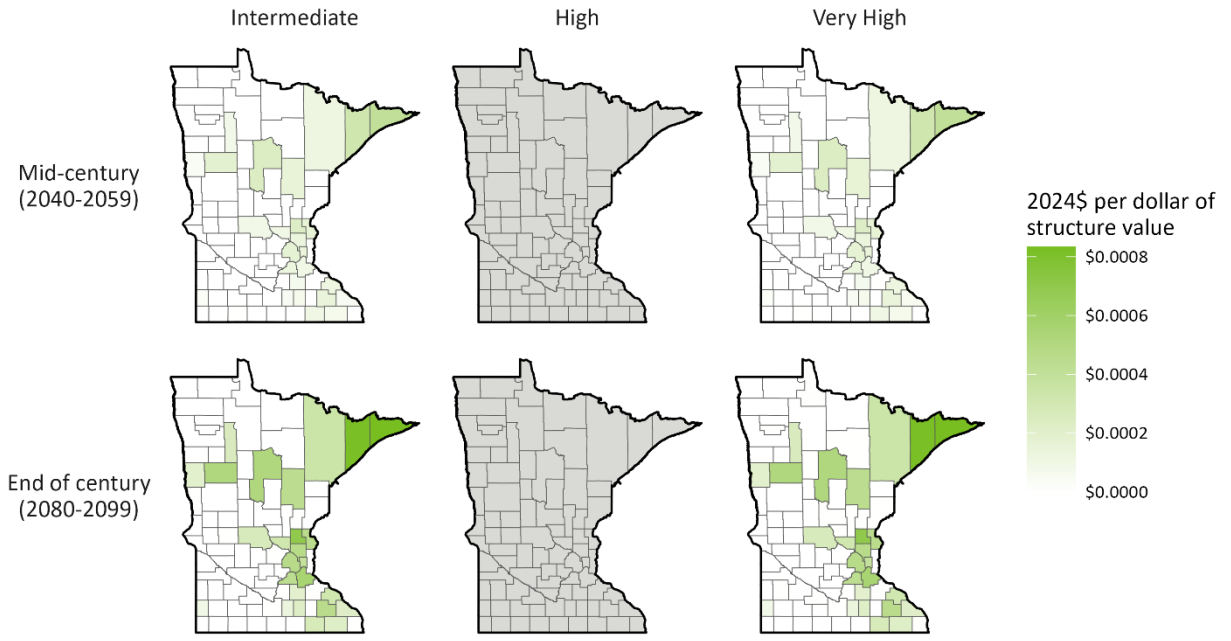
increasing runoff or shifting flood risks to downstream areas, which may necessitate complementary measures elsewhere. Changes in local hydrology and investment in certain flood adaptation measures can have environmental and ecosystem impacts. Adaptation measures can also influence social and economic dynamics, including changes in property values, land use patterns, and insurance costs.

Who pays the adaptation costs?

Structure-level adaptation costs, such as those quantified in this study, are generally paid by the owner of the building. In some cases, flood insurance may require certain preventative measures are taken or may offer reduced rates when flood protection is in place. Generally, flood protection costs are higher in the same areas that have the highest future risks. Many counties in the southeast, including the Twin Cities, indicate flood protection needs. Counties in the north also bear adaptation costs, particularly in the northeast around Lake Superior.

Figure 7-33. Distribution of Surface Flooding Costs by County

Annual costs of increased flood adaptation measures (2024$ per dollar of total structure value) by county for two time periods and three emissions scenarios (see Section 2.2.2 for more details).



What are the other costs of adaptation not quantified in this study?

The costs reported above do not reflect a comprehensive estimate of costs of adaptation, quantifying only a subset of the costs. Other, potentially important adaptation costs, not quantified above, may include:

- Structural fluvial measures such as levees and floodwalls, channelization and river straightening, and bypass channels. These measures are not uncommon in Minnesota, and some local scale analyses have assessed their costs for proposed additional measures. The type of hydrologic and hydraulic modeling needed to assess needs for these measures, however, was not available on a statewide basis. Further, costs for these measures can be highly site-specific. Under the right conditions, however, structural fluvial measures can be an efficient substitute for the individual building-scale flood protection measures modeled here.

- Stormwater system expansion and construction of retention and detention ponds. Nature-based solutions such as wetland restoration offer critical co-benefits that traditional gray infrastructure does not provide. See the textbox below for more discussion on potential nature-based solutions for expanding water storage.
- Relocation and business interruption costs associated with building occupants temporarily relocating while construction work is underway.
- Ongoing inspection and energy costs of operating sump pumps and drainage systems.
- Emergency preparedness, evacuation plans, and communications systems.
- Governance reform through updating building codes and streamlining governance structures to minimize future losses.

Nature-based solutions: Flood control benefits of wetlands

Ecosystems such as wetlands and forests along rivers and streams can provide valuable flood control benefits that help reduce flood damage downstream. These ecosystems can act as natural sponges, absorbing water during peak flow periods and slowly releasing the water later when water levels have receded. In a study of flooding in Vermont after Tropical Storm Irene in 2011, researchers found that the extensive wetlands along Otter Creek between Rutland (upstream) and Middlebury (downstream) reduced flood damage in Middlebury by 84 to 95 percent.[a] Above the wetland, the heavy precipitation led to a sharp peak in the amount of water flowing through Otter Creek leading to flood waters that inundated parts of Rutland and extensive flood damage. The wetlands between Rutland and Middlebury absorbed floodwaters coming downstream and slowly released water over many days. Downstream of the wetlands in Middlebury, there was no sharp peak in the amount of water flowing through Otter Creek, only a gradual increase and decrease in the flow, and only minor flooding. A nationwide study using information from flood insurance claims found that an average hectare of wetland generated flood protection benefits of $1,840 annually, and $8,000 per hectare in developed areas.[b]

With the likely increase in extreme precipitation events under climate change, wetlands in Minnesota will likely provide even larger flood mitigation benefits in the future than they do at present. In addition to flood control, wetlands also provide an array of other benefits, such as improving water quality by filtering out nutrients and sediment, storing carbon, and providing fish and wildlife habitats.

a) Watson, K., T. Ricketts, G. Galford, S. Polasky, J. O'Neil-Dunne. (2016). Economic valuation of flood mitigation services: The value of Otter Creek wetlands and floodplains to Middlebury, VT. Ecological Economics 130: 16-24.
b) Taylor, C.A. and H. Druckenmiller. (2022). Wetlands, flooding and the Clean Water Act. American Economic Review 2022, 112(4): 1334–1363.

7.1.3. Limitations and uncertainties

The quantified adaptation costs presented in this study are illustrative of the magnitude of costs required, though they do not cover all potential reactive and proactive responses to climate change. Adaptation decisions related to buildings are made by individual building owners and are not likely to be uniform across entire counties. Key limitations to the analysis are described below; see Appendix B for a full discussion of limitations and uncertainties:

- In the absence of available data, the analysis assumes the first floor elevation of all buildings is one foot above the ground, which affects the magnitude of the estimated damages and adaptation potential.

- In the absence of structure-level information about existing protection, this study assumes protection exists for those structures that have an estimated benefit-cost ratio of at least six. A lower benefit-cost ratio for existing protection will reduce the damage estimate and adaptation costs, and vice versa.
- It is unclear what fraction of existing homes in Minnesota have a basement and which portion of existing basements are considered "finished" basements, such that floodproofing investments would be conducted in response to water damage. Based on data for the Midwest, this study assumes that 80 percent of housing in urban areas has useable basements that can be damaged from flooding.
- The estimates reflect the current housing stock. Potential damages to new construction are not included in the results. Smart growth to minimize new construction in high-risk areas can help reduce this risk.

7.2. Wildfire and Other Natural Hazards

7.2.1. Costs of inaction

Buildings are susceptible to damage from natural hazards beyond flooding. Three natural hazards that are expected to worsen with climate change are local wildfires,[132] windstorms, and hailstorms. Local wildfire damages have been documented in Minnesota for specific recent historical events, such as the June 2025 Brimson Complex Fire which caused an estimated $2.3 million in damage to 74 parcels and 205 structures in St. Louis County.[133] There is also evidence from the Minnesota Forest Resource Council that wildfires in Minnesota have increased in recent years.[134] Wildfire affects buildings in Minnesota that are located within the wildland-urban interface – defined by FEMA as the zone of transition between unoccupied land and human development. Costs of inaction include increases in damage to structures, as well as the need to increase wildfire suppression efforts, as the risk of wildfires increases due to drier and hotter conditions in future years.

Damaging windstorms, also called derechos, have been documented for multiple instances in Minnesota, including the July 1999 Boundary Waters Canadian Derecho ($3 million in documented damage), the August 2020 midwestern derecho, and at least two major events in June and July 2025.[135] Though recent trends suggest climate change may lead to an increase in the severity, if not necessarily the frequency, of damaging derecho wind events, data were not available to estimate the potential for a change in the risk of wind damage to structures associated with climatic changes.[136]

Hail storms are also a common and damaging occurrence in Minnesota – a single storm in May 2022, for example, was estimated to cause over $2 billion in damages to structures in Minnesota's three largest

[132] Note that the term "local wildfires" refers to fires that affect the land area of Minnesota, and therefore potentially damage Minnesota's buildings. These impacts are distinct from the large-scale Canadian and western U.S. wildfires that lead to air quality decrements, which are addressed in Chapter 4.
[133] See the St. Louis County property assessors site for reference to the damage estimate from the Brimson Complex fire: https://content.govdelivery.com/accounts/MNSTLOUIS/bulletins/3e4e2d1, and this WDIO news report.
[134] See Climate Change and Minnesota's Forests: A Report Prepared for the Minnesota Forest Resources Council by the Research Advisory Committee, September 16, 2020, available at: https://mn.gov/frc/assets/Climate_Change_and_Minnesota%27s_Forests_2020_tcm1162-471265.pdf
[135] See information on the Boundary Waters – Canadian Derecho, the Bemidji Blowdown, and a smaller July 2025 event. For information on the 2020 event, see Lasher-Trapp, S., Orendorf, S. A., & Trapp, R. J. (2023). Investigating a derecho in a future warmer climate. Bulletin of the American Meteorological Society, 104(10), E1831-E1852.
[136] Lasher-Trapp et al. 2023.

cities.[137] Although the literature connecting hail storms to climate change is growing and suggests that damaging events may become both more frequent and be characterized by larger hail stones in the future, currently available data do not support quantification of the costs of inaction related to climate-driven hail damages.[138]

This analysis quantifies the costs of inaction due to **wildfire risks** based on projections of the increase in acreage burned in Minnesota from Gao et al. (2021).[139] Projected wildfire suppression costs are calculated by scaling baseline wildfire suppression costs from published estimates from the Minnesota DNR (2025) with the proportional increase in the extent of fire risk from Gao et al. (2021).[140] Future estimated annual wildfire structure damages are calculated using a similar approach. Average baseline annual risk to structures throughout Minnesota was estimated to be roughly $6 million – or roughly two to three times the estimate for the recent Brimson Complex fire – based on damage per structure from recent historical fire events in Minnesota, the median structure value of homes in Minnesota, and the number of Minnesota homes and annual risk of damage for wildfire risk zones estimated by the U.S. Forest Service (USFS), as part of their HURisk wildfire risk index classification system.[141] Projected damages were assumed to be proportional to an available projection of the incremental estimated percentage increase in total acreage burned in Minnesota for the specific fire characteristics of the region from Gao et al. (2021).[142]

The results are shown in Table 7-4 below. Wildfire suppression costs are roughly four to five times as large as structure damage, though structure damage would likely be much larger in the absence of these suppression efforts. Consistent with the projections in Gao et al. (2021), the costs of inaction increase 44 percent under the Intermediate emissions scenario and 59 percent under the Very High emissions scenario by Mid-Century, and 56 percent and 110 percent respectively by End-of-Century.

Table 7-4. Quantified Costs of Inaction (Millions per Year): Wildfire

Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2 for more details). Costs are incremental to baseline. See Appendix B for more details on methodology and limitations.

		Wildfire Suppression	Wildfire Building Damage
		MNDNR and USFS incremental fire suppression costs	Incremental building wildfire damage
Mid-Century (2040–2059)	Intermediate	$10	$2.6
	High	$11	$3.1

[137] DNR. (2023). Southern Minnesota Hailstorms, May 19 2022. https://www.dnr.state.mn.us/climate/journal/southern-minnesota-hailstorms-may-19-2022.html

[138] See for example Raupach, T. H., Martius, O., Allen, J. T., Kunz, M., Lasher-Trapp, S., Mohr, S., ... & Zhang, Q. (2021). The effects of climate change on hailstorms. Nature reviews earth & environment, 2(3), 213-226. and Mallinson, H., Lasher-Trapp, S., Trapp, J., Woods, M., & Orendorf, S. (2024). Hailfall in a possible future climate using a pseudo–global warming approach: Hail characteristics and mesoscale influences. *Journal of Climate*, *37*(2), 527-549. https://doi.org/10.1175/JCLI-D-23-0181.1

[139] Gao, P., Terando, A. J., Kupfer, J. A., Varner, J. M., Stambaugh, M. C., Lei, T. L., & Hiers, J. K. (2021). Robust projections of future fire probability for the conterminous United States. Science of the Total Environment, 789, 147872.

[140] MN DNR Annual Report on Emergency Firefighting Expenditures, Fiscal Year 2024, 01/15/2025. Available at: https://files.dnr.state.mn.us/aboutdnr/reports/legislative/2024/fy24-emergency-firefighting-fund-report.pdf This report also included multiple years of historical firefighting expenditures, which were averaged.

[141] The Forest Service HURisk program assesses and maps wildfire risk to communities, using data on fire probability, intensity, and building/population data to create risk indices – the HURisk index is part of the Wildfire Risk to Communities (WRC) initiative. See Dillon, G. K., Lazarz, M. T., Karau, E. C., Story, S. J., & Pohl, K. A. (2024). Wildfire Risk to Communities: Community Wildfire Risk Reduction Zones for the United States. https://doi.org/10.2737/RDS-2024-0030, Available at: https://www.fs.usda.gov/rds/archive/catalog/RDS-2024-0030

[142] Gao et al. (2021), Robust projections of future fire probability for the conterminous United States.

		Wildfire Suppression	Wildfire Building Damage
		MNDNR and USFS incremental fire suppression costs	Incremental building wildfire damage
	Very High	$13	$3.5
Late-Century (2060–2079)	Intermediate	$15	$3.0
	High	$18	$4.0
	Very High	$22	$5.1
End-of-Century (2080–2099)	Intermediate	$20	$3.4
	High	$26	$5.0
	Very High	$32	$6.6

Note: Results for this analysis are only available the climate model average for each emissions scenario.

Other costs of inaction (not quantified):

- Wildfire damages to commercial, industrial, institutional, and government structures
- Direct and indirect business losses associated with fire damages
- Remediation expenses and other wildfire response and recovery costs

See also Chapter 4 for a discussion of the impacts of wildfires on human health and Chapter 8 for a discussion of the impacts on ecosystems.

Who bears the costs of inaction?

The building damage costs of inaction are borne by homeowners, either through the costs of structure repairs or, more broadly, through changes in insurance premiums. The costs of fire suppression are borne by local government emergency fire operations; the State government through actions by the DNR, primarily on State-owned lands; and the Federal government for actions on USFS lands. As described above, wildfire risks to buildings are highest in the wildland-urban interface.

It is worth noting that standard property insurance policies include wildfire damage as a covered peril, but deductibles and coverage limits usually apply. Property insurance premiums in Minnesota have been increasing as information on the increased risk of future wildfires and other perils (including hail and wind) has become available.[143] Premiums are based on the current and expected average annual losses to structures – so they are designed to reflect the same factors considered in the HURisk data used here – but no estimates exist of the future change in premiums that might result in Mid-Century or later in Minnesota, though it is reasonable to conclude these premiums will increase.

What other costs of inaction are not quantified in this study?

The quantified estimates focus on the direct costs to structures and for fire suppression and exclude some structure types and the indirect costs of increased fire risk.

- Costs for damages to commercial, industrial, institutional, and government structures are not included in the HURisk data and therefore are not reflected in these results.
- For property owners, indirect costs include structure contents losses, loss of use of the property (which includes business interruption costs for commercial and industrial structures), debris removal costs, and remediation of smoke damage. Indirect costs of fire suppression include

[143] Note that flood risks are excluded from standard property insurance, but coverage can be obtained under the National Flood Insurance Program, or in infrequent cases under private insurance.

costs of maintaining pre-fire readiness, which in this analysis are considered part of the baseline but are reasonably expected to increase in the future if the scale of fire suppression required increases dramatically. An analyst at the Minneapolis Federal Reserve in 2010 estimated that total indirect fire damages over a long period of time could be 10 to 50 times larger than direct damages of fire suppression,[144] but some of the indirect damages considered include health effects from smoke exposure, which is captured in this study in Chapter 4.

7.2.2. Costs of adaptation

Adaptative actions include hardening of structures and vegetation management near homes, as well as increased pre-suppression activity such as prescribed burning of forests to reduce fuel load.

- **Structure hardening** includes a list of measures to be implemented for high-risk structures in the Mid-Century from the Minnesota DNR Firewise program, and a cost estimate from a recent Headwater Economics (2024) report, applied statewide with equal investments over 20 years.[145] Costs are then scaled up in the future years to be proportional with the estimated increase in acres burned from Gao et al. (2021).
- **Pre-fire suppression activity** estimates begin with the baseline annual pre-suppression costs for prescribed burns using a combination of Minnesota's reported annual costs over 2015 to 2024, and the reported acreage of prescribed burns for the MNDNR and USFS using the Minnesota Incident Command System 2024 annual report. The costs of per acre activity from state partners are scaled to also include federal partners to estimate total baseline costs. The estimated costs represent two adaptation scenarios: reactive response and proactive adaptation. In the reactive response scenario, future costs are calculated by scaling the baseline suppression costs using the incremental estimated percentage increase in acreage burned in Minnesota from Gao et al. (2021). For a proactive scenario, in light of information which suggests that both thinning and prescribed burning activity in the state are currently practiced at rates far less than needed to adequately reduce fire risk, costs are estimated using the same procedure as for the reactive scenario, but this scenario assumes that double the acreage would be required to be treated to respond to the increased fire risk in the future.

Additional methods details can be found in Appendix B.

Table 7-5. Quantified Adaptation Costs (Millions per Year): Wildfire

Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). Costs are incremental to baseline and averaged across six climate models. See Appendix B for more details on methodology and limitations.

		Pre-suppression Costs: Reactive Adaptation*	Pre-suppression Costs: Proactive Adaptation	Building Wildfire Protection: Proactive Adaptation
		Protection costs to pre-suppression scaled to current fire risk	Protection costs to pre-suppression scaled to 2x the incremental fire risk	Building hardening costs
Mid-Century (2040–2059)	Intermediate	$17	$33	$3.0
	High	$20	$39	$3.0
	Very High	$22	$45	$3.0

[144] See https://www.minneapolisfed.org/article/2010/counting-the-full-cost-of-wildfires

[145] Headwaters Economics. (2024). Retrofitting a Home for Wildfire Resistance: Costs and Considerations. Spring 2024. Available at: https://headwaterseconomics.org/wp-content/uploads/2024/06/Wildfire_Retrofit_Report_R5.pdf

		Pre-suppression Costs: Reactive Adaptation*	Pre-suppression Costs: Proactive Adaptation	Building Wildfire Protection: Proactive Adaptation
		Protection costs to pre-suppression scaled to current fire risk	Protection costs to pre-suppression scaled to 2x the incremental fire risk	Building hardening costs
Late-Century (2060–2079)	Intermediate	$19	$38	$3.4
	High	$26	$51	$3.8
	Very High	$32	$64	$4.3
End-of-Century (2080–2099)	Intermediate	$21	$42	$3.8
	High	$31	$63	$4.7
	Very High	$42	$83	$5.6

Note: Results for this analysis are only available for the climate model average for the emissions scenarios.
*Indicates an action with multiple alternatives; this alternative is not included in the annual summary.

Other adaptation costs (not quantified):

- Community-level land use planning
- Potential additional needs for thinning and prescribed burning

What residual risks remain after adaptation?

Even with adaptation, it is not possible to eliminate risks of wildfire to structures, or to fully suppress all damaging fires through either pre-fire or post-fire activities, so residual risks will remain if the quantified adaptation measures are adopted. Cost-effective wildfire risk mitigation to structures is the main goal of the DNR Firewise program and similar programs around the country. Unfortunately, existing studies and data to quantify residual risks in a comprehensive manner are mostly unavailable, although some studies report reductions in individual structure damage of over 70 percent for the most comprehensive combinations of vegetation management and home hardening measures.[146]

Recent North American wildfire and risk mitigation modeling work supports the development of structure insurance premiums and premium discounts associated with implementation of structure-level hardening activities, but the models are proprietary.[147] A small number of these insurance industry models also claim to incorporate the impact of community-level adaptation activities (e.g., prescribed burning and thinning), but the details of their work are also proprietary.

What other effects result from adaptation?

Prescribed burning and thinning activities have a wide range of co-benefits beyond reducing the risk of the most damaging high-intensity and -severity fires. These benefits include enhancing ecosystem health in multiple ways. In many forest and prairie ecosystems, regular and periodic low-intensity fire activity can reduce invasive and woody species encroachment, increase biodiversity, improve soil health, enhance flood protection capacity, reduce soil erosion risks, and optimize carbon sequestration potential. Prescribed burns can negatively affect air quality, but in most instances they are carefully planned to minimize the potential for downwind exposures.

[146] See for example a 2024 Guidewire report, which reports the percent changes in risk due to various adaptation measures based on empirical data in California, and a 2020 RMS/Moody's report, which presents benefits and costs of structural mitigation and vegetation mitigation measures across eight communities in the western U.S.
[147] Additional information on the insurance industry models can be found by viewing the webinar series hosted by the California Department of Insurance entitled "Wildfire Catastrophe Models Explained."

Who pays the adaptation costs?

Adaptation costs are paid by the same actors as might incur the costs of inaction – that is, building hardening costs are borne by homeowners, and the costs of pre-fire suppression activities are borne by the state government through actions by the DNR and the federal government for actions on USFS lands. The alignment of the burden for the costs of inaction and the risk mitigation costs of adaptation provides an economic incentive to adopt cost-effective adaptation, but in many cases adaptation action involves substantial upfront costs with uncertain future benefits, and so can be limited by financing barriers and other obstacles.

What are the other costs of adaptation not quantified in this study?

No costs of adaptation are included for hail and wind risks to structure. Documented hail damage in Minnesota is extensive, suggesting that a relatively high cost of risk mitigation and adaptation to a potentially increasing hail risk may be justified. In addition, as a covered peril in property insurance there may be strong incentives for risk mitigation activities at the structure level to reduce rising insurance premiums.

For fire risk, community-level land use planning and building codes may be effective in reducing losses in high wildfire risk areas and can yield high-magnitude cost savings over time. A long list of more extensive structure hardening measures, beyond those quantified here, could also be adopted and may be cost-effective in some Minnesota settings. Finally, while detailed knowledge of the accumulated deficit in the extent of lands requiring thinning and prescribed burning is incomplete, available evidence suggests that it may be cost-effective to implement thinning and prescribed burning in a much wider spatial extent than considered here to more effectively limit wildfire risks, especially if ecosystem and timber management co-benefits are considered.

7.2.3. Limitations and uncertainties

The quantified adaptation costs presented in this study are illustrative of the magnitude of costs required, though they do not cover all potential reactive and proactive responses to climate change. Key limitations to the analysis are described below; see Appendix B for a full discussion of limitations and uncertainties relevant to this section of the study.

- For the costs of inaction and adaptation costs focused on direct wildfire damage to structures, there are three key assumptions in the analysis that contribute to uncertainty:
    1. The analysis is based on a simple model of measures that could be employed to reduce risk, limited to a single high-risk class of homes, even though there is documentation of historical damage to structures in the moderate- and lower-risk classes. This limitation, combined with the inability to model risks to non-residential structures, presents a substantially major underestimation bias.
    2. Information on the baseline level of structure hardening is not available – so the assumption that no structures in the high-risk class have yet been hardened presents an overestimation bias, which is likely to be small because hardening and vegetation are not necessarily one-time activities and should be periodically updated over time.
    3. All of these analyses rely on an indirect measure of future structure risk – that is, the estimated statewide extent of future acres burned. If more time and resources were available, a more refined analysis might more carefully align the spatial extent of high fire risk areas with vulnerable structures, although that might be a task which property insurers would be willing to contribute.

- For forest area fire suppression and pre-suppression cost analyses, the same limitation around the use of an indirect measure of fire risk applies. In addition, two other limitations are incomplete information on the current and future planned spatial extent of these measures, and the use of standardized unit costs for the pre-suppression activities, which combined suggest a potentially major underestimation bias in the estimates in this study.
- The estimates reflect the current housing stock. Potential damages to new construction are not included in the results. Smart growth to minimize new construction in high-risk areas can help reduce this risk.

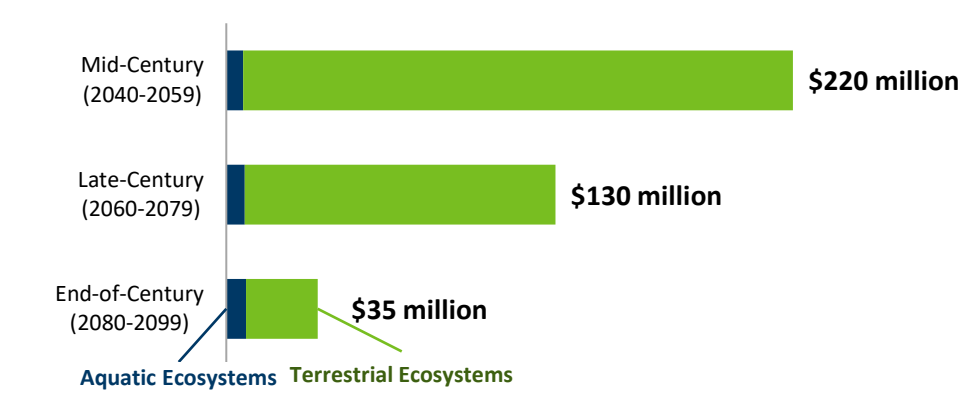
8. Cost of climate change: Ecosystems

Key takeaways: Ecosystems

- Ecosystems are critically linked to nearly all impacts and potential adaptation actions described in this study. Climate impacts on ecosystems affect social, economic, and built infrastructure while healthy ecosystems provide adaptation benefits across categories.
- This study does not fully quantify, in monetized terms, the costs of inaction to ecosystems nor the costs of adaptation. The appropriate and effective adaptation actions to address threats to ecosystems are often very site-specific and difficult to generalize.
- The quantified adaptation costs are driven by costs to protect forests from three invasive pests that are currently identified as emerging or ongoing risks. The suitable range for these pests in Minnesota is expected to peak around the Mid-Century, thus adaptation costs are also highest during this time period. New pests may emerge that require additional investments in the latter part of the century.

Quantified Annual Adaptation Costs by Period (High Emissions Scenario)

These costs are incremental of baseline adaptation costs and only include the quantified adaptation actions.



The natural environment is a critical and highly valued aspect of life in Minnesota. Natural resources support cultural and spiritual practices, recreation, economic opportunities, and subsistence harvesting. Climate change is likely to alter the suitability of Minnesota for species that have historically thrived in the state, increase stressors that affect ecosystems, and bring about more severe and frequent disturbances. Without proactive intervention, this could result in declining habitat quality and habitat loss under new climate regimes.

Ecosystems are affected by climate change in a number of ways, including through the selected impacts listed below, along with their associated potential adaptation actions. This study quantifies and costs the items in bold.

Table 8-1. Costs of Inaction (Climate Impacts) and Potential Adaptation Actions for Ecosystems

Summary of costs of inaction and potential adaptation actions. Items in bold are quantified in this study.

Costs of Inaction	Potential Adaptation Actions
Increasing climate-driven disturbances and stressors lead to forest loss, including loss of forest carbon storage and	Climate-adaptive silviculture, climate-informed reforestation, avoided forest conversion.

Costs of Inaction	Potential Adaptation Actions
sequestration. Disturbances also cause changes in forest distribution and composition.	
Increasing wildfire risk, driven by more fire-weather days and more vulnerable trees due to climate-driven disturbances and stressors, leads to widespread loss of mature forest, habitat, and ecosystem services (e.g., wildlife habitat, carbon storage).	Mechanical thinning, prescribed fire, and fire breaks (see **pre-suppression activities** in Chapter 7).
Shifting species composition in response to shifting habitat suitability areas leads to loss of culturally important species, affects **timber production** and harvest, and changes the distribution and provision of other ecosystem services (e.g. wildlife habitat, **carbon storage**).	Climate-adaptive silviculture, climate-informed reforestation, targeted land conservation.
Warmer winters increase the abundance and distribution of insect pests, while stressors like growing season drought can increase plant susceptibility to pests and disease.	Climate-adaptive silviculture, climate-informed reforestation, **removal and replacement of affected trees,** and use of chemical, mechanical or biological control methods.
Reduced frozen ground and changing precipitation patterns make forest management operations more difficult.	Changing management timing, equipment, and processes to adjust to new conditions.
Increasing water temperatures lead to increased stratification, loss of nutrients, deoxygenation, **increased bacteria**, shoreline erosion, and loss of habitat for key species. These water quality issues create **lost water-based recreation opportunities.**	Shoreline restoration, **wetland restoration, water treatment,** habitat conservation.
Increasing heavy rain events increase erosion, sediment deposition, and the runoff of nutrients and pollutants into waterways. These water quality issues also result in decreased demand for water-based recreation opportunities, increased water treatment costs, and degraded ecosystem quality.	Avoided wetland conversion, **wetland restoration,** watershed restoration, use of riparian and shoreline buffers, enhancing water infiltration/permeable surfaces.
Increased temperatures and longer periods of drought change the hydrology of wetlands and peatlands, decreasing ecosystem services like flood regulation and carbon storage. Warmer, drier conditions can also increase water demand and deplete water resources.	Avoided peatland and wetland conversion, peatland and **wetland restoration,** groundwater protection.
Reduced precipitation falling as snow, thereby **reducing winter outdoor recreation opportunities,** including alpine skiing, downhill skiing, and snowmobiling.	Increased snowmaking costs and retrofitting outdoor areas to accommodate shifting recreation demand patterns.
Reduced freshwater fishing opportunities, related to decreases in suitable habitat for native species as well as changes in ambient temperatures and precipitation patterns.	**Increased brook trout stocking costs.**
Overall increases in ambient temperatures and changes in rainfall patterns will result in an **increase in warmer weather recreation opportunities,** including hiking, hunting, boating, biking, and running.	Retrofit outdoor facilities to accommodate shifting recreation demand patterns.

The objective of this study is to quantify monetized costs of inaction and adaptation costs, which can be particularly difficult in the context of ecosystems. Valuation in dollar terms is necessarily tied back to the benefits humans derive from ecosystems, which is not the only way to think about the inherent value of the natural environment. When considering the costs of inaction, impacts to ecosystems are commonly monetized using an ecosystem services valuation approach. The National Ecosystem Services Partnership defines ecosystem services as "the benefits that flow from nature to people, for example, nature's contributions to the production of food and timber; life-support processes, such as water purification and coastal protection; and life-fulfilling benefits, such as places to recreate or to be inspired by nature's diversity."[148] Following this approach, this analysis values the climate impacts to ecosystems through changes to a select set of monetized services that flow from affected ecosystems, including recreation opportunity, carbon storage, and timber industry impacts.

Resource-dependent industries are large contributors to the Minnesota economy. Outdoor recreation is a major economic driver in Minnesota, contributing $13.5 billion to the state's GDP, $23.5 billion in economic output, and supporting nearly 100,000 jobs annually.[149] As climate change alters temperature and precipitation patterns, the conditions for safe and enjoyable recreation opportunities on land and water shift, directly impacting how and when people engage in outdoor activities. These shifts affect both the value Minnesotans derive from outdoor recreation as well as the broader economic activity tied to their spending. The forest products industry supports a similar portion of the state's economy, contributing $10.5 billion to the state's GDP, $18 billion in economic outcome, and supporting over 75,000 jobs annually.[150] Climate change affects this industry through shifting species mixes, increased forest stressors and disturbance, and challenges to harvests during wet periods.[151]

This chapter is organized into two sections defined by ecosystem type: terrestrial and aquatic, with wetlands and peatlands discussed qualitatively in the "aquatic" section.

[148] https://nespguidebook.com/
[149] Minnesota Outdoor Recreation Participation Partnership. (2025). "Minnesota's Untamed Dividend: Outdoor Recreation Fueling Our Economy."
[150] MNDNR. (2020). Forest Products Industries' Economic Contributions: Minnesota. Public Sector Consultants. https://files.dnr.state.mn.us/forestry/um/mn-forest-products-industry-report.pdf
[151] Toot, R., Handler, S., Shannon, P. D., Amman, A., Blinn, C., Butler-Leopold, P., ... & Janowiak, M. K. (2025). Climate change considerations for forest operations in northern forests. Gen. Tech. Rep. NRS-223. Madison, WI: US Department of Agriculture, Forest Service, Northern Research Station. 39 p., 223, 1-39.

The complexities of valuing ecosystems

This study is unable to comprehensively quantify the costs of inaction in all categories; however, the omissions are likely the greatest in the ecosystems category. Climate trends affect different species, resources, and habitats in nuanced ways that are difficult to measure comprehensively within the scope of this study. Even with an understanding of the physical impacts of climate change, valuation remains a challenge. Climate change threatens Indigenous lifeways in ways that cannot be adequately captured in dollar terms. The cultural, spiritual, religious, or other experiential role of ecosystems to all Minnesotans is not fully quantified in this study.

The following resources offer more information on the ways climate change is projected to impact the natural environment in Minnesota:

- MCAP's overview of climate change impacts in Minnesota
- Fifth National Climate Assessment – Midwest Chapter
- Tribal Climate Adaptation Menu
- 1854 Treaty Authority
- MCAP's Regional Climate Summaries

The remainder of this chapter includes two main sections, addressing the two main categories of ecosystems with quantified adaptation costs: **Terrestrial Ecosystems** and **Aquatic Ecosystems.** Within each of these two main sections, there are subsections for **Costs of inaction, Costs of adaptation,** and **Limitations and uncertainties.** Both cost subsections provide a high-level methodology description, detailed results, and further interpretation of the findings, including how costs are distributed across the state and which costs are not quantified in this study. Step-by-step detail on methods and specific citations to data sources, models, and peer-reviewed studies that provide a basis for estimating costs can be found in Appendix B.

8.1. Terrestrial Ecosystems

8.1.1. Costs of inaction

Climate change affects the way that people interact with land-based ecosystems in many ways, layered on top of past and current management practices, market conditions, and mixed land ownership. Increasing temperatures, changing precipitation patterns, and climate-driven disturbances such as wildfire and severe storms will affect the composition, abundance, distribution, and productivity of forests.[152] Shifting conditions also affect the composition of grassland communities, which are simultaneously facing pressure from non-climate stressors such as land use change.[153] Climate change also creates conditions for the accelerated spread of invasive species that threaten Minnesota ecosystems, including the mountain pine beetle and emerald ash borer. Changing climate conditions affect wildlife populations in the state and may be beneficial to some while causing stress for others. For

[152] Handler, S., Duveneck, M. J., Iverson, L., Peters, E., Scheller, R. M., Wythers, K. R., ... & Ziel, R. (2014). Minnesota forest ecosystem vulnerability assessment and synthesis: A report from the Northwoods Climate Change Response Framework project. Gen. Tech. Rep. NRS-133. Newtown Square, PA; US Department of Agriculture, Forest Service, Northern Research Station. 228 p., 133, 1-228. https://doi.org/10.2737/NRS-GTR-133

[153] Wilson, A.B., J.M. Baker, E.A. Ainsworth, J. Andresen, J.A. Austin, J.S. Dukes, E. Gibbons, B.O. Hoppe, O.E. LeDee, J. Noel, H.A. Roop, S.A. Smith, D.P. Todey, R. Wolf, and J.D. Wood. (2023). Ch. 24. Midwest. In: Fifth National Climate Assessment. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://toolkit.climate.gov/sites/default/files/2025-07/NCA5_Ch24_Midwest.pdf

example, warming temperatures may benefit white-tailed deer, but negatively affect the culturally important moose, which also faces increased disease spread from white-tailed deer.[154]

Minnesota's nearly 18 million acres of forestland provide significant economic benefits and are culturally important.[155] The changing conditions in forests affect revenue in the timber production sector, recreation opportunities in forests (hiking, hunting, wildlife viewing), the carbon sequestration potential of forestland, and other values people derive from healthy forests. Table 8-2 presents two quantified costs of inaction specific to **forests,** which rely upon Baker et al.'s (2023)[156] model of forest productivity under future climates. The Baker et al. study in turn relies on detailed forest species growth response to environmental factors data developed for USFS's Forest Inventory and Analysis program, combined with projections of future climatic change.[157] A negative carbon flux represents a net increase in forest carbon sequestration (a benefit of climate change), while a positive value represents a net decrease in sequestration (damage of climate change). Carbon sequestration is projected to increase in the Mid-Century under all but the Very High emissions scenario, owing to temperature increases and precipitation changes that benefit forest species for this time period – but in later years higher evapotranspiration and decreased soil moisture inhibit forest growth, leading to a decline in carbon sequestration relative to the baseline. These patterns of forest carbon sequestration are consistent with those found in Minnesota's Climate Action Framework. Carbon sequestration is valued using the Social Cost of Carbon used by MNDOT.[158] Baker et al.'s model of the timber market simulates prices, production, management, and consumption. Negative producer surplus values in the table below represent a net gain for timber producers in Minnesota, consistent with the increase in growth for key timber species in some emissions scenarios, but assume that industry and markets respond to changes in species distribution and location to take advantage of higher valued timber species abundance.[159] This portion of the analysis does not consider stands lost to invasive species, wildfire, or other hazards linked with changing climate.

Beyond forests, changing temperature and precipitation patterns alter the way people engage in other terrestrial outdoor recreation. For instance, a decrease in precipitation falling as snow reduces opportunities for **snow sports,** including alpine skiing, cross-country skiing, and snowmobiling, and abundant evidence projects a decline in winter-related recreation and tourism in Minnesota throughout the century.[160] Historically, downhill skiing has been a major contributor to regional economies in

[154] Weiskopf, S. R., Ledee, O. E., & Thompson, L. M. (2019). Climate change effects on deer and moose in the Midwest. The Journal of Wildlife Management, 83(4), 769-781.
[155] Minnesota Department of Natural Resources. "Forests" Available at" https://www.dnr.state.mn.us/faq/mnfacts/forests.html
[156] Baker, J. S., Van Houtven, G., Phelan, J., Latta, G., Clark, C. M., Austin, K. G., ... & Martinich, J. (2023). Projecting US forest management, market, and carbon sequestration responses to a high-impact climate scenario. Forest policy and economics, 147, 102898.
[157] Specifically, Baker et al. rely on a time series of the FIA Nationwide Forest Inventory data. The study has a national scope but the results for Minnesota, reflecting Minnesota's FIA plots, are used here. See https://research.fs.usda.gov/programs/fia for more details on the FIA data.
[158] MNDOT. (2025). Recommended Standard Values for Use in Cost-Effectiveness & Benefit-Cost Analysis in SFY 2025. Minnesota Department of Transportation, Office of Transportation System Management, 2024, https://www.dot.state.mn.us/planning/program/appendix_a.html.
[159] The Baker et al. model also assumes no changes in imports and export, which may be highly variable under different market and political futures.
[160] Chin, N., Byun, K., Hamlet, A. F., & Cherkauer, K. A. (2018). Assessing potential winter weather response to climate change and implications for tourism in the US Great Lakes and Midwest. Journal of Hydrology: Regional Studies, 19, 42-56. https://doi.org/10.1016/j.ejrh.2018.06.005

Minnesota, providing $118 million annually in economic activity and nearly 5,000 jobs.[161] On the other hand, warming temperatures – particularly in "shoulder season" months – create additional opportunities for traditional warm weather outdoor recreation, including biking, hunting, hiking, and running.

This analysis incorporates projections from Willwerth et al. (2023) on the lost value of snow sports trips to recreators based on the historical response of recreators to changes in temperature and precipitation.[162] By the end of the century, the model projects that Minnesotans will lose between 200,000 and 400,000 snow sport trips annually. Those lost trips are valued using willingness to pay, a measure of consumer surplus, resulting in projected annual social value loss on the order of tens of millions of dollars throughout the century. Beyond the direct loss to winter sport enthusiasts, reduced spending from those trips also impacts the snow sport industry and related businesses that depend on this revenue. Using a model from Wobus et al. (2017), this analysis projects lost ticket revenue from alpine skiing, cross-country skiing, and snowmobiling.[163] By the end of the century, the model projects that the number of trips across these activities decreases by 1.1 million for alpine skiing, 85,000 for cross-country skiing, and 79,000 for snowmobiling. Under the Very High emissions scenario, lost ticket revenue is projected to exceed $100 million annually.

Willwerth et al. also examines climate-related impacts on **other outdoor recreation** activities, including land-based pursuits such as biking, hunting, hiking, and running. The model projects an additional 4.8 million to 6.2 million trips by the end of the century depending on emissions scenario. As with snow sports, these trips are valued using willingness to pay per trip measures. The increased social value of these additional trips totals hundreds of millions of dollars annually. The spending associated with these trips will also generate increased economic activity throughout the state, although this study does not quantify those effects.

See Appendix B for more details on methodology and limitations.

Table 8-2. Quantified Costs of Inaction (Millions per Year): Terrestrial Ecosystems

Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). Costs are incremental to baseline and averaged across six climate models (range across climate models provided in parentheses). See Appendix B for more details on methodology and limitations.

		Carbon Sequest-ration Loss	Timber Producer Surplus	Other Recreation (bike, hunt, hike, run)	Snow Sport Activity*	Alpine Skiing	Cross-country Skiing	Snow-mobiling
		Social cost of change in carbon flux	Change in timber production surplus	Lost welfare per trip	Lost welfare per trip	Lost ticket revenues	Lost ticket revenues	Lost ticket revenues
Mid-Century (2040–2059)	Intermediate	-$140 (-$190 to -$120)	-$77 (-$79 to -$76)	-$150 (-$150 to -$140)	$11 ($10 to $11)	$30 ($28 to $31)	$0.3 ($0.3 to $0.3)	$0.1 ($0.1 to $0.1)
	High	-$100 (-$150 to -$62)	-$79 (-$80 to -$77)	-$150 (-$160 to -$150)	$11 ($11 to $12)	$32 ($30 to $34)	$0.4 ($0.3 to $0.4)	$0.1 ($0.1 to $0.2)

[161] Minnesota Ski Area Association, as cited in National Ski Areas Association (2023). "Climate Smart Snowmaking: Industry Study 2023." Available at: https://nsaa.org/webdocs/Sustainability/Snowmaking/ClimateSmartSnowmakingStudy_Report_2023.pdf

[162] Willwerth, J., Sheahan, M., Chan, N., Fant, C., Martinich, J., & Kolian, M. (2023). The Effects of Climate Change on Outdoor Recreation Participation in the United States: Projections for the Twenty-First Century. Weather, Climate, and Society, 15(3), 477-492.

[163] Wobus, C., Small, E. E., Hosterman, H., Mills, D., Stein, J., Rissing, M., ... & Martinich, J. (2017). Projected climate change impacts on skiing and snowmobiling: A case study of the United States. Global Environmental Change, 45, 1-14.

		Carbon Sequest-ration Loss	Timber Producer Surplus	Other Recreation (bike, hunt, hike, run)	Snow Sport Activity*	Alpine Skiing	Cross-country Skiing	Snow-mobiling
		Social cost of change in carbon flux	Change in timber production surplus	Lost welfare per trip	Lost welfare per trip	Lost ticket revenues	Lost ticket revenues	Lost ticket revenues
	Very High	$42 (-$29 to $150)	-$67 (-$75 to -$55)	-$170 (-$180 to -$160)	$13 ($12 to $15)	$42 ($37 to $49)	$0.5 ($0.4 to $0.6)	$0.2 ($0.2 to $0.3)
Late-Century (2060–2079)	Intermediate	$66 (-$40 to $190)	-$92 (-$110 to -$67)	-$170 (-$190 to -$160)	$14 ($12 to $15)	$43 ($35 to $53)	$0.5 ($0.4 to $0.7)	$0.2 ($0.2 to $0.3)
	High	$250 ($200 to $320)	-$49 (-$62 to -$32)	-$200 (-$200 to -$190)	$16 ($15 to $17)	$58 ($54 to $64)	$0.8 ($0.7 to $0.9)	$0.3 ($0.3 to $0.3)
	Very High	$520 ($420 to $590)	-$6 (-$19 to $5)	-$220 (-$220 to -$210)	$21 ($19 to $23)	$82 ($74 to $87)	$1.1 ($1.0 to $1.2)	$0.5 ($0.4 to $0.5)
End-of-Century (2080–2099)	Intermediate	$260 ($130 to $450)	-$58 (-$100 to -$3)	-$200 (-$220 to -$180)	$16 ($14 to $19)	$59 ($47 to $76)	$0.8 ($0.6 to $1.0)	$0.3 ($0.2 to $0.4)
	High	$600 ($490 to $710)	-$5 (-$18 to $13)	-$220 (-$220 to -$220)	$23 ($21 to $25)	$88 ($80 to $95)	$1.2 ($1.1 to $1.3)	$0.5 ($0.4 to $0.5)
	Very High	$940 ($770 to $1,200)	$130 ($32 to $270)	-$210 (-$220 to -$190)	$29 ($26 to $33)	$110 ($99 to $120)	$1.5 ($1.4 to $1.7)	$0.6 ($0.6 to $0.7)

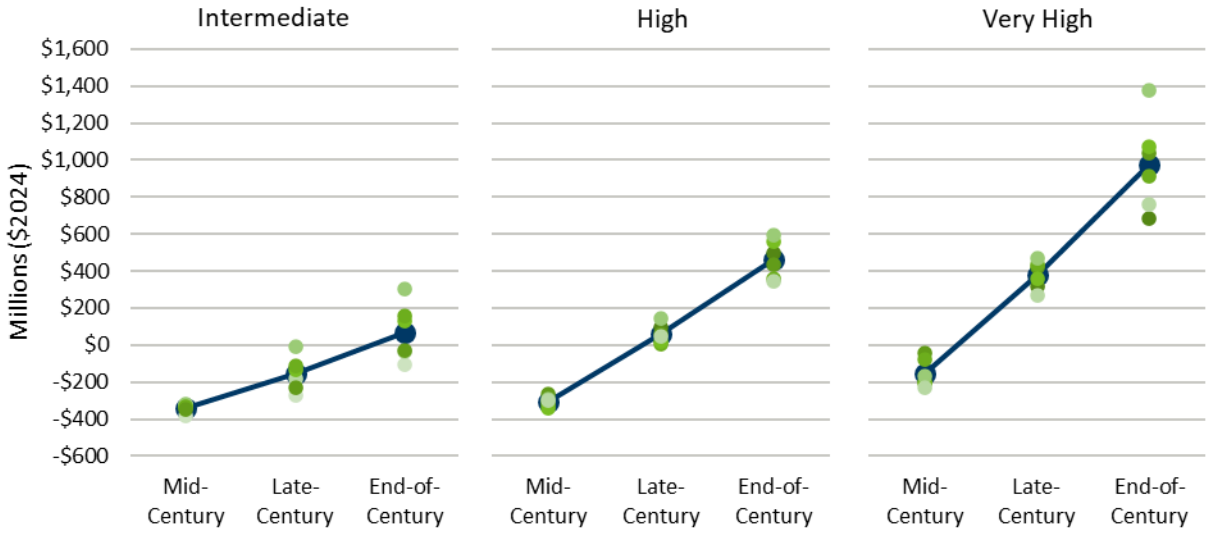
*Indicates a cost of inaction with multiple alternatives of measurement; this alternative is not included in the annual summary.

Other costs of inaction (not quantified):

- Other climate-driven disturbances
- Shifting of species composition
- Culturally important forest and wildlife species
- Damage from insect pests, pathogens, and invasive plants
- Impacts of potentially longer wet seasons on forest operations

Figure 8-1. Range of Quantified Annual Costs of Inaction: Terrestrial Ecosystems

Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (defined as Intermediate, High, and Very High; see Section 2.2 for more details). The solid lines with blue dots represent the average across six climate models per scenario, and the green dots without lines show the results for each of the six models. Note that lost opportunities for snow sports activities are excluded to avoid potential duplication with the lost revenue estimates for winter recreation activities (alpine and cross-country skiing, snowmobiling).



Who bears the costs of inaction?

Healthy ecosystems provide benefits to the people who live and work in those environments and to populations without direct proximity through the ecosystems services they provide. The same is true for the distribution of costs of inaction. The costs of inaction associated with timber production (which are primarily projected as benefits) will be enjoyed by timber harvesters, mostly concentrated in the northeastern part of the state. The carbon storage impacts are an example of the widely distributed reach of forests' ecosystem services. Changes in carbon storage affect global temperatures, which then impact people worldwide (though carbon flux in Minnesota forests is a very small portion of global carbon emissions). Other, non-quantified costs of inaction (e.g., the ecosystem service disruptions from increasing disturbance and pest stressors) will similarly affect a wide range of the population who benefit from the services healthy ecosystems provide. The changes in land-based recreation activities result in costs and benefits to recreators themselves. Additionally, changes in spending patterns associated with changes in recreation opportunities impact regional economies and the local businesses that depend on the revenue.

What other costs of inaction are not quantified in this study?

The quantified costs of inaction represent a small portion of the total potential impact of climate change on Minnesota's terrestrial ecosystems. Other important costs of inaction include:

- Losses to forests associated with wildfire, pest, windstorm, and other climate-driven disturbances. Disturbances are a part of healthy forest ecosystem dynamics and can contribute to forest heterogeneity and diversity across the landscape, but disturbance patterns have changed in many forest ecosystems in recent years, with climate being a prominent driver of this disturbance change through direct and indirect mechanisms.[164] Studies show that more

[164] Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., ... & Reyer, C. P. (2017). Forest disturbances under climate change. Nature climate change, 7(6), 395-402. https://doi.org/10.1038/nclimate3303

frequent disturbances are now shaping Minnesota's forests, where intervals between disturbances in forests have been decreasing.[165] These patterns are likely to continue with further climate change. Although the costs of inaction are not quantified, adaptation costs associated with select pest disturbances are addressed later in this section.

- Impacts (positive and negative) of shifting species composition, beyond surplus to timber producers. Climate change will make parts of Minnesota less suitable for some tree species and more suitable for others. For example, shorter periods of extreme cold will allow more southern tree species to overwinter and outcompete slower-growing species, especially in Northern Minnesota. An increase in drought may favor more drought-tolerant species across the state. Southern boreal forest species like paper birch, black spruce, quaking aspen, and balsam fir are projected to decrease, while fast-growing maples and drought-resistant oaks will continue to become more common across northern Minnesota.[166,167]
- Impacts (positive and negative) of shifting species composition to other land-based ecosystems such as grasslands.
- Losses and loss of access to culturally important forest and wildlife species, such as paper birch, ash, and moose.
- Impacts to forest management operations, including timber harvesting. These activities are affected by climate changes such as increases in extreme precipitation events and fewer days with frozen ground, which can limit operations and increase the costs of actively managing forests for a variety of ecological or commercial purposes.

8.1.2. Costs of adaptation

Selecting appropriate adaptation actions for terrestrial ecosystems depends on landscape- and site-level management goals, site conditions, and other factors. The quantified adaptation costs in Table 8-3 represent one possible response to pest and pathogen disturbances (Oak Wilt, Mountain Pine Beetle, and Emerald Ash Borer) to forests, in which **infected trees are removed and replaced.** Natural Resources Canada provides projections of the spatial extent at risk for each pest under two future emissions scenarios.[168] For each of the pests analyzed, the quantified figures represent the cost to remove and replace infected trees in the incremental risk areas (above the baseline extent) in MNDNR-maintained forests that are primarily classified by the relevant vulnerable tree species.[169] Potentially treated areas are limited to forestland within a quarter-mile of roads to reflect where treatment is most feasible and likely to occur.

[165] Wilson, D. C., Morin, R. S., Frelich, L. E., & Ek, A. R. (2019). Monitoring disturbance intervals in forests: a case study of increasing forest disturbance in Minnesota. Annals of Forest Science, 76(3), 78. https://doi.org/10.1007/s13595-019-0858-3
[166] UMN Climate Adaptation Partnership. Resilience in Natural Ecosystems. https://climate.umn.edu/resilience-natural-ecosystems
[167] Handler, S., K. Marcinkowski, M. Janowiak, and C. Swanston. (2017_. Climate change field guide for northern Minnesota forests: Site-level considerations and adaptation. USDA Northern Forests Climate Hub Technical Report #2. University of Minnesota College of Food, Agricultural, and Natural Resource Sciences, St. Paul, MN. 88p. Available at https://www.forestadaptation.org/MN_field_guide
[168] NRCan. (2020). Forest Insect and Disease Risk Maps. https://cfs.cloud.nrcan.gc.ca/bmfid/bmfid.php?lang=e
[169] Costing assumes 57 percent of the incremental area at risk is treated, based on Haight, Robert G., et al. "Assessing the cost of an invasive forest pathogen: a case study with oak wilt." *Environmental Management* 47.3 (2011): 506-517.

Table 8-3. Quantified Adaptation Costs (Millions per Year): Terrestrial Ecosystems

Annual costs (in millions, 2024$) for two time periods and two emissions scenarios (Section 2.2.2 for more details). Costs are incremental to baseline and averaged across six climate models. See Appendix B for more details on methodology and limitations.

		Removing Oak Wilt Infested Trees	Removing Mountain Pine Beetle Infested Trees	Removing and Replacing Affected Ash Trees (EAB)
		Cost to remove infected trees	Cost to remove infected trees	Removing and replacing affected ash trees (EAB)
Mid-Century (2040–2059)	Intermediate	$0.9	$0	$200
	Very High	$1.2	$0	$220
End-of-Century (2080–2099)	Intermediate	$0.7	$0	$28
	Very High	$1.5	$0.4	$24

Note: Results for this analysis are only available for Mid- and End-of-Century and for the climate model average for the Intermediate and Very High emissions scenarios.

Other adaptation costs (not quantified):

- Climate-informed reforestation or reseeding in areas of disturbance
- Targeted land conservation resulting in protection of key ecosystem services
- Climate-adaptive silviculture
- Investment into winter activities and snowmaking

What residual risks remain after adaptation?

There is limited evidence of the effectiveness of the quantified treatments on ecosystem health. Additionally, the quantified adaptation actions in this study only cover a portion of the forests in the state. There are other silvicultural actions that may be more effective and practical at a broader forest scale that are not quantified by this study.

What other effects result from adaptation?

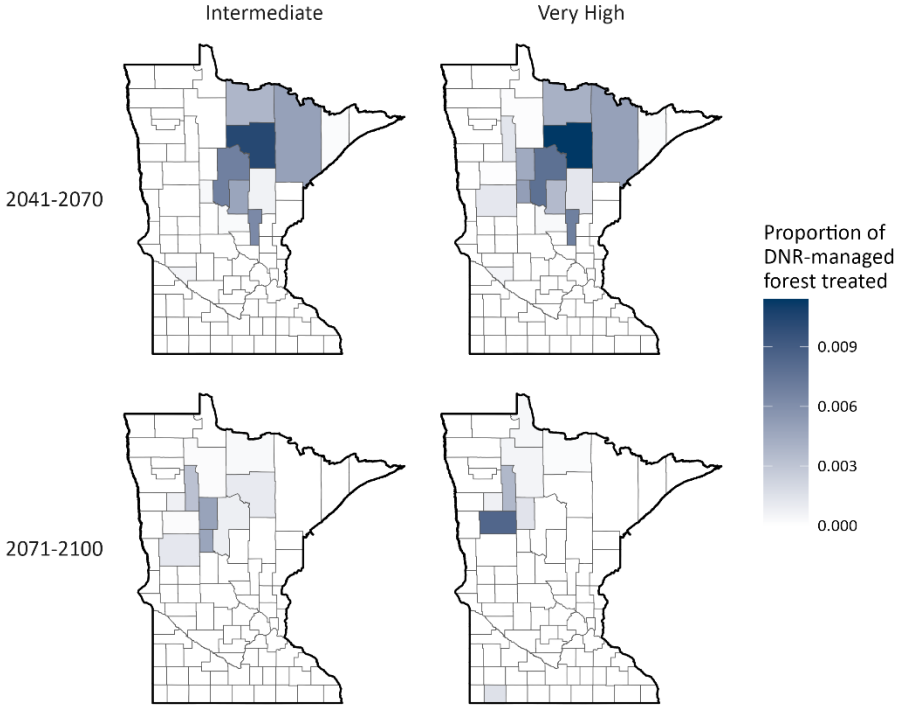
Investments in ecosystem adaptation can have vast co-benefits that are not always easy to represent in monetary terms. Ecosystem degradation increases risks to human populations, and maintaining healthy and functioning ecosystems can help reduce climate impacts in other sectors. For example, forests can improve water infiltration and reduce flooding and erosion from extreme rainfall. Ecosystem disturbance can release greenhouse gases into the atmosphere, and the loss of carbon sequestration and storage capacity from ecosystem disturbance and degradation represents a significant cost.

Who pays the adaptation costs?

The quantified adaptation costs presented in this study are limited to MNDNR-maintained forestlands, and therefore the costs would most likely be borne by MNDNR. Other landowners will face similar risks and may choose to take similar actions.

Figure 8-2. Distribution of Land Identified for Forest Invasives Treatment

Proportion of DNR-managed land identified for treatment by county for two time periods (defined by the NCAR dataset[170]) and two emissions scenarios (see Section 2.2.2 for more details).



What are the other costs of adaptation not quantified in this study?

As mentioned at the beginning of this chapter, the appropriate adaptation actions to protect ecosystems from the acute stresses of climate change (e.g., wildfires, droughts) and prepare for marginal shifts in habitat suitability will vary widely depending on the management objectives of the specific site.

- Planting or reseeding trees in impacted areas using climate-adapted species. This is not an appropriate practice for every disturbed acre, as many forests will naturally regenerate without intervention following a disturbance. However, climate changes may lead to regeneration failures that result in conversion to other ecosystem types, regeneration that is hampered by deer browse or invasive species, or regeneration of species that are less valuable for meeting goals for that landscape (e.g., timber or wildlife habitat goals). In addition, species that naturally regenerate may or may not be well-suited for future climate conditions. Options to help forests regrow to be more climate-adapted could include planting species that are expected to do well under future climates and planting trees from seed stock that aligns with expected climate conditions at the site.[171]
- Land conservation in support of ecosystem services. In response to climate stressors and disturbances, strategic land conservation can support ecosystem values that are at risk. For example, as habitat ranges shift, protecting large, connected areas of natural space can support ecosystem transitions. Healthy forests and grasslands can be maintained to help filter water and

[170] NRCan. (2020). Forest Insect and Disease Risk Maps. https://cfs.cloud.nrcan.gc.ca/bmfid/bmfid.php?lang=e

[171] Swanston, C. W., Janowiak, M. K., Brandt, L. A., Butler, P. R., Handler, S. D., Shannon, P. D., ... & Pierre, M. S. (2016). Forest adaptation resources: Climate change tools and approaches for land managers. Gen. Tech. Rep. NRS-GTR-87-2. Newtown Square, PA: US Department of Agriculture, Forest Service, Northern Research Station. 161 p. http://dx. doi. org/10.2737/NRS-GTR-87-2., 87, 1-161.

provide seed sources in key locations. Avoiding forest conversion and protecting carbon rich areas like peatlands can help promote carbon storage.

- Climate-adaptive silviculture. Specific practices will vary depending on the site, management goals, and forest type, but could include actions like managing for diverse species and stand ages, prescribed burning, thinning, and planting climate-adapted species. If planned in a climate-informed way, these actions can help forests be more adapted to future conditions and help continue to support the timber industry.
- Investments to support areas currently dependent on winter sport economies. To mitigate reduced winter outdoor recreation opportunities and revenue losses, the downhill skiing industry is investing heavily in snowmaking and infrastructure upgrades. A National Ski Areas Association report documents the steady increase in power and fuel expenses among Midwest ski areas between 2010/11 and 2020/21 driven by snowmaking needs.[172] Land managers and recreation-based businesses will also likely incur costs to retrofit outdoor areas to accommodate shifting recreation demand patterns. The Minnesota DNR already devotes resources to modernizing outdoor recreation experiences, which is expected to become more necessary throughout the century.[173]

Note that wildfire suppression costs near population centers are discussed in Section 7.2.

8.1.3. Limitations and uncertainties

The quantified adaptation costs presented in this study are illustrative of the magnitude of costs required, though they do not cover all potential reactive and proactive responses to climate change. As emphasized at the beginning of this chapter, there are significant limitations to the quantified costs related to ecosystem climate change impacts and adaptation actions. Key limitations to the analysis are described below; see Appendix B for a full discussion of limitations and uncertainties.

- The quantified costs of inaction only represent a portion of the full value of potential impacts to terrestrial ecosystems in the state.
- Estimates of species-specific timber growth in Baker et al. 2023 likely underestimate tree mortality associated with disturbance (e.g., pests and wildfire). Timber producer surplus results also treat imports and exports as fixed and exogenous – changes in trade policy could significantly impact these estimates.
- Increases in outdoor recreation do not account for the rise in other climate risks that may dampen increased demand due to temperature changes – for example, poor air quality from Canadian wildfires, extreme heat risks, and the threat of vector-borne disease.
- Removing and replacing trees infected by pests and pathogens is one of many potential adaptation actions. Further, this analysis only quantifies costs related to three pests/pathogens that are currently a concern in the state and only on accessible forestlands maintained by MNDNR. The actual scope of treatment could vary substantially.
- The quantified costs are focused on forests, prairies and other habitat types may also require more active management and intervention which are not quantified in this study.

[172] National Ski Areas Association. (2023). "Climate Smart Snowmaking: Industry Study 2023." Available at: https://nsaa.org/webdocs/Sustainability/Snowmaking/ClimateSmartSnowmakingStudy_Report_2023.pdf
[173] MNDNR. (2025). "Progress Report on Get Out MORE: Modern Outdoor Recreation Experiences." Available at: https://files.dnr.state.mn.us/aboutdnr/get-out-more/2025-get-out-more-progress-report.pdf

8.2. Aquatic Ecosystems

8.2.1. Costs of inaction

Rising temperatures and increasingly variable precipitation patterns affect the availability and quality of water resources and aquatic ecosystems. These same climate hazards increase the risk of harmful algal blooms, which threaten human health and local economies by reducing water accessibility for recreation and drinking. Warmer air temperatures also lead to warmer water temperatures, creating less suitable conditions for recreationally valuable fish species, which could decrease demand for freshwater fishing.[174] Peatlands, which provide important carbon storage benefits, are threatened by the potential for extended drought conditions.[175] Climate change is also reducing lake ice coverage, which threatens culturally important winter festivals, ice fishing, and ice skating opportunities.[176] Conversely, warmer temperatures also increase demand for warm-weather water-based recreation activities like boating and swimming.

The costs of inaction presented in Table 8-4 reflect modeled damages associated with decreased water quality and increased occurrence of harmful algal blooms, both primarily driven by increased lake surface temperatures,[177] as well as changes in water-based recreation driven by average daily temperatures.

- The lost welfare value (including the value of lost recreational opportunity) due to **water quality changes** is based on an analysis by Fant et al. (2017)[178] that measures the lost welfare (willingness to pay) associated with changes in water quality, measured by a Climate-oriented Water Quality Index, a metric that combines multiple pollutant and water quality measures focusing on nutrients, dissolved oxygen, and water temperature for all waterbodies. Recreation value losses increase over time and under higher emissions scenarios.
- Lost revenues associated with closures during **harmful algal blooms** are calculated by first using projected lake surface temperatures from Clark et al. (in review)[179] and a cyanobacteria concentration model from Chapra et al. (2017)[180] to model the number of days lakes in Minnesota would need to close due to dangerous bacteria levels. Closures are converted to lost revenues using information from the 2022 Minnesota State Park Visitor Study.[181] By the End-of-Century, harmful algal blooms are projected to result in an average of 42,000 to 56,000 fewer trips to lakes and reservoirs in Minnesota state parks annually.

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[174] Jones, R., Travers, C., Rodgers, C., Lazar, B., English, E., Lipton, J., ... & Martinich, J. (2013). Climate change impacts on freshwater recreational fishing in the United States. Mitigation and Adaptation Strategies for Global Change, 18(6), 731-758. https://doi.org/10.1007/s11027-012-9385-3

[175] Quan, Q., Zhou, J., Hanson, P. J., Ricciuto, D., Sebestyen, S. D., Weston, D. J., ... & Luo, Y. (2025). Drought-induced peatland carbon loss exacerbated by elevated CO2 and warming. *Science*, *390*(6771), 367-370. https://doi.org/10.1126/science.adv7104

[176] Filazzola, A., Imrit, M. A., Fleck, A., Woolway, R. I., & Sharma, S. (2024). Declining lake ice in response to climate change can impact spending for local communities. *PloS one*, *19*(7), e0299937. https://doi.org/10.1371/journal.pone.0299937

[177] The quantified impacts do not account for more extreme precipitation patterns which will likely increase siltation and runoff and further degrade water quality.

[178] Fant, C., Srinivasan, R., Boehlert, B., Rennels, L., Chapra, S. C., Strzepek, K. M., ... & Martinich, J. (2017). Climate change impacts on US water quality using two models: HAWQS and US basins. *Water*, *9*(2), 118.

[179] Clark, S., Liess, S., Roop, H., Projected Effects of Climate Change and Warming Lake Temperatures on Microsystis Blooms in Minnesota's Inland Lakes, In Review

[180] Chapra, S. C., Boehlert, B., Fant, C., Bierman Jr, V. J., Henderson, J., Mills, D., ... & Paerl, H. W. (2017). Climate change impacts on harmful algal blooms in US freshwaters: a screening-level assessment. Environmental Science & Technology, 51(16), 8933-8943.

[181] MNDNR. (2023). 2022 Minnesota State Park Visitor Study. Available: https://files.dnr.state.mn.us/aboutdnr/reports/parks/2022-state-parks-visitor-study.pdf

- Using modeling from Willwerth et al. (2023), Table 8-4 also includes the increased value of **water sports** trips. By the end of the century, estimate show between 3.0 million and 4.5 million additional water sports trips annually driven by the increase in warm weather days. When valued using willingness to pay, this creates additional value to recreators of over $100 million annually during the same time period. This same paper predicts changes in **recreational fishing** trips, showing a loss in over 100,000 trips annually across Minnesota by the end of the century.

These results highlight two conflicting effects of climate change on water-based recreation. With warmer weather and extended "summer" recreation seasons, demand for water sports is projected to increase, but the availability of safe locations may be constrained by harmful algal blooms and water quality issues. Additionally, increased outdoor recreation time may further expose populations to the health and wellbeing risks described in Chapter 5 (i.e., extreme heat, poor air quality, and vector-borne disease and illness).

See Appendix B for more details on methodology and limitations of each of these analyses.

Table 8-4. Quantified Costs of Inaction (Millions per Year): Aquatic Ecosystems

Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). Costs are incremental to baseline and averaged across six climate models (range across climate models provided in parentheses). See Appendix B for more details on methodology and limitations.

		Water Quality Changes	Harmful Algal Blooms	Water Sport Activity	Fishing Activity
		WTP to avoid water quality degradations	Lost revenue during waterbody closures	Lost welfare per trip	Lost welfare per trip
Mid-Century (2040–2059)	Intermediate	$41 ($39 to $43)	$2.4	-$76 (-$78 to -$71)	$2.6 ($2.5 to $2.7)
	High	$43 ($41 to $45)	-	-$79 (-$83 to -$75)	$2.7 ($2.7 to $2.8)
	Very High	$50 ($47 to $54)	$2.5	-$92 (-$100 to -$86)	$3.2 ($3.0 to $3.6)
Late-Century (2060–2079)	Intermediate	$51 ($46 to $57)	$2.6	-$94 (-$110 to -$84)	$3.2 ($2.8 to $3.7)
	High	$59 ($57 to $62)	-	-$110 (-$120 to -$110)	$4.1 ($3.8 to $4.6)
	Very High	$70 ($66 to $74)	$2.9	-$140 (-$140 to -$130)	$6.5 ($5.6 to $7.3)
End-of-Century (2080–2099)	Intermediate	$59 ($54 to $67)	$2.8	-$110 (-$130 to -$99)	$4.2 ($3.5 to $5.6)
	High	$74 ($69 to $79)	-	-$140 (-$150 to -$130)	$7.4 ($6.3 to $8.6)
	Very High	$90 ($81 to $100)	$3.8	-$170 (-$180 to -$160)	$11 ($9.2 to $12)

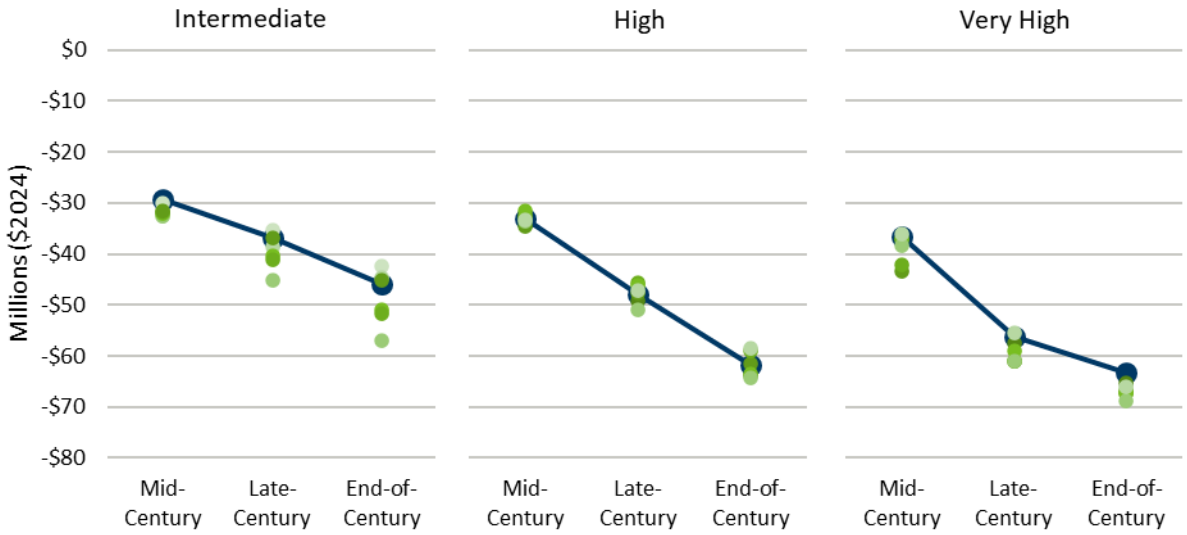
Note: Harmful algal bloom results not available for High emissions scenario. Also note that results without a range only have results available for the average outcome across climate models.

Other costs of inaction (not quantified):

- Monitoring and treatment of public waterways
- Ice cover on lakes
- Insufficient water availability during droughts
- Stressors on native aquatic species
- Wetland and peatland health

Figure 8-3. Range of Quantified Annual Costs of Inaction: Aquatic Ecosystems

Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (defined as Intermediate, High, and Very High; see Section 2.2 for more details). The solid lines with blue dots represent the average across six climate models per scenario, and the green dots without lines show the results for each of the six models.. Note that harmful algal blooms only have results for an average GCM, so they are not included in this figure.



Who bears the costs of inaction?

Healthy aquatic ecosystems provide benefits to the people who live and work in those environments and to populations without direct proximity through the ecosystem services they provide. The same is true for the distribution of costs of inaction. Minnesota, the "Land of 10,000 Lakes," has a wealth of freshwater resources that provide cultural value – degradation of these resources would be felt across the state. The quantified costs of adaptation, which in some cases may be benefits, are experienced by recreators in Minnesota, which includes a wide swath of the population.

What other costs of inaction are not quantified in this study?

Other important costs of inaction related to aquatic ecosystems include:

- Increased monitoring and water treatment costs due to harmful algal blooms for public water suppliers drawing from surface water supplies. Depending on the concentration of cyanobacteria, there are a number of treatment options available to reduce risks, but this requires increased monitoring and potentially costly treatment methods.[182] Increased sedimentation and nutrient and pollutant runoff associated with extreme precipitation events may require other monitoring and treatment costs outside of those associated with algal blooms.
- The effects of fewer days of ice cover on lakes, including increased shoreline erosion and lower wild rice yields.[183] Minnesota lakes have lost an average of two days of ice cover per decade since 1949.[184] The density of wild rice, a culturally important resource for many Indigenous

[182] https://www.epa.gov/ground-water-and-drinking-water/managing-cyanotoxins-public-drinking-water-systems
[183] UMN Climate Adaptation Partnership. Resilience in Natural Ecosystems. https://climate.umn.edu/resilience-natural-ecosystems
[184] Walsh, J. R., Rounds, C. I., Vitense, K., Masui, H. K., Blumenfeld, K. A., Boulay, P. J., ... & Hansen, G. J. (2025). Variable phenology but consistent loss of ice cover on 1213 Minnesota lakes. Limnology and Oceanography Letters. https://aslopubs.onlinelibrary.wiley.com/doi/10.1002/lol2.70015

Peoples in Minnesota, is negatively affected by shorter lake-ice durations and other climate factors, a pattern already observed.[185]

- Impacts of drought, and increased water demand during warmer and drier conditions, on groundwater availability. Projections of future groundwater recharge and availability are highly uncertain. Projected increases in average precipitation (a positive for groundwater recharge) are balanced against increases in evapotranspiration (a negative for groundwater recharge). One Minnesota-specific study found that increases in evapotranspiration were larger than increases in precipitation in six out of 10 projections, with the multi-model average showing decreased groundwater recharge across the state by the middle of the 21st century.[186]
- Stresses on native aquatic species, including degraded water quality, warming water temperatures, and aquatic invasive species that are more tolerant to a wider range of climates.
- Impacts on wetland and peatland health. Increased temperatures and longer periods of drought change the hydrology of wetlands and peatlands, decreasing ecosystem services like flood regulation and carbon storage.[187]

8.2.2. Costs of adaptation

This study quantifies the costs of three potential adaptation actions to address the costs of inaction identified above.

- **Alum treatment** is one method of reducing phosphorus loads in surface waters, mitigating risks of harmful algal blooms and other water quality issues. This analysis first estimates the cost of alum treatment relative to lake surface area using project data from Minnesota's Clean Water and Legacy Amendment and Environment and Natural Resources Trust Fund Project Database[188] and then applies those costs to each waterbody experiencing one or more days of harmful algal bloom-related closures on average across each time period.
- **Wetland restoration** is a nature-based solution to reducing nutrient loadings in surface waterbodies as well as storing water and reducing flooding during extreme precipitation events. Similar to the process described above, this analysis relies on average wetland restoration costs per acre calculated from Minnesota's Clean Water and Legacy Amendment and Environment and Natural Resources Trust Fund Legacy Project Database. Acres of wetland restoration required are a function of the number of waterbodies projected to exceed EPA nitrate limits and the average effectiveness of wetlands in reducing pollutant loading from the MPCA's Watershed Pollutant Load Reduction Calculator.[189]
- As freshwater streams warm and increasingly fail to meet the habitat requirements necessary to sustain native brook trout, the state may expand existing **restocking efforts** to maintain fish availability for recreational use. This analysis relies on projections from McCreary et al. of the future share of Minnesota streams with habitat conditions suitable to sustain brook trout.[190] Using estimates of brook trout density per stream mile, the analysis calculates the reduction in

[185] Nyblade, M., Larkin, D. J., Vogt, D., Croll, R., Ng, G. H. C., Graveen, W. J., ... & Panek, B. M. (2025). Climate change contributes to the decline in off-reservation tribal harvest availability in the Great Lakes region. Communications Earth & Environment, 6(1), 288. https://doi.org/10.1038/s43247-025-02233-0

[186] Anurag, H., & Ng, G. H. C. (2022). Assessing future climate change impacts on groundwater recharge in Minnesota. Journal of Hydrology, 612, 128112. https://doi.org/10.1016/j.jhydrol.2022.128112

[187] Quan et al., "Drought-Induced Peatland Carbon Loss Exacerbated by Elevated CO2 and Warming."

[188] https://www.legacy.mn.gov/projects

[189] https://data.pca.state.mn.us/views/Watershedpollutantloadreductioncalculator/Calculator

[190] Davenport, M., Wilson, B., Nieber, J., Seekamp, E., Smith, J., … (2017). North Shore Community Climate Readiness: Understanding Visitor Behaviors and Responses to Climate Change Projections. NC State Extension Publications. https://content.ces.ncsu.edu/north-shore-community-climate-readiness.

available native brook trout over time and applies regionally specific restocking cost estimates from Southwick and Loftus (2017) to value the associated costs.[191]

Table 8-5. Quantified Adaptation Costs (Millions per Year): Aquatic Ecosystems

Annual costs (in millions, 2024$) for three time periods and three emissions scenarios (see Section 2.2.2 for more details). Costs are incremental to baseline and averaged across six climate models. See Appendix B for more details on methodology and limitations.

		Alum Treatment	Wetland Restoration	Restocking Brook Trout for Recreational Fishing
		Alum treatment costs	Wetland restoration costs	Cost to restock
Mid-Century (2040–2059)	Intermediate	$1.3	$4.6	$0.6
	High			$0.6
	Very High	$1.3	$4.6	$0.6
Late-Century (2060–2079)	Intermediate	$1.6	$4.6	$0.8
	High			$0.8
	Very High	$1.6	$4.7	$0.8
End-of-Century (2080–2099)	Intermediate	$1.6	$4.7	$0.9
	High			$0.9
	Very High	$2.1	$5.0	$0.9

Note: Results for the Alum Treatment and Wetland Restoration analyses are only available for the Intermediate and Very High emissions scenarios. All three analyses only produce results for the model average per scenario.

Other adaptation costs (not quantified):

- Invasive species management
- Upstream pollution control
- Targeted area conservation, resulting in protection of key ecosystem services
- Water recreation infrastructure
- Peatland restoration

What residual risks remain after adaptation?

The adaptation actions quantified above do not fully protect aquatic ecosystems from climate change. This analysis does not quantify residual risks in this category. However, wetlands have proven effective at filtering and reducing harmful nitrate and other pollutants from upstream agricultural and industrial sources, which mitigates some of the risks of warming waters.[192]

What other effects result from adaptation?

Healthy ecosystems provide wide-ranging resilience benefits. The adaptation actions described above, which improve ecosystem health and resilience, will also provide broader resilience benefits. For example, restored, healthy wetlands store water during wet periods and hold water on the landscape during dry periods, reducing flood damages and mitigating drought risks. Healthy wetlands and

[191] R I Southwick and A J Loftus, *Investigation and Monetary Values of Fish and Freshwater Mollusk Kills*, Special Publication 35 (American Fisheries Society, n.d.).

[192] Hansen, A. T., Dolph, C. L., Foufoula-Georgiou, E., & Finlay, J. C. (2018). Contribution of wetlands to nitrate removal at the watershed scale. *Nature Geoscience*, *11*(2), 127-132.

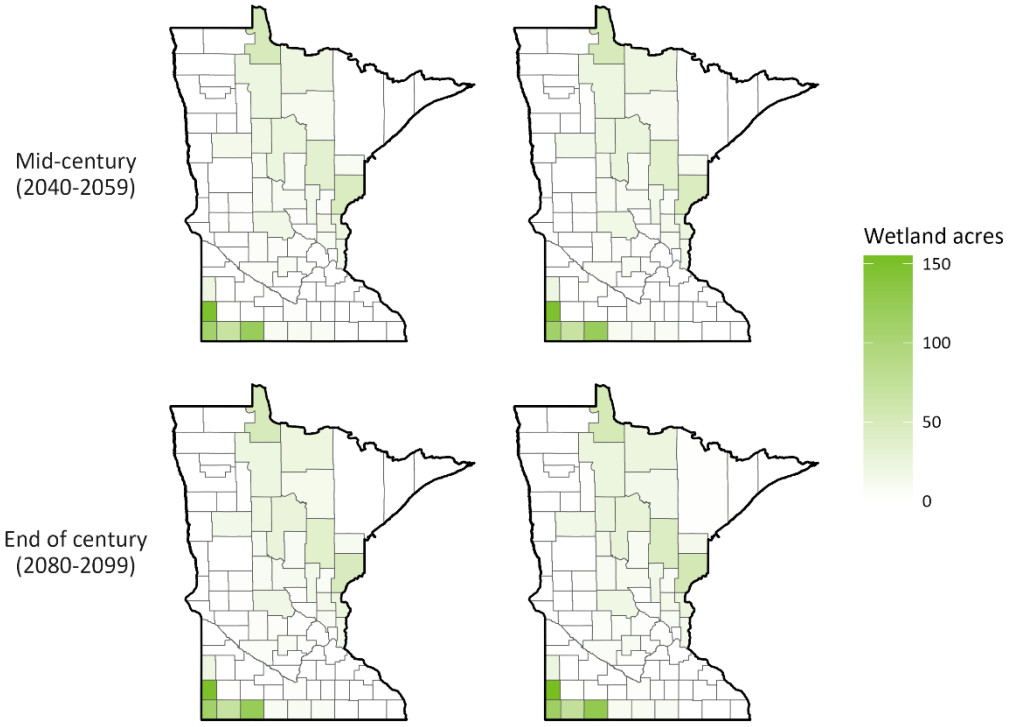
peatlands also provide carbon sequestration and storage capacity, which can help mitigate greenhouse gas emissions.

Who pays the adaptation costs?

Populations across the state value healthy aquatic resources. Support for projects such as those described above have received funding from sources like the Minnesota Clean Water and Legacy Amendment and the Environment and Natural Resources Trust Fund, which are funded from statewide sales taxes and lottery proceeds, respectively. The figure below highlights the distribution of modeled wetland restoration in response to climate-driven water quality degradation.

Figure 8-4. Distribution of Wetland Restoration Acres by County

Acres of wetlands required to remove nutrients from waterbodies to improve water quality by county for two time periods and two emissions scenarios (defined as Intermediate and Very High; see Section 2.2 for more details). Results not available from the underlying models for the High scenario.



What are the other costs of adaptation not quantified in this study?

The adaptation costs quantified in this study represent a subset of all potential actions to adapt aquatic resources to the impacts of climate change. Additional costs not quantified include:

- Aquatic invasive species management. Control of invasive species is often time- and resource-intensive and better minimized through targeted treatment that may use selective herbicides, mechanical control, or other integrated management strategies.[193]
- Other upstream pollution control measures to reduce nutrient loadings. This may include reducing source runoff from agricultural, urban, and industrial sectors upstream of the impacted waterbody to minimize harmful effects to the aquatic ecosystem or enhancing riparian and shoreline vegetated buffers.

[193] Welling, C. MnDNR. (2013). Guidance for selective treatment of invasive aquatic plants in Minnesota. https://files.dnr.state.mn.us/eco/invasives/guidance_trt_inv_aq_plants_apr_04.pdf

- Targeted conservation in support of ecosystem services. Examples of efforts include reducing habitat fragmentation to allow for species movement and increased diversity and to remove barriers to build larger habitat networks. Strategically protecting wetlands, peatlands, and areas of groundwater infiltration can help promote a variety of ecosystem services.
- Additional investments in water recreation infrastructure to support potentially higher demand, stream and river restoration through dam removals, enhanced access to recreation facilities, and modernizing infrastructure.
- Restoration of peatlands, including raising the water table, which slows erosion and revitalizes aquatic ecosystems with improved water quality.

8.2.3. Limitations and uncertainties

The quantified adaptation costs presented in this study are illustrative of the magnitude of costs required, though they do not cover all potential reactive and proactive responses to climate change. As emphasized at the beginning of this chapter, there are significant limitations to the quantified costs related to ecosystem climate change impacts and adaptation actions. Key limitations to the analysis are described below; see Appendix B for a full discussion of limitations and uncertainties.

- The water-based recreation benefits associated with extended summer recreation seasons do not account for other climate stressors that may limit people's demand for more outdoor recreation, such as air quality issues, vector-borne disease threats, and the water quality issues also described in this chapter. Additional investment in summer recreation infrastructure (e.g., boat ramps) may be necessary to support the increase in demand without causing overcrowding.
- The water quality impacts quantified do not account for the effects of increased sedimentation or erosion that may occur with increased extreme precipitation, or increased flows downstream from drainage improvements upstream.
- Application of alum treatment (to treat harmful algal blooms) and wetland restoration near waterbodies (to filter excess nutrients) are two possible treatment options for the water quality issues analyzed in this study. Effectiveness and feasibility of these treatments will vary by location.

9. The tradeoffs between investing in adaptation and incurring the adverse effects of climate impacts

This section of the study is focused on identifying methods for understanding and making decisions about climate adaptation action. The key decisions to be supported by data from this study may involve whether particular adaptation actions identified should be implemented, and when and where it would be most advantageous to undertake these actions. The information on the cost of adaptation in Minnesota presented in this study is useful as a key step in developing an adaptation roadmap at a sectoral or multi-sectoral scope. It may also be used as key information in prioritizing implementation of adaptation in response to the anticipated impacts of climate change.

Decision-making for adaptation that makes use of economic information (such as the adaptation cost information in this study) often involves clarifying the trade-offs between the financial and social costs to take action to reduce climate risks and the level of risk reduction achieved. In other words, it can be important to understand the risks of inaction, the costs of taking action (both financial and social in nature), the effectiveness of those actions in reducing risk, and the residual risk which remains after undertaking action. Throughout this chapter, however, it is important to remember that not all costs of inaction or costs of needed adaptation action can currently be quantified and/or monetized. This realization ought to affect the relative attractiveness of alternative methods of adaptation decision-making – fully quantitative methods are appropriate for decision-making in cases where one can say with some confidence that the most important costs and benefits of adapting have been captured (for example, the infrastructure sector), but methods that combine quantitative and qualitative information will be needed to support decision-making for sectors or settings where the costs and benefits are currently less well understood (such as the ecosystem cost category).

This study attempts to incorporate prior information that has been developed to characterize the need for and cost of adaptation actions. Research indicates, however, that information on the cost of adaptation in Minnesota has not been available previously to support multi-sectoral, state-wide decision-making for adaptation implementation. The 2017 Report of the Interagency Climate Adaptation Team did previously develop a list of six recommended action items for adaptation, based on structured stakeholder engagement activities conducted to support that effort, but information was not available at the time to develop a more comprehensive or prioritized approach to adaptation guidance.[194] This study, while not comprehensive in covering the costs of all possible or desirable adaptation measures, provides new economic information which might be used in an updated approach to adaptation decision-making and prioritization of adaptation investment within and across sectors.

9.1. The basics of the economics of adaptation

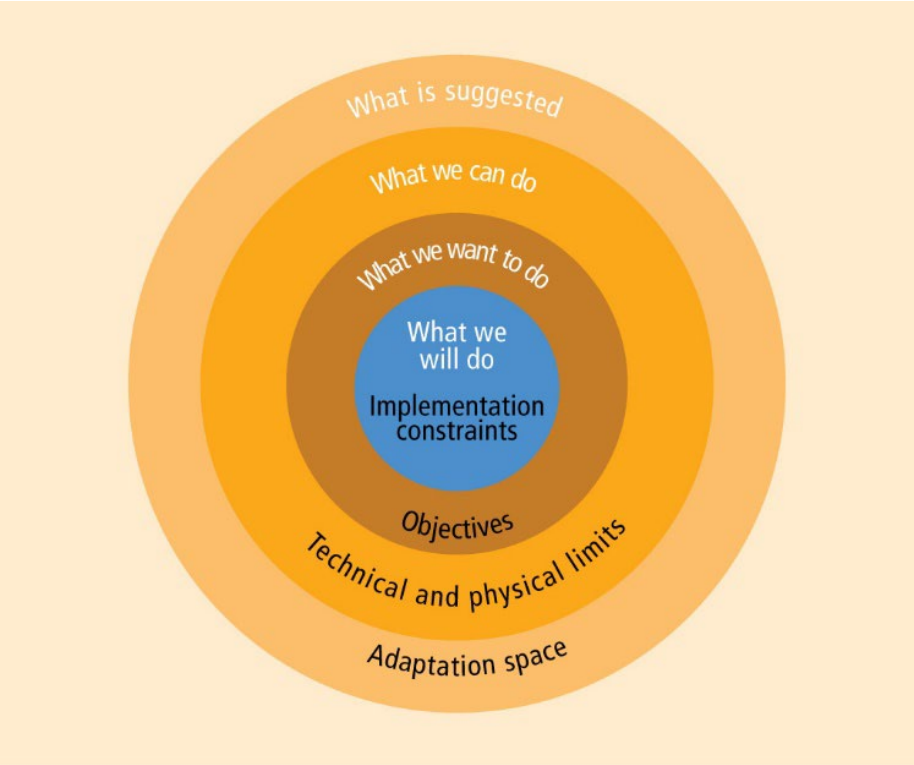
Existing research provides some useful insights about how adaptation can be implemented using economic information such as that provided in this study. For example, a chapter in the United Nations IPCC Fifth Assessment Report titled “Economics of Adaptation” provides useful examples and guidance. That chapter included a helpful graphic, reproduced as Figure 9-1 below. This figure illustrates a process of evaluating adaptation options that puts the role of economic analysis in a larger context. The largest

[194] ICAT.(2017). Adapting to Climate Change in Minnesota: 2017 Report of the Interagency Climate Adaptation Team. MPCA. Available at: https://www.pca.state.mn.us/sites/default/files/p-gen4-07c.pdf

circle in Figure 9-1 represents all the climate adaptation measures one could imagine. The nested circles show how this "adaptation space" is narrowed by various barriers to taking action.

The first barrier that limits the adaptation space is technical limits, such as engineering feasibility. It would not be practical or feasible, for example, to filter the full volume of contaminated water in a lake. The next barrier further limits the set of adaptation options because of consideration of limited resources or competing priorities – some options may be too expensive. For example, alum treatment for every lake in Minnesota to reduce harmful algal blooms could exceed budgets and/or not be cost-effective. Consideration of this type of economic resource barrier is the question this current study aims to inform, and for which the decision-making options laid out in this chapter will most often apply. The last set of barriers involves political or institutional constraints, including such things as permitting requirements – which some of the decision-making approaches described here may also be able to inform. For example, multi-metric climate adaptation prioritization effort could consider institutional or legal constraints that might hinder adaptation action. What remains in the adaptation space is the blue circle, the set of adaptation options that is chosen for implementation after considering all these constraints.[195]

Figure 9-1. The narrowing of adaptation options



Source: Chambwera et al. 2014, IPCC "Economics of Adaptation"

[195] For more technical readers, the Economics of Adaptation chapter develops this concept further and explains trade-offs between accepting the impacts or cost of climate change and the costs of adaptation – the result is that in some instances it is reasonable to accept some residual risk and acknowledge that the suite of available adaptation actions means fully adapting to all risks is not possible. See Figure 17-2 and accompanying text in Chambwera, M., G. Heal, C. Dubeux, S. Hallegatte, L. Leclerc, A. Markandya, B.A. McCarl, R. Mechler, and J.E. Neumann, 2014: Economics of adaptation. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 945-977.

In addition, implicit in most economic frameworks for adaptation decision-making is an economic efficiency criterion. In plain words, if the costs of adopting adaptation are larger than the economic impacts they are intended to counteract, Minnesotans may be less likely to support funding those costs of adapting. If adaptation costs more than the estimated economic harm of climate change, then the state and its residents might be better off using those resources in other ways. This is one reason why this study adds context to the estimates of adaptation cost by first quantifying the cost of inaction. An important caveat in this framework, however, is the understanding that being able to quantify all of the negative (and sometimes positive) costs of inaction is unlikely – a fact which is important to consider in adaptation decision-making and may impact the choice of frameworks reviewed below.

9.2. Data and tools to support adaptation decision-making

One promising development for adaptation decision-making has been the development and public availability of relevant decision support data and tools. The most widely disseminated category of data is local-scale, user-friendly climate projection data. Minnesota's Climate Mapping and Analysis Tool (MN CliMAT) is one of the best examples, and those data were used as key inputs to the work in this study. The University of Minnesota's Climate Adaptation Partnership team is also currently working on an extension of MN CliMAT that focuses on projections of the effect of changing climate on rainstorm intensity, duration, and frequency – a critical input to building resilience into infrastructure, development, agriculture, and natural system investments. The Climate Adaptation Partnership has also partnered with the Center for Sustainable Building Research (CSBR) and the Institute on the Environment to provide guidance on the use of these tools for modeling and project design, and to recommend to the Legislature a process for incorporating resilience and adaptation considerations into Minnesota's Sustainable Building Guidelines (known as the B3 Guidelines).[196]

Other states have developed similar climate tools, such as Analytics Engine from Cal-Adapt and the California Energy Commission, and the Resilient Massachusetts Action Team (RMAT) Climate Resilience Design Standards Tools. [197] The RMAT Climate Resilience Design Standards Tool, in particular, takes the decision-support framework one step beyond the provision of official state-curated climate data to provide additional project design support in the areas of:

1. Project-specific preliminary climate change hazard exposure and risk ranking;
2. Recommended climate resilience design standards for projects with physical assets; and
3. Guidance with best practices to support resilience project implementation.

The RMAT framework provides a flexible architecture to facilitate updating of new and improved climate science specific to Massachusetts, the addition or refinement of the characterization of the most relevant climate hazards, and ongoing stakeholder feedback. In addition, the related Guides for Equitable and Actionable Resilience system provides data and guidance to assess climate change impacts and incorporate community resilience concerns into projects funded by the State's Municipal Vulnerability Preparedness grants for compliance with the State's Environmental Justice statute.

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[196] Kutschke, L., Graves, R., Cipriano, P., Liess, S. Roop, H., Farris, A., Coffman, D. (2024). Resilience and Future Climate Data for Modeling and Design. Available at https://csbr.useast01.umbraco.io/publications/resilience-and-future-climate-data-for-modeling-and-design/; and Integrating Resilience into the B3 Guidelines, a report prepared for the Minnesota Legislature by The University of Minnesota Center for Sustainable Building Research, Minnesota Climate Adaptation Partnership, HGA Architects and Engineers, and Willdan. 2025. Available at: https://www.lrl.mn.gov/docs/2025/mandated/251458.pdf

[197] See Cal-Adapt's "Guidance on Using Climate Data in Decision-Making" available at: https://analytics.cal-adapt.org/guidance/using_in_decision_making/, and the RMAT website: https://resilient.mass.gov/rmat_home/designstandards/

These efforts and decision-making support tools acknowledge a simple but important fact: understanding how to use multi-dimensional climate science data to support adaptation decision-making is complex. Similar to the thinking behind the promulgation of building codes and minimum infrastructure design standards at the state level, these tools are designed to process complex climate risk assessments into digestible and readily actionable steps, with uniform applicability, to achieve a broader level of implementation of climate risk reduction projects. An important element is the aspect of explicit state support and acceptance of these tools. This is often achieved through extensive subject matter expert and stakeholder review, which provides a high level of confidence that resilience planning reflects well-established best practices and avoids risks of unintended consequences. The Massachusetts RMAT Climate Resilience Design Standards Tool is also the type of effort recommended in a recent report to the Minnesota Legislature by the University of Minnesota Institute on the Environment, CSBR, and MCAP – with the hope it could provide standardized resilience investment input for infrastructure, built environment, and natural systems sector projects.[198]

9.3. Three categories of decision-making frameworks

Following the U.S. Fourth National Climate Assessment, a group of researchers developed a framework for sustained climate assessment (Moss et al., 2019),[199] which outlines three broad categories of methods for appraising adaptation options:

1. ***Traditional benefit-cost analysis,*** which can include life-cycle analysis and optimization and cost-effectiveness analysis. The common thread in this type of analysis is to compare monetized costs with benefits as they accrue over time.
2. ***Multi-metric benefit and cost analysis,*** or multi-criteria analyses, which involves consideration of benefits and costs of adaptation using both monetary and non-monetary metrics. This class of analyses overcomes some shortcomings of traditional benefit-cost analysis and allows for consideration of factors such as non-quantified benefits and costs, equity, impacts on employment, financial market capacity, and/or risk aversion – not all of which can be expressed in dollar terms.
3. ***Robust decision-making,*** which aims to ensure that decisions provide good outcomes in many or all future "states of the world." A key advantage of this approach is that it considers the uncertainty in projecting future climate and economic growth over many decades. The technique can also be used to estimate the regrets of overinvesting (spending more than it turns out is necessary) or underinvesting (spending less than would be justified to address the risk) in adaptation.

Table 9-1 below provides a short summary of the key strengths, limitations, and typical applications of each of these three approaches. The remainder of this chapter provides additional information and examples of applications of each of the three methods.

[198] UMN Institute on the Environment, Center for Sustainable Building Research and Minnesota Climate Adaptation Partnership. (2025) Future Weather Trends + Infrastructure. A report prepared for the Minnesota Legislature. Available at: https://climate.umn.edu/reports-and-publications

[199] Moss, R.H., S. Avery, K. Baja, M. Burkett, A. M. Chischilly, J. Dell, P. A. Fleming, K. Geil, K. Jacobs, A. Jones, K. Knowlton, J. Koh, M. C. Lemos, J. Melillo, R. Pandya, T. C. Richmond, L. Scarlett, J. Snyder, M. Stults, A. Waple, J. Whitehead, D. Zarrilli, J. Fox, A. Ganguly, L. Joppa, S. Julius, P. Kirshen, R. Kreutter, A. McGovern, R. Meyer, J. Neumann, W. Solecki, J. Smith, P. Tissot, G. Yohe, and R. Zimmerman, (2019) Evaluating knowledge to support climate action: A framework for sustained assessment. Wea. Climate Soc., 11:465-487. https://doi.org/10.1175/WCAS-D-18-0134.1.

Table 9-1. Summary of strengths and limitations of three decision-making frameworks

Tool	Strengths	Limitations	Typical Applications
Benefit-Cost Analysis	• Well-established methods • Concept is intuitive - relatively easy to explain • Can estimate "rate of return" on investment if desired	• Requires all metrics to be monetized • Requires a method to standardize values over time	• Public infrastructure and private sector decisions • Cost-effectiveness variant in health sector
Multi-Metric Analyses	• Incorporates both monetary and non-monetary metrics	• Requires a rubric or formula for weighing multiple dimensions	• Multi-sectoral prioritization
Robust Decision-Making	• Rigorous method to incorporate uncertainty • Good examples for climate adaptation measures	• Data and analysis intensive • Can be difficult to explain • Requires user(s) to decide on a "decision rule"	• Large and long-lived (50-100 year) water resource investments

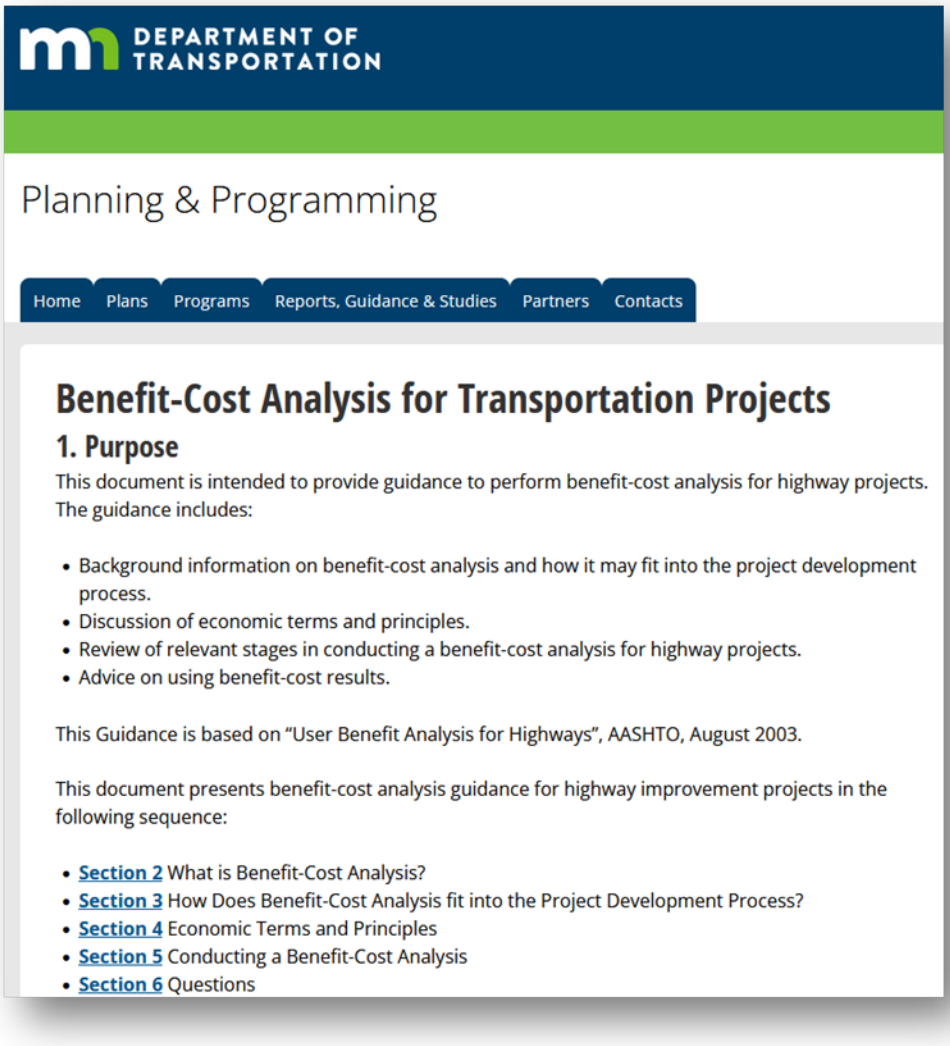
9.3.1. Benefit-cost analysis and variants

The first approach is traditional benefit-cost analysis, which is commonly applied in both the public and private sectors. In general, this approach compares dollar costs to implement adaptation with the projected benefits over time.

Benefit-cost analysis is a well-established method with some recent Minnesota government examples. MNDOT routinely conducts benefit-cost analyses for road safety, expansion, and other investments it considers. Figure 9-2 below is a screenshot from the MNDOT online benefit-cost analysis manual. A goal of this framework is to formally compare an annual program of costs, including the initial capital and yearly operating and maintenance costs, with the annual returns on investment – that is, the benefits. The benefits can include both the private revenue or government fiscal benefits – such as saving on road repairs in the future – and the social benefits that accrue to road users – such as saving time when roads are not disrupted by repair operations. The MNDOT manual also specifies a discount rate, which is used to standardize annual estimates of costs and benefits into a total cost and total benefit over time. The discount rate is used to perform a present value or lump-sum calculation. Finally, the MNDOT approach can consider greenhouse gas emissions implications for both costs and benefits, monetized using a social cost of carbon.[200]

[200] See here for a summary of the MNDOT-recommended discount rate, social cost of carbon, value of time for road users, and other parameters necessary for comprehensive benefit-cost analysis.

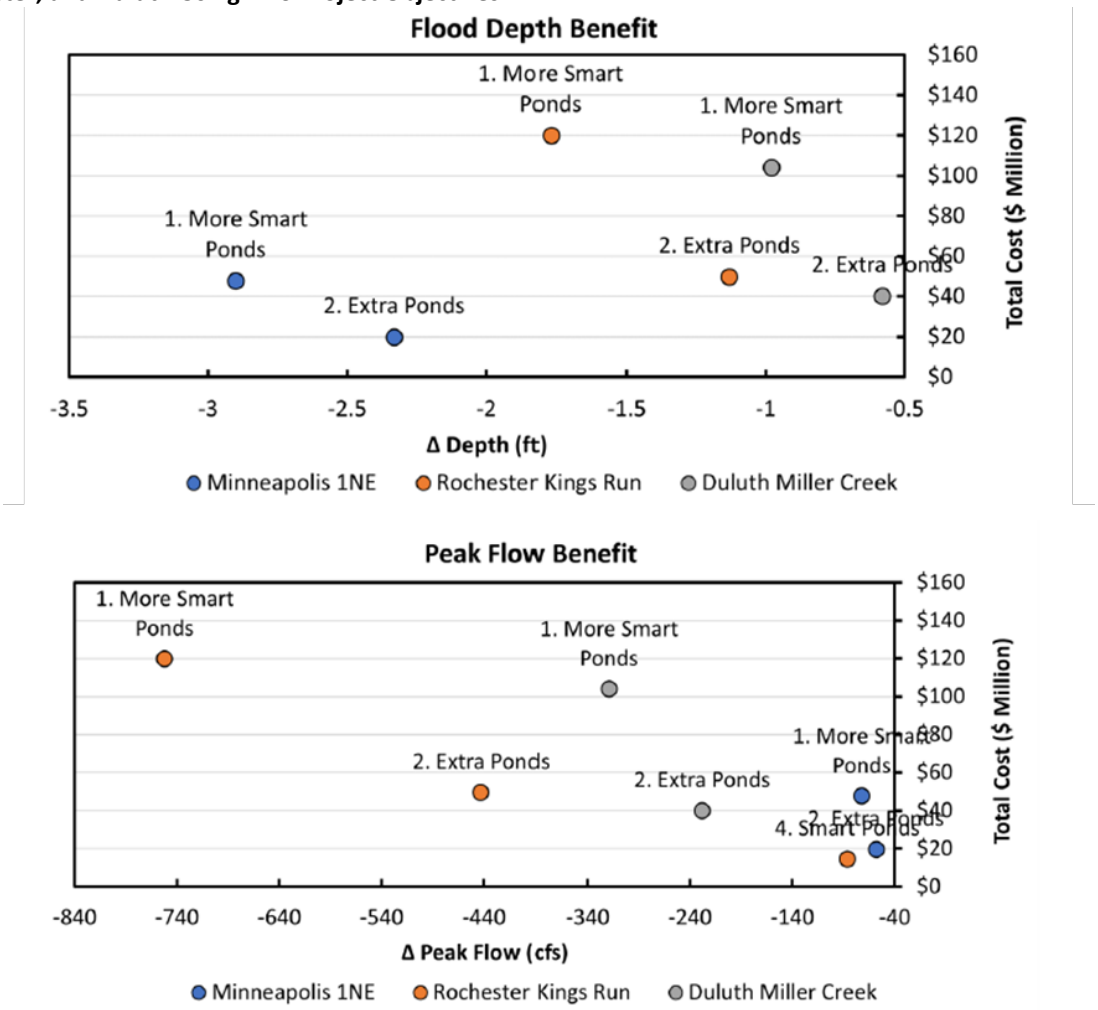
Figure 9-2. MNDOT Online Benefit-Cost Analysis Manual



There are some important limitations of benefit-cost analysis. This method requires that all metrics be monetized, and considerations that may be difficult to monetize, such as the distribution of benefits and costs among low- and high-income road users, are generally not considered. One method to overcome this limitation is to apply cost-effectiveness analysis. This variant allows the analyst to set a non-monetary performance metric, rather than requiring all components to be monetized.

In one variant of benefit-cost analysis, called cost-effectiveness analysis, a very specific goal is set, and the analysis involves finding the least costly method for achieving that goal. An example of a cost-effectiveness analysis conducted in Minnesota is illustrated in Figure 9-3 below. This analysis evaluated six urban stormwater management options in three cities: Minneapolis, Rochester, and Duluth. The options included retention ponds, underground water storage, and upsizing of drainage pipes. The authors of the study concluded that there was not enough information to estimate the flood reduction benefits of these measures in dollar terms. Instead, two flood reduction performance goals were established: reducing flood depths and reducing peak flows. The graphics in Figure 9-3 show how the benefits, on the horizontal axis, line up against costs on the vertical axis. The most desirable options have low cost (toward the bottom of the graphs) and high effectiveness (to the left of the graph). These results were used to rank options, suggesting that the "Smart Ponds" option usually had the highest ranking.

Figure 9-3. Cost-Effectiveness Analysis Results for Stormwater Management Investments in Minneapolis, Rochester, and Duluth Using Two Project Objectives



Source: Erickson et al. (2023)[201]

9.3.2. Multi-metric decision tools

Multi-metric decision tools compare benefits and costs using both monetary and non-monetary metrics. The advantage of this approach is that it can incorporate considerations of benefits that are not easily converted into monetary terms including equity, impacts on employment, provision of specific co-benefits of adaptation, or financing concerns.

In order to incorporate multi-metrics with differing units, however, a rubric or formula has to be developed to weigh these multiple dimensions. The arguments and weights in the formula can reflect overall policy goals or can be developed through stakeholder engagement. The latter approach requires ample time allocated to both develop the formula and to review the final decisions to ensure they reflect the input received – but if consensus can be reached on these aspects of the formula, a key advantage of a stakeholder-driven approach is that broad buy-in to the results can be achieved.

[201] Erickson, A.J., Herb, W.R., Gallagher, N.D., Weiss, P.T., Wilson, B. N., Gulliver, J. S., (2023). Climate Change Adaptation of Urban Stormwater Infrastructure. Published by MNDOT Office of Research and Innovation, available at: https://mdl.mndot.gov/index.php/_flysystem/fedora/2023-08/2023-21.pdf

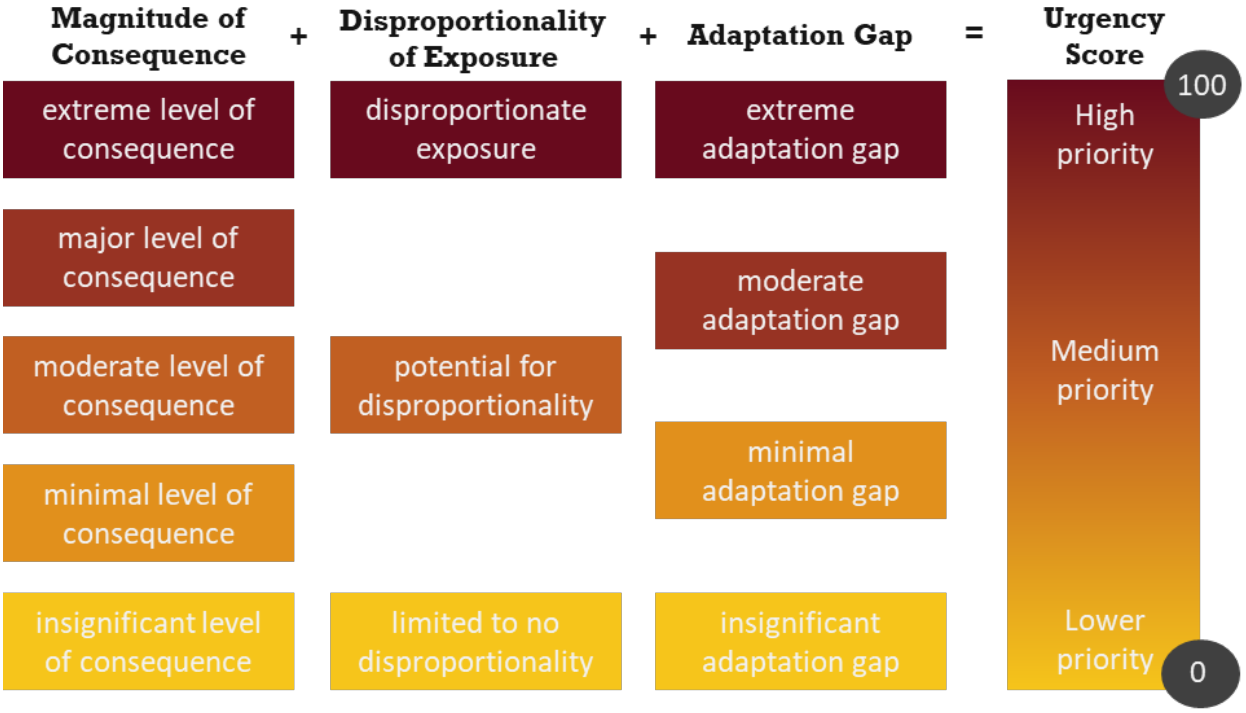
An example of an application of the multi-metric approach is the 2022 Massachusetts Climate Change Assessment. This Assessment established a set of priority impacts by considering the magnitude of climate change consequences, the level of disproportionality of impacts to state-developed environmental justice populations, and the adaptation gap. The resulting score, developed for 37 impact categories across five sectors, was a multi-sectoral prioritization of climate impacts.[202]

The goal of this project was to prioritize climate impacts and, by extension, to prioritize adaptation action to address those impacts. The idea was to develop an "urgency score," as illustrated in Figure 9-4 below, by weighting three factors:

1. The **magnitude of consequence** dimension is based on the size of the expected climate impacts. This was done for four future time periods, and quantified and monetized wherever possible, for all regions of the state. Then the relative size determined a score. In most cases, impacts could be quantified to at least some degree. For other impact categories, the approach relied on qualitative information and assessment to assign a score.
2. The **disproportionality of exposure** metric used the Commonwealth's statutorily mandated Environmental Justice delineations to estimate whether the impacts might fall disproportionately on environmental justice populations, and a score was established for the results.
3. The **adaptation gap** metric looked at current adaptation investment and the potential for more investment to make a big risk reduction impact and assigned a score for that dimension. The concept was to consider both the current status of adaptation investment and the potential effectiveness of additional adaptation investment to reduce risk.

[202] Massachusetts Exec. Office of Energy and Environmental Affairs. (2022). Massachusetts Climate Change Assessment. Available at: https://www.mass.gov/info-details/massachusetts-climate-change-assessment. The approach applied in Massachusetts was derived from an approach used in New Zealand for their National Climate Change Risk Assessment, and subsequently in the National Climate Adaptation Plan.

Figure 9-4. Multi-metric analysis in the 2022 Massachusetts Climate Assessment



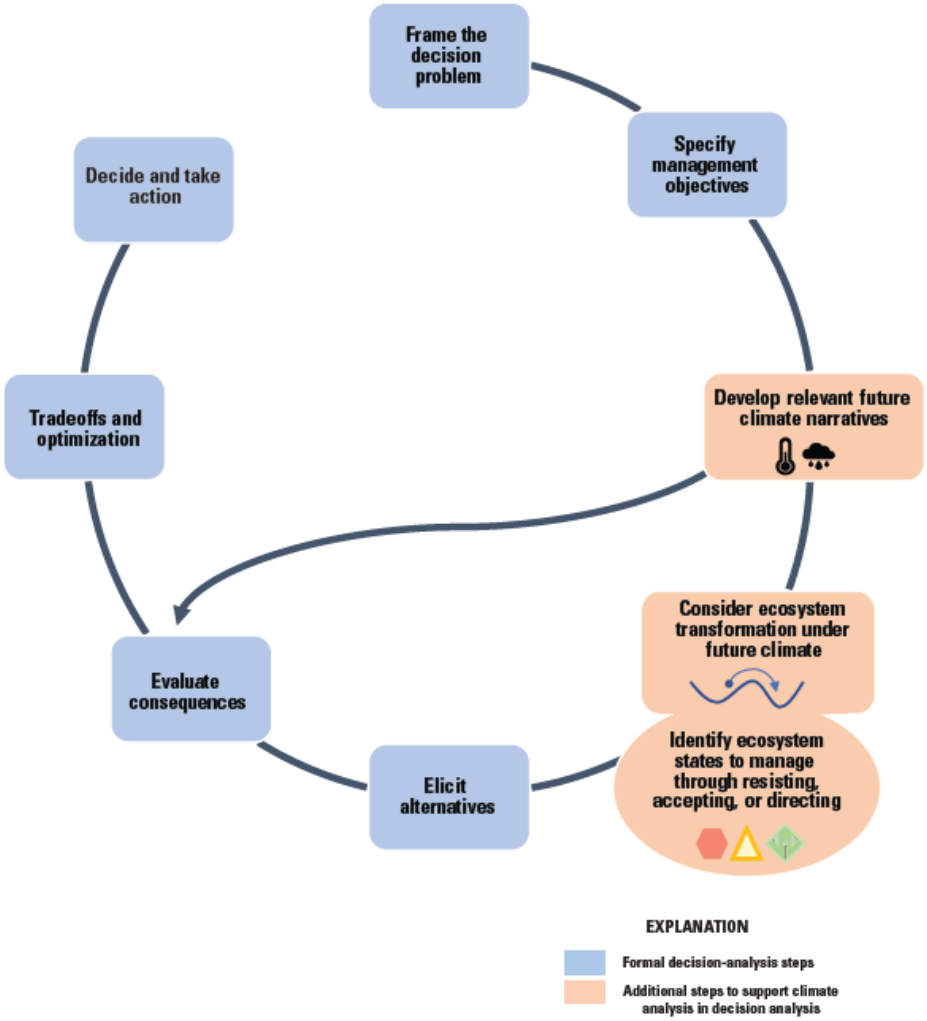
Source: Massachusetts Exec. Office of Energy and Environmental Affairs. (2022)

In subsequent work, such as the State hazard mitigation plan (titled the "Resilient Mass Plan") and the plan for coastal adaptation (the "Resilient Coasts Plan"), the prioritization has been used to guide adaptation investments. For example, Massachusetts state agencies are using the results to influence their adaptation priorities, and the State is also using them to guide awards in their Municipal Vulnerability Preparedness and Coastal Zone Management grants programs for local governments.

A second example of a multi-metric analysis is the adaptation decision framework developed for natural resource management in National Wildlife Refuges (NWRs) by the U.S. Geological Survey, U.S. Fish and Wildlife Service, and MCAP.[203] Figure 9-5 below provides a schematic of this approach. The blue boxes are formal decision analytic steps common to many contexts, while the beige boxes are steps in the framework specific to climate adaptation. The initial steps define the objectives for this application (such as maximizing ecological integrity and increasing control of water in the Agassiz NWR in northern Minnesota), which then become the key performance metrics for evaluating each adaptation option considered. Some of the analyses are quantitatively assessed through rigorous modeling analyses, but others involve scoring using expert judgment elicited in a series of workshops. Another critical step is the "tradeoffs and optimization" analysis, where the team evaluates options that perform well under multiple future emissions scenarios, and acknowledges that resource limitations usually imply tradeoffs in achieving all objectives at all refuge units.

[203] Bouska, K.L., Booker, J., Clark, S., Delaney, J., Eash, J., Post van der Burg, M., and Roop, H. (2025). Managing for tomorrow—A climate adaptation decision framework: U.S. Geological Survey Open-File Report 2025–1005, 53 p., https://doi.org/10.3133/ofr20251005.

Figure 9-5. Illustrative decision-making framework from the Climate Adaptation Decision Framework for National Wildlife Refuges



Source: Figure 1 in Bouska et al. (2025)[204]

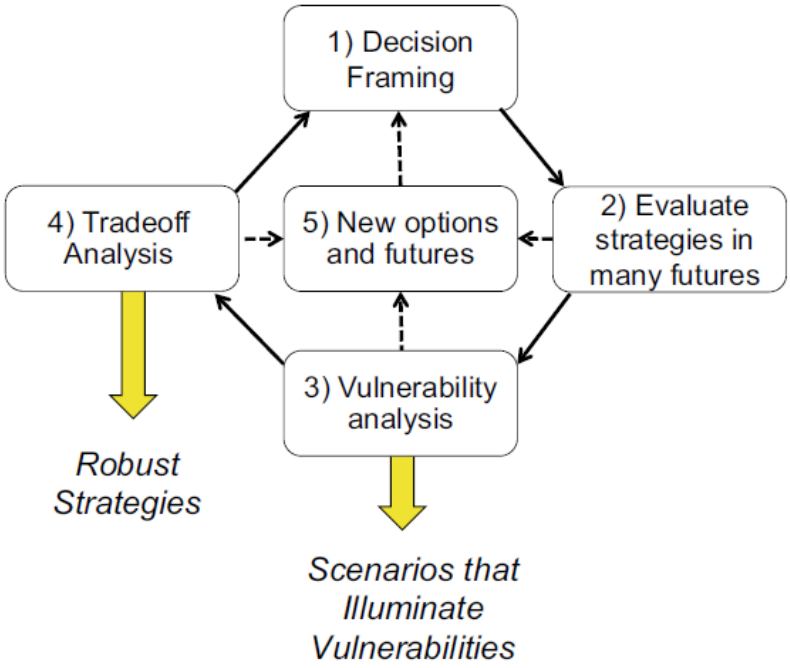
9.3.3. Robust decision-making

For over a decade, certain adaptation actions have been appraised using a method known as robust decision-making, where the goal is to ensure that adaptation decisions can provide desired outcomes in a wide range of future "states of the world." In other words, there is formal acknowledgement that for factors such as future climate change, there are important uncertainties about how it will play out in Minnesota's, or any jurisdiction's, future. Minnesota has already acknowledged this uncertainty in projecting climatic outcomes such as temperature and precipitation in the MN CliMAT tool, by employing six carefully chosen global climate models (GCMs) and three future global greenhouse gas emission scenarios (known as Shared Socioeconomic Pathways, or SSPs). The robust decision-making method can be used with tools like MN CliMAT to quantify the regrets of potentially overinvesting (that is, spending more than was necessary) or underinvesting (spending less than could be justified to address the risk) in adaptation.

[204] Bouska, K. L., Booker, J., Clark, S., Delaney, J., Eash, J., van der Burg, M. P., & Roop, H. (2025). *Managing for tomorrow—A climate adaptation decision framework* (No. 2025-1005). US Geological Survey. https://doi.org/10.3133/ofr20251005

This method has some similarities to benefit-cost analysis, but with a few important differences. The overall goal of benefit-cost analysis is to find an optimum alternative from among many options, using metrics such as benefit-cost ratios. In robust decision-making, however, the decision-making analyst is encouraged to assess each possible adaptation strategy over a wide range of plausible futures. This component is shown in step 2 of Figure 9-6. Sometimes this step is called a "stress test," assessing how each adaptation option performs across key uncertain dimensions such as future climate or sector-level economic growth projections.

Figure 9-6. Steps in a robust decision-making process



Source: Figure 4.1 in Lempert, R.J. (2025)[205]

Once the scenario exploration, or "stress test," step is complete, robust decision-making then requires the analyst to assess tradeoffs among the future outcomes (Step 4 in Figure 9-6). In some cases, an option can have negative results in some futures and positive results in others. The most frequently encountered examples of the method involve water resource planning, and a simple summary of these outcomes helps illustrate the attractiveness, as well as the potential complexity, of this approach.

Imagine that a farmer is assessing whether to invest in new groundwater irrigation pumps for their currently rainfed corn field. Up to now, under historical climate, irrigation has not been needed. But the threat of future droughts provides a rationale for considering an investment in irrigation. If the farmer chooses to invest, uncertainty in the pattern of future rainfall will influence the return on that investment. Some climate projections may anticipate a wetter future where water is abundant. In that case, the investment may not be needed, and its present-day costs may exceed its future benefits. Other climate projections, judged to be equally valid, may anticipate a much drier future. In that case, the additional water would be very valuable and could save the crop from failure during particularly dry

[205] Lempert, R.J. (2025) Supporting Climate-Related Decisions Under Uncertainty. Chapter 4 in Supporting Climate-Related Decisions Under Uncertainty, in Mearns, L.O., Forest, C. E., Fowler, H. J., Lempert, R., and Wilby, R.L., (eds). (2025). Uncertainty in Climate Change Research: An Integrated Approach. Springer: Switzerland. Available at: https://doi.org/10.1007/978-3-031-85542-9

years. Most climate projections show both dry and wet years will be possible, but with differing probabilities of wet and dry years over long periods of time.

The key question is whether investing in irrigation is more robust than not investing across these possible futures. The answer is that it depends on the preferred decision rule of the farmer. A risk-averse farmer may worry that a particularly dry year or sequence of years may lead to bankruptcy and tilt the decision toward investment. The investment, however, will decrease profits, with certainty, in every future year the wells are in operation whether the water is needed or not. Other options, such as investing in small storage ponds, may be less expensive and provide a sufficient measure of protection from particularly dry years. Different farmer decision rules can lead to differing options (or no investment at all) being preferred.

There are many examples of this approach in the literature, and there is an excellent primer on the approach available freely online (Mearns et al., 2025).[206] Nonetheless, the method is often data- and analysis-intensive and can take a long time to complete the required analyses. It can also be difficult to explain and does require development of a decision rule, such as minimizing regrets or choosing an option with the highest average returns across various futures.

Sometimes, one option is dominant across many or all possible decision rules, but that is not always true. In one recent example, the Metropolitan Water District of Southern California began undertaking an robust decision-making analysis of the district's Integrated Water Resource plan, described in a Rand Corporation online case study.[207] The case study itself walks through each of the five steps in Figure 9-6. However, the complex dimensions of the "stress test" analysis in Step 2 and the lack of consensus on a decision rule for the tradeoff analysis in Step 4, seems to have pushed the District to seek a simpler decision-making approach. In the end, the District decided to pursue more of a multi-metric or multi-objective approach, which remains in progress.[208]

The robust decision-making method is most applicable for large and long-lived infrastructure investments. It is commonly applied for water sector investments such as hydropower or large water supply dams, wells, or water demand reduction investments (such as drip irrigation). Simpler examples that apply some elements of robustness checks are also possible. For example, the adaptation cost assessment for Electricity Transmission and Distribution infrastructure in this study includes a reactive scenario (in which electric transformer infrastructure is specified to be appropriate for current climate) and a proactive scenario (in which the transformer is specified to be suitable for future, warmer temperatures). The effect of heat on the transformer reduces its useful life, so the tradeoff is between investing in a more expensive transformer now to improve resiliency or investing in a less expensive transformer which might nonetheless need to be replaced sooner. The robust decision-making analysis can help illuminate whether the investment is worthwhile in a wide range of future climates.

9.4. Other considerations

The most recent IPCC report suggests that the methods described here might be undertaken in an overall adaptation decision-making process called iterative climate risk management (New et al.

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[206] Mearns, L.O., Forest, C. E., Fowler, H. J., Lempert, R., and Wilby, R.L., (eds). (2025). Uncertainty in Climate Change Research: An Integrated Approach. Springer: Switzerland. Available at: https://doi.org/10.1007/978-3-031-85542-9 See Chapters 3 and 4 in particular for illustrations of and a primer on robust decision-making principles and techniques.
[207] Metropolitan Water District of Southern California Case Study, available at: https://www.rand.org/pubs/tools/TL320/tool/case-studies/southern-california.html
[208] See "Addressing Climate Change" on the District website, available here: https://www.mwdh2o.com/addressing-climate-change/

2022).[209] The techniques described above are designed to achieve two of the four steps in an iterative risk management process: assessing climate risk and contextual factors, and choosing and planning context-specific adaptation responses. The next two steps are to implement adaptation and risk management strategies, and to monitor progress and outcomes to evaluate and learn from the implemented options. Adaptation implementation is an obvious goal, but measurement and evaluation is often a neglected part of the adaptation process.[210] Commentors on the Wave 2 stakeholder engagement for this project, for example, noted that a robust adaptation strategy could include a wide range of low-cost adaptation experiments, which could be monitored over time for their efficacy and performance and then scaled up if evidence suggests they are or could be widely beneficial.

A key consideration in any decision-making process is achieving clarity on who is making the decision. The recent IPCC work notes that adaptation action can be managed and governed primarily by communities or individuals (e.g., crop choices and planting times in agricultural settings); by the private sector (building infrastructure and insurance options); or by the public sector (through social safety nets or buyouts of the most flood-vulnerable properties). Many options involve multiple sectors. For example, flood-risk-aware building codes are developed and enforced largely by the public sector, but implementation is achieved mostly through ongoing private sector investment.

Finally, adaptation is only part of the overall risk management process for a changing climate. Another key component of the portfolio of potential action involves directly reducing the risk of all climatic hazards through greenhouse gas emissions reductions. Decision-making can explicitly recognize this fact by establishing a preference for GHG emission-friendly adaptation options. Examples include air conditioning options that reduce health risk while being powered by clean energy sources such as geothermal or renewable electricity sources, or forest regeneration steps that increase carbon sequestration potential. All three of the major decision-making frameworks reviewed in this chapter can incorporate those considerations using a social cost of carbon in benefit-cost analyses, qualitative consideration of GHG emissions implications in a multi-metric analysis or in either the “stress test” or decision rule components of a robust decision-making process. In all these instances, the information developed for this study on the costs and potential risk reduction effectiveness of adaptation options can be an essential component of making informed decisions.

9.4.1. A note on distributional analysis: Who bears the impacts, and who pays the costs?

Distributional analysis provides detailed information regarding the distribution of impacts, costs, and benefits to communities as defined either geographically or through other socioeconomic or demographic characteristics. Performing an informative distributional analysis requires data that are highly resolved both geographically (i.e., provided in a large number of very small geographic units) and temporally (i.e., provided for a clear and consistent period of time across datasets).

[209] New, M., D. Reckien, D. Viner, C. Adler, S.-M. Cheong, C. Conde, A. Constable, E. Coughlan de Perez, A. Lammel, R. Mechler, B. Orlove, and W. Solecki, 2022: Decision-Making Options for Managing Risk. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2539–2654, doi:10.1017/9781009325844.026.

[210] Minnesota has already developed resilience metrics with intend of tracking progress on both mitigation and adaptation priorities. Report available at: https://climate.umn.edu/MN_resilience_metrics

Highly resolved analytic units tend to be relatively homogeneous; that is, a single square mile or Census block group is likely to contain a neighborhood or neighborhoods with populations who are similar to one another. The homogeneity of individual analytic units allows for effective comparison across units, which may be very different from one another. For this study, many cost categories could only be evaluated at the county scale because that is the finest resolution for which data are available. However, the geographic, demographic, and socioeconomic makeup within Minnesota's counties differs significantly. Therefore, this study does not include a distributional analysis of the costs of inaction or adaptation at the county or state scale.

Distributional analysis may be possible in future work, consistent with Minnesota's presentation of analyses to understand potential inequities in impacts across communities of color, of people with disabilities, and of otherwise disadvantaged communities. One category of the costs of inaction and adaptation, for flood risk, is assessed at geographic units more resolved than county level. If such an analysis is pursued in the future, it will be important to address not only the costs of inaction and adaptation costs in the future, but also the current risk inequities that could exist across community types, to put future risks in the proper context.

10. Conclusion and areas of further research

10.1. Study conclusions

The analysis in this study shows climate change is expensive for Minnesotans. The costs of climate change affect many sectors and aspects of people's lives. The study also shows clear economic benefits for investing in a range of climate adaptation actions to address the impacts of climate change on the health and wellbeing of Minnesotans as well as the built infrastructure and natural systems of the state.

This study is a significant advance in the understanding of the costs of climate change and climate adaptation in Minnesota. To make progress on climate adaptation to protect Minnesotans from the impacts of climate change, further work is needed. This work could include:

- **Sharing the conclusions of this study via a publicly available dashboard or interactive website.** Ideally the dashboard would be integrated into a growing suite of climate planning and analysis tools, including MN CliMAT.
- **Developing a state adaptation plan or series of hazard-focused adaptation plans that build on this study and Minnesota's Climate Action Framework.** The plans would create specific actionable adaptation paths for different sectors and include guides and other support for local governments as they cost, plan, and implement climate adaptation.
- **Developing a plan for adaptation financing.** This plan would identify existing sources of finance and the strengths along with limitations of types of financing. It would also provide recommendations for new mechanisms to fund adaptation action that consider State government, local government, private sector, and other sources of implementation funding. Considering the scale of funding needed for adaptation will be particularly important to make the financing plan effective.
- **Developing a process to test and evaluate adaptation action.** The iterative work of adaptation is most effective when it includes sharing lessons learned on past and existing resilience investments. Additional information from near-term testing of actions assessed in this study and other related Minnesota-specific evidence (e.g., University of Minnesota Climate Adaptation Partnership reports) can also improve adaptation action.

10.2. Identifying areas for further research

As noted in the introductory chapter, this study focuses on adaptation actions where costs could be estimated using available evidence, on a statewide scale. These actions are not necessarily those that the MPCA promotes or recommends. Furthermore, actions will require additional assessment of their technical feasibility in specific locations throughout Minnesota and to address concerns about required permitting and availability of adequate financing.

With this understanding, estimates presented in this study could be improved to provide a stronger basis for adaptation measure cost estimating, planning, and implementation. 2024 Session Laws, Chapter 116, Article 2, Section 33, Subdivision b requires identification of additional research, data, modeling, stakeholder engagement, and other resources needed to estimate cost impacts on a range of sectors and areas within the state.

To address this requirement, priorities for further assessment within each of the five major cost categories analyzed in Chapters 4 through 8 of the study are identified below. These recommendations reflect both technical expert suggestions for adding to the available evidence base to support

adaptation planning. They also include recommendations made by State and local government, private sector, and civil society sector stakeholders who were engaged during the development of this study.

Health and Wellbeing

1. Conduct additional analyses to clarify the cost-effectiveness of space cooling to mitigate mortality and morbidity risk from heat, with a special focus on evaluation of energy-efficient and renewable energy-based space cooling capacity.
2. More robustly analyze the non-fatal health impacts of extreme heat on the population. While the health impacts of extreme heat are already estimated to be one of the greatest future costs of inaction, gathering a more comprehensive estimate of the health impacts of extreme heat – with a focus on vulnerable populations like children, older adults, and pregnant people – would better contextualize the cost of adaptation measures.
3. Conduct additional research on methods to prevent wildfire-derived air pollution infiltration to buildings to ensure that indoor spaces provide temporary sanctuaries for reducing outdoor air pollution health risks.
4. Explore options for continuing to improve effectiveness and minimize negative consequences of control of vectors (mosquitos and ticks) that worsen the risk of climate-change-induced vector-borne disease (West Nile virus, Lyme disease, and other forms of mosquito and tick-borne diseases).

Agriculture and Livestock

5. Assess risks to a broader range of key crops than could be examined in this study including potatoes, sugar beets, and specialty crops (e.g., high-value fruits and vegetables).
6. Evaluate a broader range of available and in-development options to enhance crop resilience, including soil moisture retention measures (for dry periods), soil drainage enhancement (for wet period), and advanced crop varieties. Encourage broader demonstration of the benefits and adoption of no-till/low-till soil management practices where possible.
7. Assess the greenhouse gas emissions implications of adaptation measures considered in this study and for other measures not considered here, to identify measures with the most robust resilience and carbon emissions mitigation qualities.
8. Develop a dataset to characterize the current rates of adoption of livestock and poultry climate risk mitigation measures, including strategic use of feedstock and watering innovations, focused on alleviating animal mortality during extreme heat events.
9. Research additional measures to improve the resilience of turkey farming to extreme heat mortality beyond the cooling measures explored in this study. Further identify whether climate change might increase the risk of avian flu transmission through migratory bird interactions.

Transportation and Electricity Infrastructure

10. Develop a Minnesota-specific transportation resilience best practices guide that reflects proactive adaptation measures with high rates of return on road system life cycle repair and rehabilitation costs.
11. Incorporate more robust freeze-thaw evaluation methods into the existing modeling of risks of inaction and adaptation measure cost-effectiveness for roads.
12. Improve the assessment of flood risk analyses on asphalt road surface and roadbed integrity.
13. Assess risks of railbed flooding on rail operation and maintenance costs in Minnesota.
14. In cooperation with Minnesota electric utilities, research the applicability of the Electric Power Research Institute's Climate Readi tools to quantify costs and benefits of proactive investment in electric sector resilience – including the Risk Screening Tool and Investment Guidance products.

Begin efforts to integrate resilience enhancement efforts in plans for greenhouse gas emissions reduction efforts in this sector to take best advantage of infrastructure investments that can achieve both objectives.

Buildings

15. Provide available comprehensive flood risk data to enhance the capacity of local governments to develop flood risk assessments, to assess land-use planning and floodplain risk management efforts, and to assess the cost-effectiveness of community-level mitigation activities that might be implemented by local governments, such as enhancements to drainage infrastructure and retention ponds.
16. Improve understanding of the costs of inaction for basement flood risk through below-ground infiltration.
17. Assess the cost-effectiveness of additional community-level flood risk projects, with a particular focus on nature-based solutions such as strategically located wetland enhancements for flood storage.
18. Pursue options to integrate climate resilience (in addition to energy efficiency) into Minnesota's Sustainable Building Guidelines (known as the B3 Guidelines) as a first step toward building code enhancements. Consider options for enhancing building code requirements to ensure flood resilience with a focus on the highest-risk areas of the known riverine and high rainfall risk floodplains.

Ecosystems

19. Improve the economic assessment of risks to winter recreation by adopting measures of overall economic welfare loss that are broader than the commercial winter venue revenue measures employed in the existing literature used in this study.
20. Provide stronger representation for ecosystem adaptation measures designed to ensure stability of cultural values for ecosystem services, including e.g., loss of winter season, impacts on wild rice, and impact on subsistence lifestyles.
21. Promote research on the feasibility and cost-effectiveness of nature-based adaptation options that provide both ecosystem resilience and ecosystem service flows for human settlements and managed lands, such as strategic wetland construction for flood protection and climate-adapted silviculture.
22. Integrate the assessment of measures for ecosystem resilience considered in Minnesota's Climate Action Framework with those considered in this study. A particular focus could be on those measures designed to maintain forest health (such as strategic tree planting) and peatland function (such as peatland wetting) to ensure robust carbon sinks on these natural lands.

Appendices

Appendix A. Stakeholder engagement summary

Executive summary

Stakeholder engagement objectives and key takeaways

The stakeholder engagement process was designed to: (1) ground-truth the technical analysis with lived experience and expertise of practitioners across Minnesota; (2) integrate factors of importance to stakeholders that might not be fully captured in economic models; (3) vet the feasibility and credibility of adaptation options and develop preliminary guidance for decision-making; and (4) provide transparent feedback loops so participants could see how their input was considered.

- **Engagement achieved broad geographic and sector representation.** 223 unique individuals from 135 entities participated across two waves, generating 479 total touchpoints, representing key sectors and 46 of Minnesota's 87 counties.
- **Stakeholder input directly shaped technical analysis.** Among other examples, the study incorporated Canadian wildfire impacts in air quality modeling and added cost data on urban tree canopy maintenance, culvert infrastructure, and mosquito control.
- **Adaptive engagement methods proved essential.** The team shifted from passive surveys to active targeted interviews when survey fatigue emerged.

Purpose and scope of stakeholder engagement

Stakeholder engagement was undertaken to solicit necessary input from Minnesota subject matter experts and other stakeholders over the course of two "Waves": Wave 1 (September-October 2025) validated climate impact screening and identified data sources; Wave 2 (October-November 2025) refined adaptation actions, identified data sources to use in costing, and vetted adaptation decision-making guidance. Methods included plenary and sector-specific meetings, surveys, and targeted follow-ups.

Summary of stakeholder engagement

Following outreach to 524 individuals from 397 entities, 223 unique individuals from 135 entities participated across Waves 1 and 2, representing state and local agencies, Tribal government agencies, utilities, academia, and advocacy organizations from ~50% of Minnesota counties. Wave 1 revealed practitioners "stuck in response mode" with budgets overwhelmed by weather extremes, emphasizing avoided costs, nature-based solutions, and hidden costs like administrative burden. Wave 2 led to key refinements: updating wildfire air quality analysis to include Canadian wildfire impacts, adding urban tree canopy maintenance costs to heat adaptation strategies, conducting detailed culvert infrastructure analysis based on Minnesota-specific inventory data, and incorporating mosquito control costs.

Conclusions and best practices

The engagement process successfully grounded the study in local expertise through systematic documentation and transparent feedback integration. Adaptive approaches proved valuable as the team responded to survey fatigue by increasing targeted interviews from 8 to 33 between waves. Best practices include integrating technical experts directly in discussions, providing multiple engagement forums, maintaining documentation, and respecting capacity constraints for Tribal governments and

small communities. Future work should include formal government-to-government consultation protocols with Tribal nations and address governance and capacity constraints as barriers to adaptation.

1. How we approached stakeholder engagement

The Minnesota Climate Adaptation and Resilience Cost Study examined how Minnesotans, their environment, and the State's infrastructure systems will be affected by climate change through the end of the century. It aimed to quantify the financial implications of climate impacts and adaptation measures needed to address them. Understanding the costs of climate adaptation in Minnesota requires a quantitative analysis to determine estimates of climate change costs (cost of inaction, adaptation costs, residual risks). These projections were enhanced by input from communities across the state.

Robust engagement of key stakeholders with direct experience of weather and climate-related impacts in Minnesota, as well as knowledge of current, planned, and potential adaptation actions across sectors was a critical complement to the in-depth literature review and technical analysis that formed the basis of this study. At the outset, the project team developed a Stakeholder Engagement Plan (SEP) to structure how stakeholders would be meaningfully involved and how their insights would be reflected across two “Waves” of engagement corresponding to the phases of the project. This plan articulated the engagement objectives for each wave; which entities and stakeholders needed to be involved; what information needed to be prepared to enable them to give meaningful input; which kinds of data or feedback were being sought from them; what tools, channels, and methods would be used to have these discussions; and what key outputs or decisions would result to advance the next phase of the project.

The two-wave structure created deliberate windows where stakeholder input could most meaningfully influence the analysis. Wave 1 focused on validating the preliminary screening of climate impacts and identifying data sources. Wave 2 concentrated on identifying, refining, and costing actual and potential adaptation actions to address those impacts and on gathering feedback and vetting preliminary guidance for decision making and weighing tradeoffs in adaptation investment.

Throughout the process, the technical teams from Industrial Economics (IEc, the project lead) and the University of Minnesota Climate Adaptation Partnership (MCAP) and facilitation and engagement teams from the Consensus Building Institute (CBI) and Two Degrees Adapt (2DA) worked closely with MPCA representatives and jointly staffed all stakeholder meetings. Having the technical analysis leads and subject matter experts directly involved in discussion in the virtual “rooms” ensured that feedback gathered from stakeholders was as specific and nuanced as possible and allowed immediate follow-up questions as needed to inform the study, while expertise in process design and facilitation ensured that information was being shared clearly, the full range of perspectives were heard, and that feedback was documented and integrated into the analysis.

1.1 Engagement objectives

The SEP was anchored by four primary objectives that shaped the structure and methods of the engagement process. These objectives were designed to ensure that stakeholder input would not only inform the study, but would shape its technical direction and outputs.

The first objective was to ground-truth the technical analysis with the lived experience and expertise of key stakeholders across Minnesota. Local practitioners, from municipal engineers managing flooding in their jurisdictions to farmers adapting cropping systems to changing precipitation patterns, possess important knowledge about how climate impacts are already being felt and will manifest in the future in

their communities and sectors, as well as what adaptation strategies work or should be explored, what they cost, and what barriers prevent their broader adoption. This knowledge is critical to vet the findings in the available literature and to provide additional data points to fill gaps in the understanding of climate impact and adaptation action costs. This objective requires creating engagement mechanisms for technical team members to hear directly from practitioners and incorporate their insights into model parameters and assumptions.

The second objective was to integrate factors of importance to stakeholders that might not be fully captured in economic models to identify and prioritize the most consequential climate hazards and impacts. This included applying criteria such as which impacts threaten culturally significant resources, and which face the widest gaps between current preparedness and needed adaptation. By engaging with these participants, the study sought to ensure that its final recommendations would reflect both technical rigor and community priorities.

The third objective was to use stakeholder input to vet the feasibility and credibility of adaptation options to be costed and to develop preliminary guidance for decision making and weighing tradeoffs in adaptation investment. Stakeholders working on the ground have a unique understanding of how and whether adaptation strategies can be implemented given real-world constraints of funding, staffing, governance structures, and community acceptance. Additionally, stakeholders provided critical input on decision-making guidance, commenting on the advantages and disadvantages of the three broad decision-making paradigms presented by the consulting team.

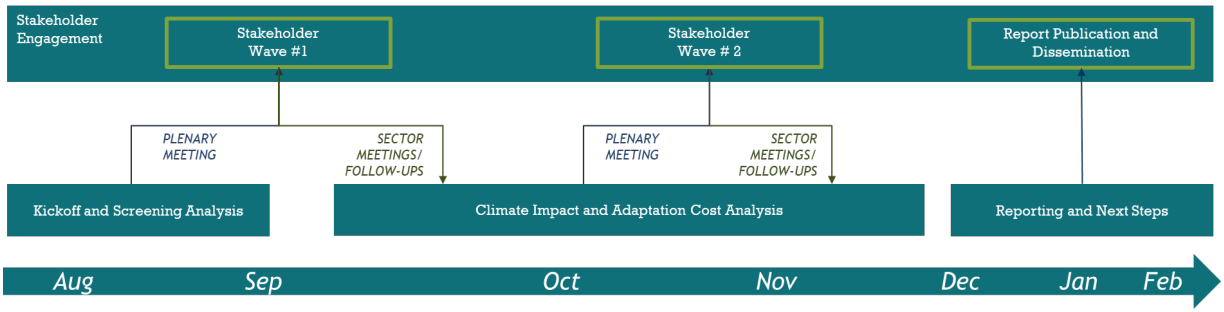
The fourth objective was to provide transparent feedback loops so participants could see how their input was integrated over the course of the study. The project team understood that meaningful engagement requires closing the loop, showing participants that their time and expertise were valued and that their contributions helped to shape the final product. This objective influenced the wave structure itself, with each wave building upon feedback from the previous one and providing opportunities for stakeholders to review how their input had been integrated. It also required systematic documentation of how stakeholder feedback was incorporated into technical decisions and what feedback was noted for future work beyond the study's scope.

1.2 Engagement timeline

The engagement approach supported consistent interplay between subject matter expert input and the technical assessment phases (Figure A1). The process began in September 2025 with Wave 1, which focused on screening and scoping, followed by Wave 2 in October and November 2025 to refine adaptation actions and cost data. Waves 1 and 2 addressed specific key questions, such as "Are we considering the right list of impacts?" (Wave 1), and "What adaptation actions seem most to address the biggest impacts?" (Wave 2) to ensure the engagement remained focused and productive.

Figure A1. Stakeholder engagement design.

The design was structured around two waves of engagement.



1.3 Engagement methods

To achieve breadth and depth, we used a mix of four engagement formats including: (1) plenary meetings, (2) sector-specific sessions, (3) surveys, and (4) targeted follow-ups. The various methods of outreach used throughout each wave of the engagement process are described in more detail below. Elements of the SEP were adjusted throughout the process based on input from stakeholders and lessons learned from public participants and partners.

1.3.1 Plenary sessions

Plenary sessions were large-format virtual meetings hosted via Zoom. They were designed to ensure consistent messaging across all groups. Plenary sessions served as the launch point for each wave by providing project updates and high-level findings. For example, the Wave 1 plenary (September 29, 2025) introduced the project scope, while the Wave 2 plenary (October 31, 2025) focused on explaining the top-down costing methodology. To maintain interactivity, we utilized real-time polling (Mentimeter/Zoom) to gauge immediate sentiment and priorities. All meetings were recorded and made available on the project website for those who could not attend but still wanted to provide input or review the content.

1.3.2 Sector sessions

Following each Plenary session, stakeholder engagement transitioned into smaller, sector-based workshops. Six sectors were organized into three larger groupings to allow for efficient scheduling. The sector sessions included an introductory discussion with the whole group, followed by breakouts into smaller groups for sector-specific discussion.

- Group one
  - Buildings: residential, commercial, public
  - Cross-Sector Governance/Finance
- Group two
  - Critical Infrastructure: water, transportation, utilities
  - Public Health & Emergency Management
- Group three
  - Working Lands: agriculture, forestry
  - Natural Lands: protected areas, recreation, ecosystems

Two session times were offered for each sector grouping to accommodate different schedules. In Wave 1, six sector meetings were held across two weeks in early-to-mid October 2025. In Wave 2, six sector meetings were held during the weeks beginning October 31 and November 7, 2025. To help participants prepare for Wave 2 meetings, the team distributed reference slides ahead of time that summarized the draft adaptation actions, information needs, and decision-making frameworks.

Each meeting began with a short presentation to orient participants. The facilitated discussions enabled participants to provide feedback verbally and via the chat function. Facilitators then guided participants into sector-specific breakout discussions with directions to review materials for their sector and provide input on key questions. These breakout rooms utilized digital collaboration tools to organize participant input. Sector meetings concluded in plenary for report-backs and synthesis discussions.

1.3.3 Surveys

Surveys provided an asynchronous option for participants to share quantitative data and input. The team deployed two types of surveys during the engagement process.

A short post-Plenary survey was delivered immediately upon meeting conclusion via a Zoom pop-up. This survey gathered feedback on the meeting format and solicited referrals for additional stakeholders to include in subsequent waves.

To capture quantitative data and input from those unable to attend live sessions, we deployed SurveyMonkey instruments after each Plenary. These surveys were important for gathering detailed cost examples and allowing stakeholders to provide nuanced feedback on specific adaptation options. In Wave 1, this detailed survey was designed to capture specific cost examples, focusing on three core areas: reactive response actions (damage repair, emergency response), proactive adaptation actions (infrastructure upgrades, nature-based solutions), and publicly available reports or data on costs and performance. In Wave 2, a detailed online survey was distributed to all email contacts, achieving six responses. The survey was designed to capture specific cost examples and data sources for adaptation actions across all sectors for anyone unable to attend the sector-specific meetings.

1.3.4 Targeted follow-ups

Targeted follow-ups filled gaps in representation and technical data. Where specific expertise was needed or underrepresented groups required additional outreach, the team conducted one-on-one phone interviews, email exchanges, and small virtual meetings.

In Wave 1, the team conducted eight targeted follow-up interviews with stakeholders who had specific technical expertise or represented underrepresented groups . In Wave 2, while the survey response rate was lower than anticipated, the team compensated by significantly increasing targeted follow-up activities. Targeted follow-ups facilitated more in-depth discussion and ultimately provided a higher level of detail and consultant team responsiveness in the Wave 2 feedback. The team conducted 33 targeted follow-ups; as in Wave 1, the team conducted follow-ups using phone interviews, email exchanges, and small virtual meetings. These follow-ups provided additional detail that complemented the plenary and sector meetings. The approach to Wave 2 was modified to reach groups that did not participate in Wave 1, or that held specialized knowledge needed for the technical analysis.

Targeted outreach was conducted with outdoor recreation industry representatives, insurance entities and risk management offices, Tribal government staff, agricultural producers and commodity organizations, forestry professionals, state agency staff, local flood management professionals (including one representing an agricultural area), and municipal engineering and public works departments. Many of these calls had a direct impact on the adaptation cost technical analyses, providing concrete examples of multi-sectoral impacts from natural hazards, local-scale technical data to cross-check the magnitude of impacts and adaptation costs in the statewide results, and data to support adaptation cost estimation. Participants from state agencies, cities, Tribal governments, utilities, universities, and recreation organizations offered cost examples from active projects and pointed the team to datasets and reports that helped refine the adaptation action list and strengthened the costing framework where statewide data had previously been limited.

2. Who participated

2.1 Overall participation

After email outreach to 524 individuals from 397 entities, a total of 223 individuals from 135 entities participated in stakeholder engagement activities across Waves 1 and 2 (Table A1). Stakeholder participation spanned one Plenary session and six Sector meetings in Wave 1 (September-October 2025), followed by one Plenary session and six Sector meetings in Wave 2 (October-November 2025). In addition, surveys and targeted follow-up interviews provided opportunities for stakeholders to contribute input outside of scheduled meetings.

Table A1. Engagement summary

Unique individual and entity participation as well as the total touchpoints across the engagement lifecycle to date. Touchpoints are defined as individual participation instances across all forums.

Engagement Forum	Wave 1	Wave 2	Total (to date)
Plenary Meeting	77 individuals, 59 entities	61 individuals, 45 entities	115 individuals, 81 entities
Sector Meetings	105 individuals, 75 entities	66 individuals, 46 entities	137 individuals, 93 entities
Survey(s)	81 individuals, 74 entities	6 individuals, 6 entities	65 individuals, 57 entities
Targeted Follow-ups	8 individuals, 6 entities	33 individuals, 23 entities	41 individuals, 27 entities
Unique Engagement	155 individuals, 102 entities	125 individuals, 80 entities	223 individuals, 135 entities
Total Touchpoints	297 instances	182 instances	479 instances

In Wave 1, 109 participants from 76 entities registered for the virtual Plenary session, and 77 participants from 59 entities joined the meeting. All six Sector meetings engaged 105 individuals from 75 entities. The post-plenary survey received 56 responses, and the detailed survey received 25 responses. Eight targeted follow-up interviews were conducted with six entities. Overall, Wave 1 saw participation from 155 unique individuals representing 102 entities and generated 297 touchpoints (i.e. instances of individual participation).

In Wave 2, 61 participants from 45 entities joined the Plenary session. The six Sector meetings drew 66 individuals from 46 entities. The detailed online survey achieved 6 responses, while 33 targeted follow-ups were conducted with 23 entities. Overall, Wave 2 saw participation from 125 individuals representing 80 entities and generated 166 touchpoints. Wave 2 engagement dipped slightly compared to Wave 1 for the plenary, sector meetings, and surveys, however targeted follow-ups increased.

2.2 Sector representation

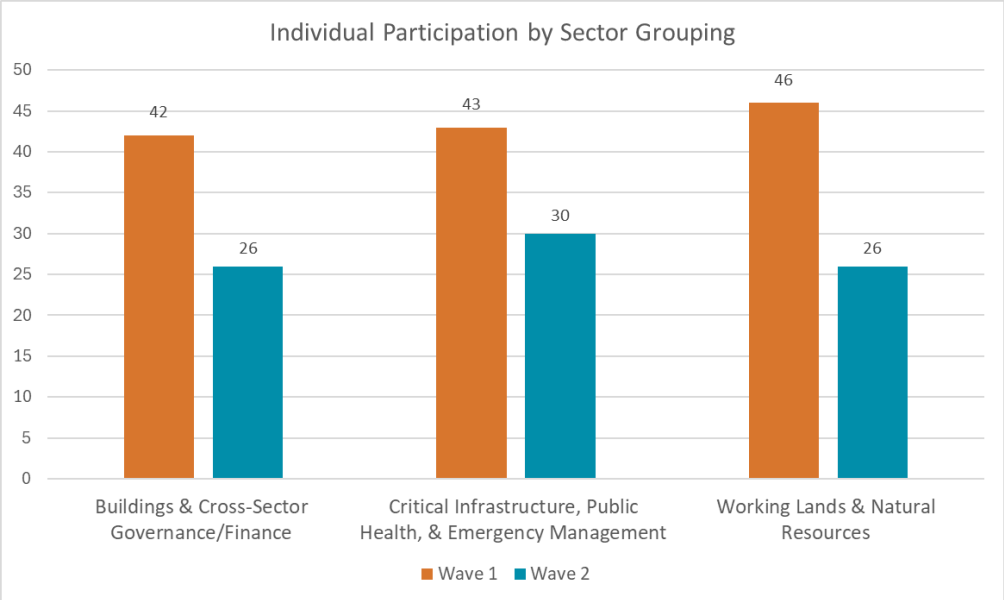
Entities representing Minnesota's diverse economy and governance structure were included in stakeholder engagement activities. Stakeholders represented eleven state agencies (Minnesota Pollution Control Agency [MPCA], Minnesota Department of Natural Resources [DNR], Minnesota Department of Transportation [MnDOT], Minnesota Department of Health [MDH], Minnesota Department of Agriculture [MDA], Board of Water and Soil Resources [BWSR], and Minnesota Department of Public Safety [DPS], Minnesota Department of Labor and Industry, Minnesota

Department of Administration, Minnesota Department of Commerce, and Minnesota Department of IT Services), Tribal government agencies through liaisons, Soil and Water Conservation Districts (SWCDs), watershed districts and management organizations, emergency managers, regional economic development organizations, and city governments, as well as environmental advocacy organizations and other nonprofits.

Participation was broadly representative of the sectors requested by MPCA project oversight: floodplain management, water resource management, utilities, transportation and infrastructure, educational facilities, public health managers, emergency managers, state agencies, local and regional government, Tribal governments, environmental justice organizations, academics, and regional development commissions. The study also engaged with the private sector, including utilities, engineering consultants, philanthropic organizations, and healthcare organizations.

Figure A2. Sector meeting participation.

Participation totals by sector grouping for individuals attending either of two sessions.



2.3 Geographic representation

The outreach strategy sought to balance engagement between Greater Minnesota entities and Twin Cities Metro Area entities to ensure that the study was representative of geographic and sectoral perspectives across the state (Figure A3). In practice, outreach successfully reached all 87 Minnesota counties (Figure A4). Participation was roughly split between the seven-county Twin Cities Metro Area (53%, 72 entities) and Greater Minnesota (45%, 60 entities). The pattern of participation in Greater Minnesota appears random rather than systematic, suggesting that full participation could be achieved with enough time and effort.

Figure A3. Stakeholder engagement geographic representation by area

Outreach (email invitations) and participation (engagement with any of the four engagement methods for the seven-country Twin Cities Metro Area, Greater Minnesota, and Other areas outside of Minnesota.

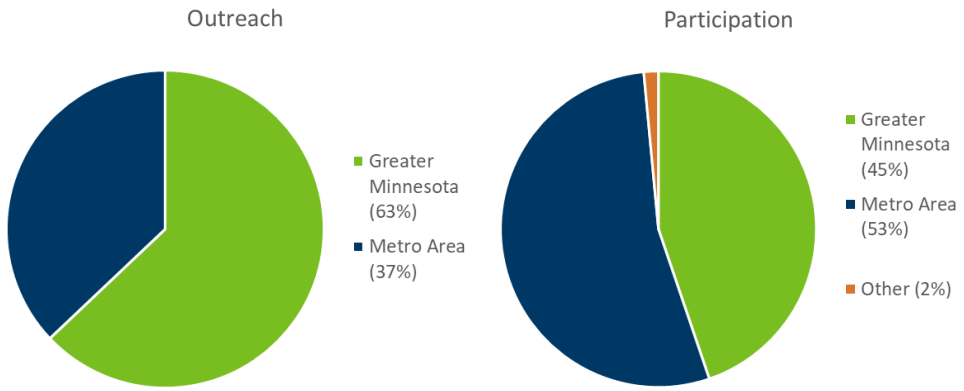
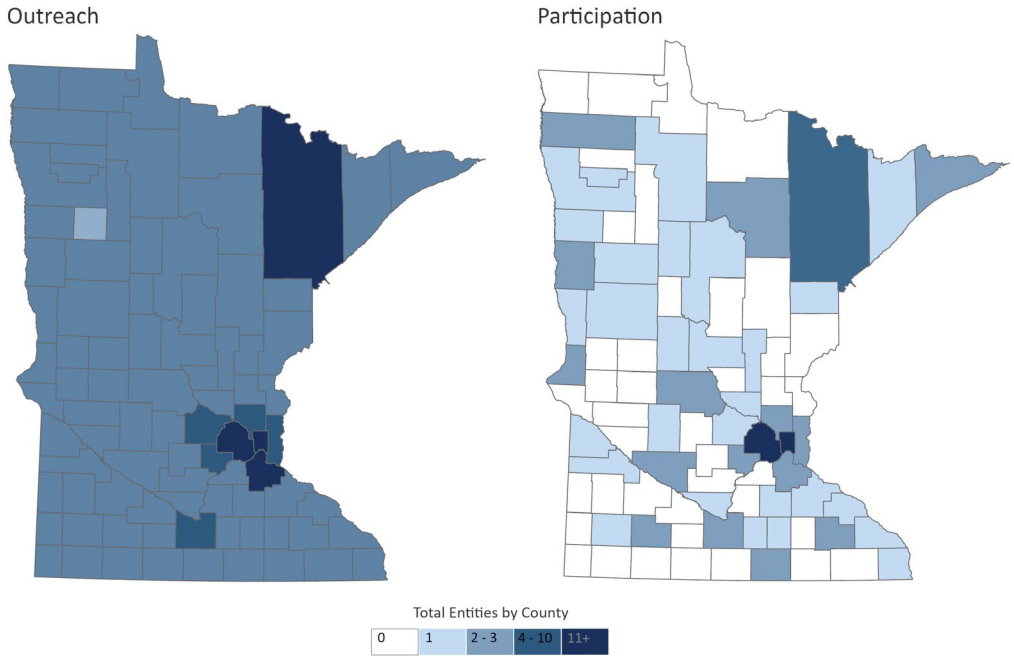


Figure A4. Stakeholder engagement geographic representation by county

Colors represent entities engaged for outreach (left) and participation (right), from 0 (white) to 11+ (blue).



To date, the study has engaged 52% of counties (46 out of 87). Stakeholders from 38 counties participated in Wave 1. In Wave 2, participants represented 28 counties across Minnesota. The study successfully engaged subject matter experts and entities throughout the State of Minnesota (Figure A4).

3. What unfolded in each wave

3.1 Wave 1: Screening and scoping

3.1.1 Objectives

The primary objective of Wave 1 was to ground-truth the initial screening analysis. This involved identifying which climate hazards (e.g., extreme heat, flooding, etc.) were most consequential to Minnesotans and ensuring that the study's scope addressed their most pressing concerns. Wave 1 also aimed to gather preliminary cost data, identify ongoing adaptation practices, and establish a foundation for deeper technical work in subsequent waves.

3.1.2 Participation

A total of 155 individuals from 105 entities participated in Wave 1 activities (plenary session, sector meetings, survey responses, and targeted follow-ups). This represents a total of 297 touchpoints with participants and their associated entities (Table A1).

The project team invited 440 individuals from over 300 entities to participate in the first Plenary session. The team sent a series of three emails: an initial invitation, a reminder, and a last call for registration. The email included a description of the study and a Zoom registration link. 109 individuals registered for the virtual Plenary session held at 10am CT on September 29th, 2025. 77 participants joined the meeting. 56 participants responded to the post-plenary survey, which included feedback on the meeting itself and recommendations for additional individuals and entities to include in the project outreach.

Two meetings were held for each of the sector groups introduced previously in Section 1.3.2: Buildings & Cross-sector Governance/Finance meetings were held on Monday, October 6th at 10:30am CT and Friday, October 10th at 1pm CT; Critical Infrastructure, Public Health & Emergency Management meetings were held on Friday, October 10th at 10am CT and Thursday, October 16th at 1pm CT; Working Lands and Natural Lands meetings were held on Wednesday, October 15th at 11am CT and Thursday, October 16th at 9:30am CT.

The project team used online surveys both to supplement live engagement and to collect quantifiable data. A short Post-Plenary Survey, delivered immediately upon meeting conclusion via a Zoom pop-up. This survey provided feedback and solicited critical referrals used to refine the Wave 2 engagement list. A second, more comprehensive survey was administered via SurveyMonkey to all contacts by email. This survey was designed to capture detailed cost examples, focusing on three core areas: reactive response actions, proactive adaptation actions, and publicly available reports or data on costs and performance.

3.1.3 Key feedback

Feedback from the initial engagement phase revealed that all sectors are already grappling with the financial realities of climate change (Table A2). Stakeholders reported that they are frequently "stuck in response mode," with existing maintenance and emergency budgets overwhelmed by the increasing frequency of weather extremes. This lack of fiscal and staff capacity emerged as a primary barrier to long-term planning.

Table A2: Wave 1 Specific Technical Input by Impact Category

Stakeholder-identified climate impacts, adaptation strategies, and cost benchmarks by category.

Impact Category	Key Concerns & Adaptation Practices	Representative Costs/Examples
Heat & Air Quality	Energy burden/cooling access	Resilience Hubs: $250k–$2M

Impact Category	Key Concerns & Adaptation Practices	Representative Costs/Examples
	School HVAC adequacy Filtration for wildfire smoke "Beat the Heat" campaigns	Filtration kits: $30–$75/household
Agriculture & Livestock	Soil stability Livestock heat stress Conservation tillage Precision agriculture Subsurface drainage coordination	Cover crops: $55–$75/acre Flood impoundments: $20M–$60M
Transportation Infrastructure	Slope instability (bluffs) Freeze-thaw damage Culvert capacity Resilient design standards	Slope stabilization: $8M Culvert replacement: $20k–$600k
Energy Infrastructure	Reliability during ice/storms Energy affordability Grid undergrounding Microgrids for critical facilities	Undergrounding lines: ~$1M/mile Solar Storage (40kW): $130k–$150k
Water Quality & Recreation	Algal blooms (beach closures) Erosion along North Shore Green infrastructure (rain gardens & bioswales)	Stream restoration: $200k-$2M/mile Wetland Banking: $25k-$50k/acre
Ecosystems & Natural Lands	Invasive species Forest pests Peatland restoration Adaptive silviculture Assisted migration	Peatland restoration: $10k–$15k/acre Prescribed burning: $1k–$5k/acre
Public Health	Emerging West Nile patterns Longer tick/mosquito seasons Rural broadband for telehealth	Telehealth upgrades: $10k–$25k/clinic Vector surveillance: (Cost rising annually)

There was a strong consensus that the study must prioritize the quantification of avoided costs, meaning the reduction in expected climate impacts due to adaptation. Participants underscored that the final report would be most useful to decision-makers if it presented a clear business case for proactive investment – explicitly comparing the cost of a project today against the avoided cost of future impacts such as flood damage or infrastructure failure.

Many participants expressed a preference for nature-based and hybrid adaptation solutions that maximize co-benefits. Representatives from watershed districts and working lands emphasized the inherent cost-effectiveness of wetland restoration and soil health initiatives, noting that these green solutions offer critical co-benefits such as improved water quality and carbon sequestration that traditional grey infrastructure does not provide. Finally, feedback highlighted significant hidden costs that are often missed in existing models and that should be resourced going forward to use adaptation funds efficiently, such as staff time required for inter-agency coordination and the complex administrative burden of navigating fragmented grant systems.

In addition to the detailed feedback by impact category, participants identified overarching priorities for adaptation investment and planning within their sectors (Table A3). Stakeholders highlighted that the

state's building stock is not uniformly equipped to withstand increasing heat, precipitation, and air quality challenges. Transportation, energy, and communications infrastructure were among the most frequently cited priorities for adaptation. Health agencies and emergency managers identified heat, air quality, and flooding as primary threats to public health and safety. Farmers, landowners, and conservation partners identified soil health, water management, and crop diversification as foundational adaptation strategies. Forest and wetland restoration were repeatedly highlighted as valuable resilience investments. Across all sectors, participants cited governance and finance barriers as central challenges to advancing climate adaptation.

Table A3: Sectoral Investment Priorities

Priority investments that address the most significant climate vulnerabilities in each sector

Sector	Primary Adaption Priority	Strategic Focus
Buildings	Retrofitting & Standards	• HVAC/insulation for schools and public housing • Climate-ready building codes
Critical Infrastructure	System Integration	• Cross-agency coordination • Standardized resilience criteria
Public Health & Emergency Management	Preparedness & Safety	• Early warning systems • Resilience hubs • Climate-integrated emergency operations
Working Lands	Soil & Water Security	• Technical assistance via SWCDs • Performance-based incentives for carbon/water
Natural Lands	Nature-Based Solutions	• High-return forest/wetland restoration • Workforce capacity for long-term management
Governance & Finance	Process Streamlining	• Consolidated state finance framework • Equitable funding allocation • Simplified grant administration

3.2 Wave 2: Adaptation options & decision framework

The overall goal of Wave 2 was to solicit public input on the reasonableness of the draft adaptation actions, as well as on the decision-making frameworks proposed to guide future adaptation investments. This input was used to refine the adaptation actions list and collect detailed cost data to support the technical analysis.

3.2.1 Objectives

Wave 2 shifted focus toward a detailed sector-by-sector vetting of adaptation actions and their associated financial costs and benefits, as well as the decision-making frameworks used to prioritize them. The objective was to ensure the list of adaptation actions and the cost analysis was credible, feasible (if funding were not a barrier), and equitable. Significant focus was placed on refining the list of adaptation actions, clarifying data needs, and shaping the guidance that will help a range of actors evaluate adaptation investments, including state, local, Tribal, and private partners.

3.2.2 Participation

Stakeholder engagement in Wave 2 used a layered approach to continue the outreach activities conducted in Wave 1, as well as to address gaps in stakeholder participation. To this end, outreach activities included a Plenary session, Sector meetings, a detailed survey, and targeted follow-up interviews. The approach to Wave 2 was modified to reach groups that did not participate in Wave 1, or who held specialized knowledge needed for the technical analysis.

The Wave 2 Plenary session was held on October 31, 2025, at 11:00am CT via Zoom. Sixty-one participants joined the session, which presented the draft adaptation actions and explained the top-down costing approach, and introduced the tiered structure for linking actions to data and projected hazards. The session also previewed the study chapter on adaptation decision-making guidance, including benefit-cost analysis, multi-metric analysis, and robust decision-making approaches.

Six sector meetings were held during the weeks of October 31 and November 7, 2025, with two sessions offered for each of the six sectors. A total of 82 participants attended these meetings, representing 66 unique individuals as some attended multiple sessions.

A detailed online survey was distributed via SurveyMonkey to all contacts, achieving six responses. The survey was designed to capture specific cost examples and data sources for adaptation actions across all sectors. While this response rate was lower than anticipated, the team compensated by significantly increasing targeted follow-up activities. The team conducted 33 targeted follow-ups through phone interviews, email exchanges, and small virtual meetings.

A total of 125 stakeholders participated in Wave 2 activities across Minnesota through the plenary session, sector meetings, survey responses, and follow-up discussions. This represents a total of 182 touchpoints with participants and their associated entities (Table A1).

3.2.3 Key feedback

During Wave 2, feedback transitioned from high-level priorities to specific data requests and refinements to cost estimates. A critical finding was the identification of a "Cold Season Gap" in existing climate literature. Stakeholders from the transportation and energy sectors pointed out that standard national frameworks often overlook Minnesota-specific winter risks, such as the damage caused by frequent freeze-thaw cycles on pavement or the cost of ice loading on power lines (Table A4).

The financial discussion narrowed to the distinction between capital and operational expenditures. Local officials clarified that while capital projects are often attainable through one-time grants or bonding, the recurring operating costs (OpEx) for maintenance represent the true long-term barrier to local resilience.

Finally, stakeholders across sectors emphasized that governance and policy are themselves forms of adaptation. They identified that updating building codes and streamlining governance structures are relatively low-cost actions that can yield high-magnitude cost savings over time.

Table A4: Wave 2 Key Cost Drivers & Data Gaps Identified

The table below summarizes the specific cost drivers and data gaps identified by stakeholders during the sector-specific breakout sessions

Sector Group	Key Cost Drivers & Feedback Identified	Data Sources/Needs Identified
Buildings & Governance	**Code Compliance:** Lack of climate-resilient codes increases long-term retrofit costs **Site Measures:** Need to cost site-level adaptations (tree canopy, stormwater) alongside building shell retrofits	**B3 Guidelines:** Cited as a model for performance standards **Insurance Data:** Need for premium data to quantify avoided loss
Critical Infrastructure	**Cold Season Gap:** Standard models miss freeze-thaw damage and ice loads on power lines **OpEx vs CapEx:** Cooling centers and filtration require high operating budgets, not just capital for construction	**Urban Heat:** Cooling center operation logs **Power:** Undergrounding cost estimates ($1M/mile) **Water:** Private well vulnerability data
Working & Natural Lands	**Restoration Costs:** Invasive species management costs scale non-linearly **Co-benefits:** Soil health practices (cover crops) provide unquantified water storage benefits	**Ski Industry**: Snowmaking cost data (MN Ski Areas Association) **Forestry:** Nursery capacity and sourcing costs **Agriculture:** Soil health grant data

4. How feedback shaped the study

4.1 Integration by study component

Stakeholder feedback influenced three primary components of the study: hazard identification, adaptation action vetting, and the decision-making framework. During the scoping phase, practitioners provided the necessary ground-truthing to adjust the project's boundaries, ensuring that the economic models did not overlook regionally specific risks. In the vetting phase, sectoral experts refined the list of adaptation actions to cost to ensure that the cost estimates were reflective of the highest priority adaptation actions that are being or could be deployed in Minnesota and provided input into the considerations that should be reflected in decision-making guidance.

4.2 Examples of feedback integration

Several critical shifts in the study's methodology were driven directly by participant input:

- **Wildfire Air Quality Impacts from Canadian Sources**: The initial screening assessment for air quality impacts from wildfires was limited to fires originating in the United States and therefore did not incorporate effects of Canadian wildfires, which stakeholders identified as having a large impact in Minnesota. In response to this feedback, the team updated the analysis to use a new study that accounts for Canadian wildfire smoke transport into Minnesota.
- **Urban Tree Canopy Maintenance Costs**: Following feedback on heat adaptation strategies, the study expanded beyond building-level retrofits to include the cost of maintaining urban tree canopy as a heat mitigation measure. This addition reflects stakeholder emphasis on nature-based solutions and the ongoing operational costs necessary to sustain green infrastructure.

- **Culvert Infrastructure Analysis**: After stakeholders provided access to Minnesota-specific culvert inventory data and identified culvert failure as a significant concern, the team completed a detailed analysis of climate impacts on culverts.
- **Mosquito Control Costs**: Based on conversations with mosquito control district representatives, the study incorporated vector control costs associated with changing climate conditions and the expanded range and season of disease-carrying mosquitoes in Minnesota.
- **Avoided Cost Prioritization:** Stakeholders across sectors emphasized avoided costs as a key component of the financial case for adaptation. This led to researching insurance entities and risk management offices to invite to participate in Wave 2, and the incorporation of avoided cost calculations as a central element of the decision-making framework.
- **Governance Reform as Adaptation:** Feedback revealed that updating building codes and streamlining governance structures are relatively low-cost actions that can yield high-magnitude cost savings over time.

Many of the impacts and potential adaptation stakeholders flagged as missing from the draft analyses could not be quantitatively integrated into the analysis due to a lack of defensible methodologies for modeling future impacts and/or costs. These items were flagged as recommendations for future work, and discussed qualitatively in the report (e.g. CapEx vs OpEx; cold-season damage functions).

The project team maintained a systematic approach to documenting how stakeholder input was integrated. After each wave, the team produced comprehensive memos (Wave 1 Summary, Wave 2 Summary) documenting all feedback received, organized by theme and sector. Following compilation of feedback, the technical team held dedicated review sessions to determine which input could be directly integrated into current analysis, which required additional data collection, and which should be noted for future work. Specific cost examples and data sources provided by stakeholders were integrated into the analysis where possible, with full attribution.

4.3 Feedback noted for future work

While many suggestions were integrated, some stakeholder concerns fell outside the current study's technical scope or timeline. These have been documented in the main report to guide subsequent research. Key items include: (1) the need for more granular data on private-sector supply chain disruptions and the development of specific cost curves for the loss of non-market cultural resources, such as the ecological health of manoomin (wild rice) waters, which requires a specialized valuation framework beyond the scope of this economic assessment; (2) integration of climate adaptation costs with other environmental stressors and regulatory requirements to understand total community burden; (3) deeper analysis of administrative and technical capacity constraints in rural and frontier communities, with specific attention to grant application and project management barriers; and (4) more detailed tracking of nature-based solutions maintenance requirements over multi-decade timeframes as these costs are often underestimated in initial project planning.

5.How we addressed gaps and challenges

The project team encountered several predictable risks and real-world constraints during stakeholder engagement. Where possible, the engagement strategy was adapted to address these challenges.

5.1 Participation challenges

As the project transitioned from broad scoping in Wave 1 to technical vetting in Wave 2, the team observed signs of survey fatigue. Wave 2 survey response rates (6 responses) were notably lower than

Wave 1 (29 responses) despite sustained meeting attendance. The team shifted resources away from passive outreach (surveys) toward active engagement (targeted interviews and follow-ups). Wave 2 included 33 targeted follow-ups compared to 8 in Wave 1. This ensured that meaningful input was incorporated and allowed the team to pursue specific data needs identified during sector meetings.

Initial participation showed strong representation from the Twin Cities Metro area, with lower participation from some Greater Minnesota regions. The team conducted targeted follow-up outreach to underrepresented counties and regions, particularly in Northwestern and Southwestern Minnesota. The team also partnered with regional planning organizations and Soil and Water Conservation Districts to reach practitioners in rural communities. Participation expanded to include 46 out of 87 counties across the two waves, though depth of engagement varied by region based on capacity and interest.

5.2 Representation gaps

5.2.1 Community advocacy groups

Initial outreach saw lower-than-desired participation from community-based organizations. To address this, the team conducted targeted outreach to these stakeholders. Feedback from these groups provided additional support for explicit consideration of social vulnerability as a factor in the decision-making guidance.

5.2.2 Outdoor recreation industry

Recognizing that publicly available data on the costs industry incurs to withstand the economic impacts of shorter winters is limited, the team contacted the Minnesota Ski Area Association. This discussion confirmed how the industry is responding to changing climatic conditions and best available data sources on snowmaking costs.

5.2.3 Tribal Nations

Tribal governments are sovereign nations with their own decision-making processes and priorities. Meaningful engagement requires adequate time for internal Tribal coordination, consultation, and review with timelines that often extend beyond those of typical state studies. The project team recognized that the compressed timeline of this study limited the depth of Tribal engagement. Meaningful Tribal engagement will require more time and resources, including supporting government-to-government consultation where appropriate.

The study engaged several individual Tribal staff members who participated in sectoral meetings and provided valuable input. However, the team recognized that individual staff participation does not constitute formal Tribal government input or represent official Tribal positions. The team ensured Tribal input was framed appropriately in documentation and noted feedback about where additional formal Tribal consultation would be beneficial for future work.

Government-to-government consultation requires different protocols and approaches than general stakeholder engagement. While MPCA has established Tribal liaison relationships, this study operated under a general stakeholder engagement framework rather than a formal consultation process. The team noted that future state climate work for processes with implications for Tribal treaty rights, subsistence resources, or Tribal lands, formal government-to-government consultation protocols are the most appropriate method for engaging Tribes. This includes direct communication with Tribal leadership, sufficient time for review and meaningful input, and respect for Tribal sovereignty in all engagement activities.

5.3 Communication challenges

5.3.1 Outreach limitations

The project team worked within the constraints of existing stakeholder databases and professional networks. While outreach was extensive, reaching all relevant stakeholders remained a challenge. The team addressed this by continuously expanding the stakeholder database through referrals from participants, partnering with regional organizations that had established networks, online research, and conducting targeted outreach between waves to address identified gaps.

5.3.2 Managing expectations

Some stakeholders expected the study to produce detailed project-level guidance or identify specific funding sources for local adaptation projects. The team clarified in each wave that the study would provide statewide cost estimates and decision-making frameworks to inform future policy and investment decisions but is not a project-level planning tool or funding program. The team also emphasized that stakeholder input would directly shape the analysis, providing a clear value proposition for continued engagement.

6. Conclusions and best practices

Stakeholder engagement was an iterative process that incorporated lessons learned between waves. Overall, stakeholders provided positive and invaluable feedback regarding the engagement process. This feedback was used to develop a list of general best practices, building on what was effective in this process, and to support future stakeholder engagement efforts in Minnesota.

Consider the Audience: Develop communication methods to be accessible to stakeholders with varying levels of background knowledge on the topic. Avoid using jargon in presentation materials. Provide materials with a range of levels of technicality to allow participants to engage at their level of expertise.

Provide Engagement Options: Provide multiple options for stakeholder engagement: public meetings, smaller focus groups, interviews, surveys. It is also important to keep in mind potential stakeholder commitments (e.g., work, family, etc.) when scheduling public meetings. Conduct multiple engagement activities at different times so that stakeholders can participate repeatedly throughout the project.

Work Through Community Connections: Connect with community-based organizations or leaders that have established trust with key stakeholder groups. Similarly, look to align engagement outreach with regularly scheduled meetings such as regional planning council meetings or other community meetings.

Maintain Flexibility and Adapt Approaches as Needed: Monitor participation patterns and adjust approaches based on what is working. For example, when survey fatigue emerged in Wave 2, shifting toward active interviews and targeted follow-up allowed the team to maintain quality engagement even as survey response rates declined.

Integrate Technical Expertise Directly in Stakeholder Discussions: Having technical team members participate directly in Sector meetings enabled immediate identification of useful data sources and real-time clarification of technical assumptions, significantly improving efficiency and ensuring stakeholder input was accurately captured.

Document Throughout the Process: Maintaining detailed notes, an engagement database, and an integration tracker throughout the engagement process ensured that stakeholder contributions were properly acknowledged and/or incorporated.

Manage Scope and Expectations: Be explicit about what the study can and cannot do. Clear communication about scope helped maintain appropriate expectations and ensured stakeholders understood the value of their participation.

Respect Capacity Constraints: Tribal staff, small community officials, and community organization leaders face significant competing demands. Providing multiple pathways to engage and pause when follow-up is not possible is essential to maintaining relationships and for supporting future collaboration.

Appendix B. Technical analysis details

Population projection used

Population projections are necessary for characterizing future impacts and adaptation needs quantified through the FrEDI tool to the end of the century throughout the State. We formulate a comprehensive population projection for Minnesota from 2010-2100 using available projections from the Minnesota State Demographic Center and other data sources to fill in an annual trajectory of population by county to the end of the century.[1]

Minnesota's state-specific annual projections are provided at the county-level by age, sex, and race for 2024 to 2055. State-level projections are provided for a longer period, from 2024 to 2075. Population projections for FrEDI need to cover 2010 to 2100. Therefore, we supplement the Minnesota county-level projections with the U.S. Census data and state-level Minnesota data to estimate a projected population across this time period. From 2010 to 2024, we interpolate between the county-level Census Decennial populations for 2010 and 2020, and then again interpolate between the 2020 population and the start of the Minnesota projections. From 2024 to 2055, we use the raw county-level projections from the state demographer. From 2056 to 2075 we first calculate the population percentage of each county relative to the total state population for using the county-level projections for the known years and then extrapolate to 2075. The population distribution percentages are then applied to the projected state-level population through 2075. Finally, from 2076 to 2100 we hold population for each county constant in absence of additional data as the Minnesota population projects a decline by the middle to late century.

Value of a Statistical Life (VSL)

Categories which estimate premature mortality impacts are monetized using the value of a statistical life (VSL). VSL refers to an individual's willingness to pay for avoiding in the future annual risk of their own premature death. Baseline estimates are projected out to the end of the 21st century using national GDP, individual average income projections, and a longitudinal income elasticity of 1.0 as shown in the following equation:

$$VSL_t = VSL_{base\ year} \times \left(\frac{GDPcap_t}{GDPcap_{base\ year}}\right)^{elasticity}$$

This methodology is consistent with best practices outlined in the U.S. EPA BenMAP-CE manual for estimating a valuation of avoided premature mortality as a result of improved health conditions from changes in environmental pollution.[2] Importantly, this value is not placing a dollar value on individual lives.

Analysis styles and data use definitions

The following section provides analysis details for each analysis in this study. A summary table per category identifies certain characteristics about each study, including a field noting "CMIP6 Data Used". This field notes the type of climate data used in the underlying model.

A number of analyses relied on CMIP6 CONUS data and modeled results via the Framework for Evaluating Damages and Impacts (FrEDI). FrEDI is a tool used and developed by the U.S.EPA and co-developed and maintained by Industrial Economics (IEc) to rapidly quantify physical and economic

[1] https://mn.gov/admin/assets/2024-Minnesota-Long-Term-Population-Projections-Methods_tcm36-626201.pdf
[2] OAR US EPA, "BenMAP-CE Manual and Appendices," Data and Tools, 2023, https://www.epa.gov/benmap/benmap-ce-manual-and-appendices

impacts of climate change across over 20 impact sectors relevant to Minnesota, and over 25 impact sectors overall in the tool as of August 2025. The tool is a peer-reviewed, open-source, reduced form model that draws on results from existing peer-reviewed literature and climate change models to estimate the relationship between future degrees of warming and the associated physical and economic impacts under any custom temperature trajectory and socioeconomics (e.g., population and GDP). Results cover a range of sectors, including, but not limited to, temperature-related mortality, air quality mortality and morbidity, road and rail infrastructure, electricity supply and demand, and recreation impacts. FrEDI rapidly projects annual climate-related damages across each sector, state, and population group through the end of the 21st century (and optionally through 2300). FrEDI uses a temperature projection for the contiguous United States (CONUS) across the same Shared Socioeconomic Pathways (SSPs) and Global Climate Models (GCMs) as used in the University of Minnesota Climate Adaptation Partnership's Climate Mapping Analysis Tool (known as MN CliMAT), so MN CliMAT can be used as an input to FrEDI. See Section 2.2 for more details.

FrEDI does not currently account for all ways in which Minnesota may be impacted by future climate change, so additional analyses for other related impacts, including those highlighted by stakeholders throughout the state, use outside peer-reviewed sources to calculate costs of inaction and adaptation. These non-FrEDI sectors typically use more spatially detailed climate data from MN CliMAT, which provides the best available science applicable to Minnesota at the county level. Table B1 summarizes the quantification approaches between FrEDI and Non-FrEDI costs of inaction.

Table B1. Summary of Cost of Inaction Quantification Approaches

FrEDI-Based Costs of Inaction	Non-FrEDI Costs of Inaction
Health and Wellbeing • **Heat.** Premature mortality*, student learning loss, lost labor participation • **Air Quality.** Climate-induced: ozone mortality, ED visits, ozone school days lost, ozone childhood asthma • **Vector-borne Disease.** Lyme disease morbidity **Transportation and Electricity Infrastructure** • **Transportation.** Road repair and user delay*, rail repair and user delay • **Electricity.** Transmission and distribution infrastructure damage and repair **Ecosystems** • **Terrestrial Ecosystems.** Timber carbon flux, timber production losses*, lost activity opportunities: other activity (bike, hunt, hike, run), snow sport, alpine skiing, cross-country skiing, snowmobiling • **Aquatic Ecosystems.** Lost activity opportunities: recreational fishing, water sports	**Health and Wellbeing** • **Heat.** Pediatric Emergency Department (ED) visits • **Air Quality.** Wildfire (PM2.5) mortality • **Vector-borne Disease.** West Nile Virus mortality and morbidity **Agriculture and Livestock** • **Crops.** Lost corn, soybean, and wheat yields • **Livestock.** Lost dairy milk **Transportation and Electricity Infrastructure** • **Transportation.** Culverts repair and user delay **Buildings** • **Flooding.** Pluvial and fluvial building damages • **Wind and Wildfire.** Structure damage, wildfire suppression **Ecosystems** • **Aquatic Ecosystems.** Water quality, harmful algal blooms

*Indicates costs where FrEDI outputs were adjusted for this analysis.

Health and Wellbeing

Public health is impacted by climate change through extreme temperature, extreme weather events, worsening air quality, increases in vector borne diseases, water scarcity, and reduced food production.[3] Additional vulnerabilities, including demographic characteristics, baseline health, socioeconomic and sociopolitical conditions, location, and available health services have a role in how climate hazards impact people. To understand the climate change-related costs for health and wellbeing in Minnesota, we calculate costs associated with inaction and costs associated with adaptation. We rely on publicly available federal, state, and county data, as well as information and data from peer-reviewed literature to understand how climate impacts health and wellbeing. We include premature mortality, pediatric emergency department visits, lost learning in students, and lost labor participation in the sum of the costs of inaction, acknowledging that this set of impacts is incomplete.

Absent any mitigation, remediation, or adaptation strategies, hazards associated with climate change will cause health impacts from exposure to heat. We estimate the costs of inaction in Table B2.

Heat

Costs of inaction

Exposure to extreme heat leads to cardiovascular, respiratory, and cerebrovascular diseases and hospitalizations, as well as heat stroke and death.

Table B2. Costs of Inaction Summary: Heat-related Health and Wellbeing Impacts

Impact	Cost Measure	CMIP6 Data Used	Spatial Scale	Underlying Study	Methods Table
Premature Mortality	Value of a statistical life (VSL)	Annual CONUS Temp (FrEDI*)	State	Mills et al., 2015[4]	Table B3
Pediatric Emergency Department (ED) Visits	Pediatric ED visit costs	Daily County Temp (CHR)	County	Bernstein et al., 2022[5]	Table B4
Lost Student Learning	Lost future earnings	Annual CONUS Temp (FrEDI)	County	Park et al., 2020[6] EPA, 2023[7]	Table B5
Lost Labor Participation	Lost wages	Annual CONUS Temp (FrEDI)	State	Neidell et al., 2021[8]	Table B6

*Adjusted FrEDI output

[3] American Public Health Association. (2025). How climate change effects your health. https://www.apha.org/news-and-media/multimedia/infographics/how-climate-change-affects-your-health

[4] Mills, D., Schwartz, J., Lee, M., Sarofim, M., Jones, R., Lawson, M., Duckworth, M., & Deck, L. (2015). Climate change impacts on extreme temperature mortality in select metropolitan areas in the United States. *Climatic Change*, *131*(1), 83–95. https://doi.org/10.1007/s10584-014-1154-8

[5] Bernstein, A. S., Sun, S., Weinberger, K. R., Spangler, K. R., Sheffield, P. E., & Wellenius, G. A. (2022). Warm season and emergency department visits to US children's hospitals. Environmental health perspectives, 130(1), 017001.

[6] R Jisung Park et al., "Heat and Learning," *American Economic Journal: Economic Policy* 12, no. 2 (2020): 306–39.

[7] U.S. Environmental Protection Agency, *Climate Change and Health and Well-Being in the United States*, EPA 430-R-23-001 (2023).

[8] Matthew Neidell et al., "Temperature and Work: Time Allocated to Work under Varying Climate and Labor Market Conditions," *PLOS ONE* 16, no. 8 (2021): e0254224, https://doi.org/10.1371/journal.pone.0254224.

Table B3. Heat-related Premature Mortality Methods

Step	Description	Key Data Sources and Models
1	One of the heat and premature morality estimates incorporated into FrEDI is based on Mills et al. (2015). This paper estimates city-specific mortality relationships for extremely hot and cold temperatures for 33 Metropolitan Statistical Areas (MSAs) in the United States, including the Minneapolis-St. Paul-Bloomington, MN-WI MSA, to develop mortality projections for historical and potential future climates. Because the underlying study estimates damage in Minneapolis but we are estimating results for the full state, first estimate the ratio of Minnesota to Minneapolis population projections in 2050, 2070, and 2090.	Mills et al., 2015[9] Bierwagen et al., 2010[10] EPA, 2025[11]
2	Run FrEDI with CMIP6 temperature projections and MN-specific population projections.	FrEDI[12] KNMI Climate Explorer, 2025[13] MN State Demographic Center, 2024a[14]
3	Apply ratio of Minnesota to Minneapolis population in future eras to MN-specific FrEDI run outputs. Only consider premature mortality related to extreme heat.	
4	Apply default FrEDI Value of Statistical Life (VSL) in 2050, 2070, and 2090 to time period physical results. VSL is adjusted for changes in FrEDI default GDP/capita and adjusted from 2015$ to 2024$. (2050 VSL: $23.1 million. 2070 VSL: $ 30.0 million. 2090 VSL: $38.0 million).	U.S Bureau of Economic Analysis (BEA), 2025[15]

[9] David Mills et al., "Climate Change Impacts on Extreme Temperature Mortality in Select Metropolitan Areas in the United States," *Climatic Change* 131, no. 1 (2015): 83–95, https://doi.org/10.1007/s10584-014-1154-8.
[10] Britta G. Bierwagen et al., "National Housing and Impervious Surface Scenarios for Integrated Climate Impact Assessments," *Proceedings of the National Academy of Sciences* 107, no. 49 (2010): 20887–92, https://doi.org/10.1073/pnas.1002096107.
[11] EPA. (2025). ICLUS Fourth National Climate Assessment (Version 2.1.1) [Dataset]. Data Catalog. https://catalog.data.gov/dataset/iclus-v2-1-1-population-projections13
[12] https://epa.gov/cira/about-fredi/index.html
[13] KNMI Climate Explorer. (2025). https://climexp.knmi.nl/start.cgi
[14] Minnesota State Demographic Center. (2024). *Long-Term Population Projections for Minnesota By Age and Sex* [Dataset]. https://mn.gov/admin/demography/data-by-topic/population-data/our-projections/
[15] U.S. Bureau of Economic Analysis, "Table 1.1.9. Implicit Price Deflators for Gross Domestic Product," 2025, https://apps.bea.gov/iTable/?ReqID=19&step=4&isuri=1&1921=flatfiles.

Table B4. Heat-related Emergency Department Visits among Children Methods

Step	Description	Key Data Sources and Models
1	Estimate baseline heat-related ED visits and incidence rates among children. a. Record baseline heat-related ED visits per 100,000 by age group 2018-2022. Relevant age groups include 0-4, 5-14, and 15-34. b. Record county populations by age 2018-2022 from the US Census. Relevant age groups include 0-4, 5-9, 10-14, 15-19, 20-24, 25-29, and 30-34. Combine age groups to match MN Department of Health data (0-4, 5-14, and 15-34). c. Multiply county populations by state-level incidence rates to estimate county level cases. d. Select relevant age groups to estimate child cases. Assume cases are evenly distributed across the 15-34 age group and multiply total age group cases by 0.2 (15-18 / 15-34) to estimate cases 15-18. e. Divide child cases by child population to estimate child incidence rates.	MN Department of Health, 2022[16] U.S Census Bureau, 2019[17] U.S Census Bureau, 2024[18]
2	Estimate the number of future Cooling Degree Days (CDDs) over 62°F in each county, year, SSP, and GCM from May to September. Calculate the number of additional CDDs over the observed period (1995-2014).	Liess et al. [19]
3	Adjust the statistical relationship from Bernstein et al. 2022 to estimate excess risk per CDD over 62°F, using the same process outlined in EPA (2023). Bernstein et al. 2022 reports a Relative Risk (RR) for heat-related pediatric Emergency Department (ED) visits of 1.83. Assuming RR is 1 at 62°F, from Figure S1 of Bernstein et al. 2022 we estimate the 95th percentile temperature is 95°F, where we assign an RR of 1.83. This temperature-risk relationship suggests for each CDD over 62°F the percent change in heat-related ED visits is ~2.5%.	Bernstein et al., 2022[20] EPA, 2023[21]
4	Estimate increased risk for each year/county/SSP/GCM by multiplying the number of CDDs by 2.5%.	
5	Estimate future population 0-18 by county and year. Use all-age county population projections from the Minnesota State Demographic Center. Isolate the child population using FrEDI's internal 0-18 scalar built on ICLUS projections.	Minnesota State Demographic Center, 2024a[22] EPA, 2025[23]

[16] MN Department of Health, "Heat-Related Illness ED Visits in Minnesota, by Age," Minnesota Public Health Data Access, 2022, https://data.web.health.state.mn.us/heat_ed#byage.
[17] U.S Census Bureau, "Annual County and Puerto Rico Municipio Resident Population Estimates by Selected Age Groups and Sex: April 1, 2010 to July 1, 2019 (CC-EST2019-AGESEX)," 2019, https://www.census.gov/data/tables/time-series/demo/popest/2010s-counties-detail.html.
[18] U.S Census Bureau, "Annual County and Puerto Rico Municipio Resident Population Estimates by Selected Age Groups and Sex: April 1, 2020 to July 1, 2024 (CC-EST2024-AGESEX)," 2024, https://www.census.gov/data/tables/time-series/demo/popest/2020s-counties-detail.html.
[19] S Leiss et al., "Fine-Scale Climate Projections over Minnesota for the 21st Century," version 1.1, September 2025, https://climate.umn.edu/MN-CliMAT.
[20] Aaron S. Bernstein et al., "Warm Season and Emergency Department Visits to U.S. Children's Hospitals," *Environmental Health Perspectives* 130, no. 1 (2022): 017001, https://doi.org/10.1289/EHP8083.
[21] U.S. Environmental Protection Agency, *Climate Change and Children's Health and Well-Being in the United States*.
[22] Minnesota State Demographic Center, "Long-Term Population Projections for Minnesota By Age and Sex," May 2024, https://mn.gov/admin/demography/data-by-topic/population-data/our-projections/.
[23] EPA, "ICLUS Fourth National Climate Assessment," version 2.1.1, Data Catalog, June 25, 2025, https://catalog.data.gov/dataset/iclus-v2-1-1-population-projections13.

Step	Description	Key Data Sources and Models
6	Estimate cases given future population and baseline risk. Divide baseline cases (Step 1) by baseline population (Step 1) to estimate baseline incidence rates. Multiply future populations (Step 5) by baseline incidence rates.	
7	Multiply change in risk (Step 4) by cases given future population and baseline risk (Step 6)	
8	Group years by time period and average across eras. 2040-2059: mid-century 2060-2079: late century 2080-2099: end-of-century	
9	Apply unit cost from Newgard et al. 2023. Unit cost reflects cost of acute care (facility and professional costs for emergency and inpatient services). Average across reported range. Adjust from 2022$ to 2024$.	Newgard et al., 2023[24] BEA, 2025[25]
10	Sum to state level and average across years in each time period.	

Table B5. Heat-related Learning Losses among Children Methods

Step	Description	Key Data Sources and Models
1	FrEDI incorporates projections of learning losses among high school students associated with increasing temperatures, which relies on a statistical relationship and baseline data from Park et al. (2020) and projections presented in EPA (2023). Park et al find that learning losses, proxied with PSAT scores, are reduced when schools and students' homes have A/C. The cost of learning losses is calculated using an estimate of lost future income from Chetty et al., applying the same approach in Park et al.	FrEDI[26] Park et al., 2020[27] EPA, 2023[28] Chetty et al., 2011[29]
2	Run FrEDI with CMIP6 temperature projections and MN-specific population projections. Adjust dollar year from 2015$ (FrEDI default) to 2024$. Total population projections from Minnesota were adjusted to the portion that is high school aged (14-17) using default Minnesota-specific scalars incorporated into FrEDI.	FrEDI[30] KNMI Climate Explorer, 2025[31] MN State Demographic Center, 2024a[32]
3	Sum to state level and average across years in each time period.	

[24] Craig D Newgard et al., "The Cost of Emergency Care for Children across Differing Levels of Emergency Department Pediatric Readiness," *Health Affairs Scholar* 1, no. 1 (2023): qxad015, https://doi.org/10.1093/haschl/qxad015.
[25] U.S. Bureau of Economic Analysis, "Table 1.1.9. Implicit Price Deflators for Gross Domestic Product."
[26] https://epa.gov/cira/about-fredi/index.html
[27] Park et al., "Heat and Learning."
[28] U.S. Environmental Protection Agency, *Climate Change and Health and Well-Being in the United States*.
[29] Raj Chetty et al., "How Does Your Kindergarten Classroom Affect Your Earnings? Evidence from Project Star *," *The Quarterly Journal of Economics* 126, no. 4 (2011): 1593–660, https://doi.org/10.1093/qje/qjr041.
[30] https://epa.gov/cira/about-fredi/index.html
[31] KNMI Climate Explorer. (2025). https://climexp.knmi.nl/start.cgi
[32] Minnesota State Demographic Center. (2024). *Long-Term Population Projections for Minnesota By Age and Sex* [Dataset]. https://mn.gov/admin/demography/data-by-topic/population-data/our-projections/

Table B6. Heat-related Lost Labor Participation Methods

Step	Description	Key Data Sources and Models
1	FrEDI contains projections of changes in labor participation associated with increasing temperatures using methods and findings from Neidell et al. (2021). The study relies on a statistical model to relate time spent working among weather exposed workings (defined as those in the agriculture, forestry, fishing, hunting; mining; construction; manufacturing; and transport and utilities sectors) with temperature. The authors find that in periods of economic growth, workers decrease their working time by 2.6 minutes for every degree above 90°F. The authors also project future labor participation per weather exposed worker under various climate models and value the lost time using wage rates from the affected sectors.	Neidell et al., 2021[33] U.S. Bureau of Labor Statistics, n.d.[34]
2	Run FrEDI with MN CliMAT temperature projections. Adjust dollar year from 2015$ (FrEDI default) to 2024$. Consistent with Neidell et al., population projections are not applied to this impact category because forecasting the number of workers in specific industries is too uncertain. Therefore the number of workers is held constant at 2010 levels and costs inflate in proportion to GDP per capita growth.	FrEDI[35] KNMI Climate Explorer, 2025[36] MN State Demographic Center, 2024a[37] BEA, 2025[38]
3	Sum to state level and average across years in each time period.	

Adaptation costs

Measures for adapting to the extreme heat and poor air quality that increases adverse human health effects are not necessarily one to one. That is, actions that allow for human adaptation to heat, thus avoiding premature mortality, also allow for human adaptation to heat to avoid emergency department visits, as well as respiratory, cardiovascular, and cerebrovascular disease. Table B7 provides a suite of adaptation measures and the costs affiliated with those measures. Within Table B7, we describe which costs are included in the action and the impacts addressed at measure-specific spatial scales.

Table B7. Costs of Adaptation Summary: Health and Wellbeing Adaptation Actions

Action	Cost Components	Impacts Addressed	Quantified Residual Risks	Spatial scale of Analysis	Methods Table
A/C in homes	Installation, energy costs	Heat morbidity, mortality, safety Lost learning	None	County	Table B8

[33] Neidell, M., Graff-Zivin, J., Sheahan, M., Willwerth, J., Fant, C., Sarofim, M., & Martinich, J. (2021). Temperature and work: Time allocated to work under varying climate and labor market conditions. PLoS ONE 16(8): e0254224. https://doi.org/10.1371/journal.pone.0254224

[34] U.S. Bureau of Labor Statistics. American Time Use Survey. Available at https://www.bls.gov/tus/datafiles-0318.htm

[35] https://epa.gov/cira/about-fredi/index.html

[36] KNMI Climate Explorer. (2025). https://climexp.knmi.nl/start.cgi

[37] Minnesota State Demographic Center. (2024). *Long-Term Population Projections for Minnesota By Age and Sex* [Dataset]. https://mn.gov/admin/demography/data-by-topic/population-data/our-projections/

[38] U.S. Bureau of Economic Analysis (BEA). (2025). *Table 1.1.9. Implicit Price Deflators for Gross Domestic Product* [Dataset]. https://apps.bea.gov/iTable/?ReqID=19&step=4&isuri=1&1921=flatfiles

Action	Cost Components	Impacts Addressed	Quantified Residual Risks	Spatial scale of Analysis	Methods Table
A/C in schools	Installation, O&M costs	Heat morbidity, mortality, safety Lost learning	None	County	Table B9
A/C in commercial and public buildings	Energy costs	Heat morbidity, mortality, safety	None	County	Table B10
Cooling centers	Operating costs	Heat morbidity, mortality, safety	None	Select cities	Table B11
Worker heat protections	Cost of worker breaks and water	Heat morbidity, mortality, safety Labor productivity	None	County	Table B12
Heat/climate resilience planning	Admin costs	Heat morbidity, mortality, safety	None	Select cities	Table B13
Urban tree maintenance	Water and labor costs	Tree mortality Heat morbidity, mortality, safety Energy demand	None	Select cities	Table B14
Urban ash tree replacement	Removal and replacement cost	Tree mortality Heat morbidity, mortality, safety Energy demand	None	Select cities	Table B15
Shade structures at playgrounds	Installation	Heat morbidity, mortality, safety Learning losses	None	State	Table B15

Note: We currently do not include any quantitative cost estimates for adaptation to the increasing risk of vector-borne disease and illness. Additional air quality adaptation actions (e.g., air filter installation and improved air quality forecasting) are forthcoming.

Table B8. A/C Installation in Homes Costing Methods

Step	Description	Key Data Sources and Models
1	Estimate when each county/SSP/GCM will surpass 15 days per year with temperatures over 80°F. This threshold drives A/C installation timing. Then, estimate the number of hours per year each county/SSP/GCM will experience temperatures over 65°F following the threshold established by the MN Department of Commerce (CEE 2020). Consider both total hours and additional hours relative to historical observations 1995-2014. Total hours will be used to estimate operating costs for newly installed A/C units. Additional hours will be used to estimate operating costs over the historical baseline for already installed units.	Liess et al.[39] Number of hours threshold: Center for Energy and Environment (CEE), 2020[40] Number of days threshold: See Table 9 for details.
2	Collect the most recent observed home A/C penetration in the Minneapolis-St. Paul (MSP) and Duluth Metropolitan Areas. Distinguish between homes with window units, central A/C systems, and both window and central A/C systems.	Duluth: U.S Census Bureau, 2013a[41] MSP: U.S Census Bureau, 2021[42]
3	Estimate the number of window units used by each household with window units installed. Average across all available AHS data for MSP and Duluth. We assume that households with window units operate the same number of window units each year.	U.S Census Bureau, 2013b[43]
4	Multiply observed survey A/C penetration from the AHS by the number of households by county in Minnesota to estimate number of households by county with window units, central A/C systems, and both window and central A/C systems.	Minnesota State Demographic Center, 2024b[44]

[39] Leiss et al., "Fine-Scale Climate Projections over Minnesota for the 21st Century."
[40] Center for Energy and Environment, *Reconsidering Cooling Loads in Minnesota*, Contract #138722 (Minnesota Department of Commerce, Division of Energy Resources, 2020), https://mn.gov/commerce-stat/pdfs/card_2020_cee_cooling-loads.pdf.
[41] U.S Census Bureau, "AHS 2013 National Public Use File," American Housing Survey (AHS), 2013, https://www.census.gov/programs-surveys/ahs/data/2013/ahs-2013-public-use-file--puf-/ahs-2013-national-public-use-file--puf-.html.
[42] U.S Census Bureau, "AHS 2021 Metropolitan Public Use File (PUF)," American Housing Survey (AHS), 2021, https://www.census.gov/programs-surveys/ahs/data/2021/ahs-2021-public-use-file--puf-/2021-ahs-metropolitan-puf-microdata.html.
[43] U.S Census Bureau, "AHS National Public Use Files 1995-2013," 2013, https://www.census.gov/programs-surveys/ahs/data.html?text-list-0ff840ba34%3Atab=all#text-list-0ff840ba34.
[44] Minnesota State Demographic Center, "PopFinder For Minnesota, Counties, & Regions," 2024, https://mn.gov/admin/demography/data-by-topic/population-data/our-estimates/pop-finder1.jsp.

Step	Description	Key Data Sources and Models
5	Designate counties with greater than 1,000 persons per square mile as "urban" counties, and those with less than 1,000 persons per square mile as "rural" counties" following the threshold defined by the US Census. Assign observed MSP A/C penetration to "urban" counties and observed Duluth A/C penetration to "rural" counties.	Ratcliffe et al., 2016[45]
7	Assume, in the first year each county eclipses 15 days per year with temperatures over 80°F, all households in the county currently without A/C will adopt A/C. - In the "conventional technologies" scenario, the observed distribution of window, central, and combination households remains constant over time. - In the "energy efficient technologies" scenario, all new adoptions are for entry-level variable speed air source heat pumps (as defined by the MN Department of Commerce).	Center for Energy and Environment (CEE), 2022[46]
8	Households with window units may operate multiple simultaneously. Estimate the total number of A/C units in operation in each year. Multiply the number of households with window units by the number of window units necessary to mimic the cooling capacity of a central A/C unit or heat pump. We estimate the number of total operating units, rather than the number of households operating units.	
9	Estimate the number of future A/C operating hours. Future operating hours include increased operation of existing units over baseline operation, and all operating hours for newly installed units.	

[45] Michael Ratcliffe et al., *Defining Rural at the U.S. Census Bureau*, ACSGEO-1 (U.S. Census Bureau, 2016), https://www2.census.gov/geo/pdfs/reference/ua/Defining_Rural.pdf.
[46] Center for Energy and Environment, *Investigation of Air Source Heat Pumps as a Replacement of Central Air Conditioning*, Contract 187376 (Minnesota Department of Commerce, Division of Energy Resources, 2022), https://mn.gov/commerce-stat/pdfs/187376_CEE_HP-for-AC_Report_Final%20Secure.pdf.

Step	Description	Key Data Sources and Models
10	Estimate initial investment of new A/C system specific to each population density group. Annualize costs across system-specific lifespans from the DOE. Adjust to 2024$. Multiply by new A/C units to estimate annualized initial investment by A/C type and scenario.	Initial Investment: Window and Central: Homewyse, 2025[47]; Modernize, 2025[48]; Joe Sexton, 2023[49]; Hansen, S, 2023[50] Heat Pump: CEE, 2022[51] Lifespan: Window: DOE, 2016[52] Central and Heat Pump: DOE, 2017[53] BEA, 2025[54]
11	Estimate costs per operating hour by unit type (window, central, and heat pump). Necessary information includes cost per kilowatt-hour (kWh), nameplate capacity, and Energy Efficiency Ratio (SEER/CEER). Multiply cost per operating hour by number of future A/C operating hours to estimate operating costs per A/C type and scenario.	Minnesota cost per kWh: CEE, 2022[55]; U.S. Energy Information Administration (EIA), 2020[56]; CEE, 2020[57] Nameplate Capacity: Window: Minnesota Department of Commerce, Division of Energy Resources, 2023[58] Central and Heat Pump: CEE, 2022[59] EER: Window: Minnesota Department of Commerce, Division of Energy Resources, 2023[60] Central and Heat Pump: CEE, 2022 [61]

[47] Homewyse, "Cost to Install Air Conditioning - 2025 Cost Calculator (Customizable)," 2025, https://www.homewyse.com/services/cost_to_install_air_conditioning.html#google_vignette.
[48] Modernize, *HVAC Costs: 2025 HVAC Replacement Cost Calculator by Brand & Size*, 2025, https://modernize.com/hvac/cost-calculator.
[49] Joe Sexton, "Cost to Install Air Conditioning in 2025 - Inch Calculator," Inch Calculator, 2023, https://www.inchcalculator.com/cost-to-install-air-conditioning/.
[50] Steven Hansen, *Packaged HVAC Cost Calculator | New or Replacement Estimates*, December 6, 2023, https://www.costimates.com/calculators/packaged-hvac-system/.
[51] Center for Energy and Environment, *Investigation of Air Source Heat Pumps as a Replacement of Central Air Conditioning*.
[52] U.S Department of Energy (DOE), *NOTICE OF PROPOSED RULEMAKING TECHNICAL SUPPORT DOCUMENT: ENERGY EFFICIENCY PROGRAM FOR CONSUMER PRODUCTS AND COMMERCIAL AND INDUSTRIAL EQUIPMENT: PORTABLE AIR CONDITIONERS*, Appliances and Commercial Equipment Standards (Office of Energy Efficiency and Renewable Energy, 2016), 339, https://www.regulations.gov/document/EERE-2013-BT-STD-0033-0018.
[53] U.S Department of Energy (DOE), *Energy Conservation Program: Energy Conservation Standards for Residential Central Air Conditioners and Heat Pumps*, Direct final rule (Office of Energy Efficiency and Renewable Energy, 2017), 339, https://www.federalregister.gov/documents/2017/01/06/2016-29992/energy-conservation-program-energy-conservation-standards-for-residential-central-air-conditioners.
[54] U.S. Bureau of Economic Analysis, "Table 1.1.9. Implicit Price Deflators for Gross Domestic Product."
[55] Center for Energy and Environment, *Investigation of Air Source Heat Pumps as a Replacement of Central Air Conditioning*.
[56] U.S. Energy Information Administration, "Residential Energy Consumption Survey (RECS) Mircodata," EIA, 2020, https://www.eia.gov/consumption/residential/data/2020/index.php?view=microdata.
[57] Center for Energy and Environment, *Reconsidering Cooling Loads in Minnesota*.
[58] Minnesota Department of Commerce, Division of Energy Resources, *State of Minnesota Technical Reference Manual for Energy Conservation Improvement Programs*, 4.0 (MN Commerce Department, 2023), https://mn.gov/commerce-stat/trm/releases/4.0.pdf.
[59] Center for Energy and Environment, *Investigation of Air Source Heat Pumps as a Replacement of Central Air Conditioning*.
[60] Minnesota Department of Commerce, Division of Energy Resources, *State of Minnesota Technical Reference Manual for Energy Conservation Improvement Programs*.
[61] Center for Energy and Environment, *Investigation of Air Source Heat Pumps as a Replacement of Central Air Conditioning*.

Step	Description	Key Data Sources and Models
12	Heat pumps use the same infrastructure to cool and heat homes, while homes with central or window A/C systems require separate heating infrastructure. According to the Minnesota Department of Commerce, heating a household with a heat pump is 26 to 56 percent less expensive than a traditional furnace powered by natural gas, propane, or fuel. Given that the analysis models an entry-level heat pump, we applied the 26 percent to estimate baseline annual household heating savings associated with heat pump installation.	CEE and ACEEE, 2017[62] U.S Department of Health and Human Services, 2022[63]
13	Using the number of projected future heat pumps installed under the "energy efficient technologies" scenario from Step 7, estimate the number of households that will install heat pumps and rely less on traditional technologies for heating.	
14	Assume households begin heating homes when temperatures drop below 65°F (the inverse of the cooling assumption from Step 1). Estimate the number of hours a household will require heating during the baseline period and in the future by county, SSP, and GCM.	Number of heating hours threshold: Center for Energy and Environment (CEE), 2020[64] Leiss et al. [65]
15	Estimate the percent change in operational hours from the baseline to future periods.	
16	Multiply the percent change in operational hours by the number of future heat pumps and baseline annual heating savings to estimate future annual heating savings by county, SSP, and GCM.	
12	Combine additional operating costs for current A/C infrastructure with future investment, A/C operating costs, and heating savings to estimate costs in the "conventional technologies" and "energy efficient technologies" scenarios by county, year, SSP, and GCM.	
13	Sum to state level and average across years in each time period.	

[62] Center for Energy and Environment (CEE) and American Council for an Energy Efficient Economy (ACEEE), *Cold Climate Air Source Heat Pump*, Conservation Applied Research and Development (CARD) FINAL Report (Minnesota Department of Commerce, Division of Energy Resources, 2017), https://mn.gov/commerce-stat/pdfs/card-air-source-heat-pump.pdf.
[63] U.S Department of Health and Human Services, *Projected Impact of Increased Energy Costs during FY 2023 - Minnesota*, LIHEAP Households by Main Heating Fuel Type (Low Income Household Energy Assistance Program, 2022), https://liheappm.acf.gov/sites/default/files/private/priceprofiles/2023/FY23-ProjectedEnergyExpenditures-MN.pdf.
[64] Center for Energy and Environment, *Reconsidering Cooling Loads in Minnesota*, Contract #138722 (Minnesota Department of Commerce, Division of Energy Resources, 2020), https://mn.gov/commerce-stat/pdfs/card_2020_cee_cooling-loads.pdf.
[65] Leiss et al., "Fine-Scale Climate Projections over Minnesota for the 21st Century."

Table B9. A/C Installation in Schools Costing Methods

Step	Description	Key Data Sources and Models
1	Estimate current school A/C coverage across counties by extracting data from Figure 6 (panel a) of Park et al. 2020, which represents the fraction of classrooms lacking A/C, as reported by counselors. The inverse of this fraction is used as the percent of the schools within the county that have A/C already installed.	Park et al., 2020[66]
2	Match county level baseline school A/C coverage from Park et al. 2020 with district level future projections of A/C coverage from LeRoy et al. 2021. LeRoy et al. provides state- and district- level adaptation costs of installing, and operating and maintaining school A/C units, including energy costs within a 30-year period around two eras (2025 and 2055) relative to a baseline centered around 1980. This matching was accomplished using the county listed in the National Center for Education Statistics (NCES) database and NCES District ID from LeRoy et al 2021.	LeRoy et al., 2021[67]
3	Determine threshold at which schools "should" adopt A/C. This threshold was determined by reviewing data from Step 1 alongside the number of school days over 80°F in 2025 from LeRoy et al. 2021. We identify that appropriately 75% of schools have A/C installed when there are 15 days during the school year above 80°F. We also note that 80°F is the threshold at which A/C installation reduces mortality risk (Barreca et al. 2015) and also noted as a threshold at which learning losses are typically identified in the literature (USLA Luskin 2025). Therefore, this analysis demonstrates costs assuming schools "should" have A/C installed to limit both learning losses and adverse health impacts once there are 15 days above 80°F in a school year.	Barreca et al., 2015[68] "Rising Temperatures", 2025[69]

[66] Park et al., "Heat and Learning."
[67] Sverre LeRoy et al., *Hotter Days, Higher Costs: The Cooling Crisis in America's Classrooms* (Center for Climate Integrity, 2021), 62, https://coolingcrisis.org/uploads/media/HotterDaysHigherCosts-CCI-September2021.pdf.
[68] Alan Barreca et al., "Adapting to Climate Change: The Remarkable Decline in the US Temperature-Mortality Relationship over the Twentieth Century," *Journal of Political Economy* 124, no. 1 (2016): 105–59, https://doi.org/10.1086/684582.
[69] "Rising Temperatures Cause Students to Underperform Across the World," *UCLA Luskin*, August 4, 2025, https://luskin.ucla.edu/rising-temperatures-cause-students-to-underperform-across-the-world.

Step	Description	Key Data Sources and Models
4	Estimate A/C installation and annual O&M costs (2024$) per school under two scenarios: 1. *Conventional A/C systems:* Estimate A/C installation and annual O&M costs from LeRoy et al 2021. a. Installation: LeRoy et al. provides an average cost per square foot for elementary, middle, and high schools ($32, $32, $35 respectively). The average cost per square foot is then applied to the national average in school size (~143,000 sq ft) and scaled to 2024$. We estimate installation costs per school to be $5,407,051 (2024$). Installation costs assume a useful life of approximately 25 years before the unit at the school would likely need to be replaced. These costs are therefore incurred through the end of the century. b. O&M: Derived from an annual average all schools in the Midwest for both the year 2025 and 2055. A linear slope using the number of days above 80°F in both 2025 and 2055 for Minnesota provides an average O&M cost per-school per day over 80°F. We estimate daily costs of $1,245 (2024$) for each school day over 80°F. For schools which had A/C installed in the baseline, we estimate the increased operation of existing units over baseline operation. 2. *Geothermal cooling system:* Estimate installation costs from St. Paul school (source estimates in 2022$, then converted to 2024$): a. Installation: We calculate a cost per sq ft for installing a geothermal system ($86.24) using data from a 218,000 sq ft school in St. Paul which installed a system costing $18.8 million in 2022. The average cost per square foot is then applied to the same national average in school size used for the conventional A/C systems (~143,000) and scaled to 2024$. We estimate installation costs per school to be $13,105,851 (2024$). Installation costs assume a useful life of approximately 37 years before the unit would likely need to be replaced. These costs are therefore incurred through the end of the century. b. O&M: Geothermal systems significantly lower schools' annual heating and cooling energy costs. Lacking data on the annual O&M costs, we calculate the average heat savings from a subset of schools who implemented a geothermal system.	National average school size: Abramson, 2015[70] St. Paul school geothermal project: Jossi, 2022[71] Useful life: United States Department of Energy, 2024[72] United States Department of Energy, n.d.[73] Geothermal energy use: United States Department of Energy, n.d.[74]

[70] Paul Abramson, *20th ANNUAL SCHOOL CONSTRUCTION REPORT* (School Planning and Management, 2015).
[71] Frank Jossi Network Energy News, "St. Paul School Is Latest in Minnesota to Conclude Geothermal Is 'the Way to Go' • Minnesota Reformer," *Minnesota Reformer*, June 22, 2022, https://minnesotareformer.com/2022/06/22/st-paul-school-is-latest-in-minnesota-to-conclude-geothermal-is-the-way-to-go/.
[72] Department of Energy (DOE), *Energy Conservation Program: Energy Conservation Standards for Air-Cooled Commercial Package Air Conditioners and Heat Pumps*, 2024.
[73] United States Department of Energy (DOE), "Heat Pump Systems," Energy.Gov, accessed November 25, 2025, https://www.energy.gov/energysaver/heat-pump-systems.
Department of Energy (DOE), "Geothermal Heat Pumps," accessed November 23, 2025, https://www.energy.gov/energysaver/geothermal-heat-pumps.

Step	Description	Key Data Sources and Models
5	Estimate the number of days above 80°F for each county/SSP/GCM. Identify the year at which each county/SSP/GCM reaches at least 15 days above 80°F during the 2018-2019 school year (defined as September 4th to June 6th using data provided by the authors of LeRoy et al. 2021). This is defined by the school year of the most populous school district in the state (Anoka-Hennepin school district).	Leiss et al., [75] LeRoy et al., 2021[76]
6	Apply installation costs once a country reaches at least 15 days above 80°F during the school year. - For schools that did not have A/C installed in the baseline, assume installation starting the year that crosses the threshold. Costs are evenly distributed across the subsequent 30-year period. - For schools that had A/C installed in the baseline, no future installation costs.	
7	Apply O&M costs per day and per school once a country reaches at least 15 days above 80°F during the school year. - For schools that did not have A/C installed in the baseline, O&M costs are applied per school with A/C using the number of days above 80°F during the school year. - For schools that had A/C installed in the baseline, we apply O&M costs even if the county has not passed the threshold. For example, if 35 percent of the schools in the county have already adopted A/C, but the county is not expected to reach 15 days above 80°F until 2050, O&M costs will only be applied to the 35 percent of schools assumed to have already adopted until 2050. The O&M costs for these units take the number of days above 80°F in the current year and subtract the average number of days above 80°F in the baseline period to calculate the annual O&M costs above what was being done in the historical period.	
8	Calculate an annual heat savings per school using publicly available historical data from three St. Paul area public schools that transitioned from natural gas to geothermal energy.	Jossi, 2024[77]
9	Using the number of projected future installed energy efficient systems from step 6, apply the annual average heat savings per school to the number of schools per county expected to install geothermal systems in the projected time periods.	
10	Assume that schools begin heating their buildings when temperatures drop below 65°F (see assumptions made in step 14 of household costing methods in Table 8). Calculate the average hourly heating use during the baseline period and in the future by county, SSP, and GCM.	
11	Estimate the percentage change in operational hours from the baseline to future periods.	
12	Multiply the percent change in operational hours by the number of future geothermal systems and baseline annual heating savings to estimate future annual heating savings by county, SSP, and GCM	

[75] Leiss et al., "Fine-Scale Climate Projections over Minnesota for the 21st Century."
[76] LeRoy et al., *Hotter Days, Higher Costs: The Cooling Crisis in America's Classrooms*.
[77] Frank Jossi, "Geothermal Cuts Emissions and Costs at These Minnesota Public Schools," Canary Media, March 28, 2024, https://www.canarymedia.com/articles/geothermal/geothermal-cuts-emissions-and-costs-at-these-minnesota-public-schools.

Step	Description	Key Data Sources and Models
13	Calculate annual installation and O&M costs for each county/SSP/GCM for both the convention and geothermal scenarios. Sum to state level and average across years in each time period.	

Table B10. A/C Installation in Other Buildings (i.e., Non-School Buildings) Costing Methods

Step	Description	Key Data Sources and Models
1	Estimate the number of hours per year each county/SSP/GCM will experience temperatures over 65°F following the threshold established by the MN Department of Commerce. Estimate when each county/SSP/GCM will eclipse 15 days per year with temperatures over 80°F.	Leiss et al. [78] Number of hours threshold: CEE, 2020[79] Number of days threshold: See discussion in Table 9.
2	Estimate the number of additional hours per year each county/SSP/GCM will experience temperatures over 65°F relative to historical observations 1995-2014.	Leiss et al. [80]
3	Collect the most recent observed commercial/public A/C penetration in the West North Central Census Division.	U.S Energy Information Administration (EIA), 2018[81]
4	Identify the percentage of buildings that currently use heat pumps for cooling from EIA data. Assume all other buildings use central A/C systems.	EIA, 2018[82]
5	Using an inventory of the number of commercial buildings by county, estimate the number of public buildings given the ratio of commercial to public buildings in CBECS 2018.	U.S. Department of Energy National Renewable Energy Laboratory (NREL), 2024[83] EIA, 2018[84]
6	Designate counties with greater than 1,000 persons per square mile as "urban" counties, and those with less than 1,000 persons per square mile as "rural" counties" as defined by the U.S Census Bureau.	Ratcliffe et al., 2016[85]
7	Estimate the total number of A/C units in operation by multiplying A/C penetration in the West North Central Census Division by the inventory of commercial and estimated public buildings in each county. According to representatives of Hennepin County, public buildings that serve people already have complete A/C coverage, and there are no plans to add additional A/C. Therefore, we assume public and commercial buildings throughout the state are at maximum penetration and will not install new units in the future.	Communication with representatives of Hennepin County

[78] Leiss et al., "Fine-Scale Climate Projections over Minnesota for the 21st Century."
[79] Center for Energy and Environment, *Reconsidering Cooling Loads in Minnesota*.
[80] Leiss et al., "Fine-Scale Climate Projections over Minnesota for the 21st Century."
[81] U.S Energy Information Administration, "Commercial Buildings Energy Consumption Survey (CBECS)," EIA, 2018, https://www.eia.gov/consumption/commercial/data/2018/.
[82] U.S Energy Information Administration, "Commercial Buildings Energy Consumption Survey (CBECS)."
[83] U.S. Department of Energy National Renewable Energy Laboratory, "City and County Commercial Building Inventories," Data Catalog, 2024, https://catalog.data.gov/dataset/city-and-county-commercial-building-inventories-010d2.
[84] U.S Energy Information Administration, "Commercial Buildings Energy Consumption Survey (CBECS)."
[85] Ratcliffe et al., *Defining Rural at the U.S. Census Bureau*.

Step	Description	Key Data Sources and Models
8	Estimate future A/C operating hours from increased operation of existing units over baseline operation based on the number of additional hours per day over 65°F (see Step 2). Public and commercial buildings are assumed to not make future A/C investments driven by changes in temperature so only additional operating hours of current units are considered.	
9	Estimate costs per operating hour by unit type (central and heat pump). Necessary information includes cost per kilowatt-hour (kWh), nameplate capacity, and Seasonal Energy Efficiency Ratio (SEER). Multiply cost per operating hour by number of future A/C operating hours to estimate operating costs per A/C type.	Minnesota cost per kWh: CEE, 2022[86] EIA, 2020[87] CEE, 2020[88] Nameplate Capacity: CEE, 2022[89] SEER: CEE, 2022[90]
10	Sum to state level and average across years in each time period.	

Table B11. Cooling Center Costing Methods

Step	Description	Key Data Sources and Models
1	We estimate operating costs of cooling centers using methods from Power a Clean Future (PCFO) Ohio. PCFO estimated costs of additional operating hours for current cooling centers and total operating hours for centers that would provide coverage to all residents in nine Ohio cities. To do so, PCFO heavily relies on a paper from Carnegie Mellon University detailing cooling center need in Pittsburgh, PA. They estimate cooling centers should be available when the heat index, a measure of temperature and humidity, eclipses 90°F. Given daily temperature max and relative humidity by county, GCM, SSP, and year, estimate heat index using function from the National Oceanic and Atmospheric Administration (NOAA). Count the number of days per county, GCM, SSP and year with a heat index over 90°F.	Power a Clean Future Ohio (PCFO), 2022[91] NOAA, n.d.[92] Bradford et al., 2015[93]

[86] Center for Energy and Environment, *Investigation of Air Source Heat Pumps as a Replacement of Central Air Conditioning*.
[87] U.S. Energy Information Administration, "Residential Energy Consumption Survey (RECS) Mircodata."
[88] Center for Energy and Environment, *Reconsidering Cooling Loads in Minnesota*.
[89] Center for Energy and Environment, *Investigation of Air Source Heat Pumps as a Replacement of Central Air Conditioning*.
[90] Center for Energy and Environment, *Investigation of Air Source Heat Pumps as a Replacement of Central Air Conditioning*.
[91] Power a Clean Future Ohio (PCFO), *The Bill Is Coming Due Calculating the Financial Cost of Climate Change to Ohio's Local Governments* (Ohio Environmental Council, 2022), https://static1.squarespace.com/static/602c33437336ed7a5ac5b3e6/t/62d5af4852f5bb7fd5abc700/1658239260260/OH-MunicipalCostsOfClimateChange.pdf.
[92] NOAA, "What Is the Heat Index?," NOAA's National Weather Service, accessed November 20, 2025, https://www.weather.gov/ama/heatindex.
[93] Kathryn Bradford et al., "A Heat Vulnerability Index and Adaptation Solutions for Pittsburgh, Pennsylvania," *Environmental Science & Technology* 49, no. 19 (2015): 11303–11, https://doi.org/10.1021/acs.est.5b03127.

Step	Description	Key Data Sources and Models
2	Subtract the average number of days with a heat index over 90°F from the observed baseline (1995-2014) to estimate additional days over the threshold in the projected period (2040-2099). Additional days over baseline will be used to estimate operating costs for current cooling centers. Total days exceeding the heat index threshold will be used to estimate operating costs for new cooling centers.	
3	Following methods from PFCO (2022), assign county-level temperature data to cities in Minnesota with a population of at least 60,000. If a city is located in multiple counties, then average total and additional days over the heat index threshold across counties.	Power a Clean Future Ohio (PCFO), 2022[94]
4	Estimate the number of *current* cooling centers per city. Using methods from PCFO (2022), use heat-related death rates as a proxy for heat risk and population. Given baseline (2010) Minneapolis heat-related mortality reported in Mills et al. 2015 (1.81 per 100,000), estimate heat-related mortality in Minnesota cities assuming per capita heat-related mortality is constant across the state. Take the ratio of estimated baseline heat-related deaths in each Minnesota city to baseline (2010) Pittsburgh heat-related mortality reported in Mills et al. 2015 (3.28 per 100,000) and multiply by the number of cooling centers in Pittsburgh (19). Adjust for geographic size using the ratio of square miles in each Minnesota city to the square miles of Pittsburgh to estimate the number of current cooling centers in each Minnesota city. We check the reasonableness of the current cooling center estimate. According to research from the University of Minnesota, residents frequently utilize libraries as cooling centers during days of extreme temperature. The number of libraries in the selected cities (46) compares well with the number of estimated cooling centers following methodology from PCFO 2022 (52).	PCFO, 2022[95] Mills et al., 2015[96] Bradford et al., 2015[97] U.S Census Bureau, 2021a[98] U.S Census Bureau, 2021b[99] Ren, 2025[100] Institute of Museum and Library Services, 2023[101]
5	Estimate the number of cooling centers *needed* to provide maximum coverage to Minnesota city residents. Multiply estimated current cooling centers in each Minnesota city by the ratio of new cooling centers needed in Pittsburgh to current cooling centers (127/19).	PCFO, 2022[102]
6	Subtract the number of cooling centers needed for full coverage (Step 5) from the number of estimated current cooling centers (Step 4) to find the number of additional cooling centers needed.	

[94] Power a Clean Future Ohio (PCFO), *The Bill Is Coming Due Calculating the Financial Cost of Climate Change to Ohio's Local Governments*.
[95] Power a Clean Future Ohio (PCFO), *The Bill Is Coming Due Calculating the Financial Cost of Climate Change to Ohio's Local Governments*.
[96] Mills et al., "Climate Change Impacts on Extreme Temperature Mortality in Select Metropolitan Areas in the United States."
[97] Bradford et al., "A Heat Vulnerability Index and Adaptation Solutions for Pittsburgh, Pennsylvania."
[98] U.S Census Bureau, "American Community Survey 5-Year B01003_001," 2021, https://www.census.gov/data/developers/data-sets/acs-5year.2021.html#list-tab-1806015614.
[99] U.S Census Bureau, "2021 Urban Area TIGER/Line Shapefile," 2021, https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.2021.html#list-tab-790442341.
[100] Lifeng Ren, "Validating the Agent-Based Model for Cooling Options Utilization During Extreme Heat Events in Hennepin County," Department of Applied Economics, University of Minnesota, 2025, https://hdl.handle.net/11299/276873.
[101] Institute of Museum and Library Services, "Public Libraries Survey (PLS)," 2023, https://www.imls.gov/research-evaluation/surveys/public-libraries-survey-pls.
[102] Power a Clean Future Ohio (PCFO), *The Bill Is Coming Due Calculating the Financial Cost of Climate Change to Ohio's Local Governments*.

Step	Description	Key Data Sources and Models
7	Following methods from PCFO 2022, adjust the estimated cost of operating a cooling center in Los Angeles ($2,000) for one day with the change in front desk receptionist salary from Los Angeles to each relevant metro area in Minnesota. Adjust costs to 2024$.	PCFO, 2022[103] Reyes, 2020[104] U.S Bureau of Labor Statistics (BLS), 2024[105] BEA, 2025[106]
8	Multiply the estimated number of current cooling centers by the projected additional number of days over 90°F and the daily operational cost. Multiply the number of additional cooling centers needed by the projected total number of days over 90°F and the daily operational cost.	
9	Sum to state level and average across years in each time period.	

Table B12. Worker Heat Protection Costing Methods

Step	Description	Key Data Sources and Models
1	Employers may choose to keep workers safe on high-heat days through multiple mechanisms. We rely on the mandatory break and water access requirements described in a proposed rule from the U.S. Occupational Safety and Health Administration (OSHA) to estimate the cost employers may face. This proposed rule has specific requirements on days between 80-90°F ("initial heat trigger") and over 90°F ("high heat trigger").	OSHA, 2024[107]
2	Calculate the number of future days that will require the initial and high heat trigger responses, by year, county, SSP, and GCM in the future. Because workers typically work 5 days a week, we multiply the number of total days per year that fall into these categories by 5/7 to approximate the number of days per year that will result in costs to employers.	Leiss et al. [108]

[103] Power a Clean Future Ohio (PCFO), *The Bill Is Coming Due Calculating the Financial Cost of Climate Change to Ohio's Local Governments*.
[104] Emily Reyes, "Few Used L.A. Cooling Centers during Record Heat Wave - Los Angeles Times," Las Angeles Times, 2020, https://www.latimes.com/california/story/2020-09-19/la-deadly-heat-empty-cooling-centers.
[105] U.S Bureau of Labor Statistics, "Occupational Employment and Wage Statistics Query System: Occupation: Receptionists and Information Clerks (SOC Code 43-4171)," 2024, https://data.bls.gov/oes/#/occGeo/One%20occupation%20for%20multiple%20geographical%20areas.
[106] U.S. Bureau of Economic Analysis, "Table 1.1.9. Implicit Price Deflators for Gross Domestic Product."
[107] U.S. Department of Labor, Occupational Safety and Health Administration (OSHA). Heat Injury and Illness Prevention in Outdoor and Indoor Work Settings [Notice of proposed rulemaking; Federal Register Document No. 2024-14824]. *Federal Register*, *89*, 70698. https://www.federalregister.gov/documents/2024/08/30/2024-14824/heat-injury-and-illness-prevention-in-outdoor-and-indoor-work-settings
[108] Leiss et al., "Fine-Scale Climate Projections over Minnesota for the 21st Century."

Step	Description	Key Data Sources and Models
3	Calculate employer costs associated with mandatory breaks per worker. Calculate the per worker time devoted to mandatory breaks by future year, county, SSP, and GCM. - Initial heat trigger: 10-minute break per worker per day (0.167 hours) - High heat trigger: 15-minute break every two hours, equivalent to 45 minutes assuming an 8-hour shift (0.75 hours) Value this break time using MN median wage rates (for 2024) for Farming Fishing, and Forestry; Construction and Extraction; Production; Transportation and Material Moving. Take and apply the average across the four occupation categories.	BLS, 2024[109]
4	Calculate employer costs associated with providing sufficient water per worker. In line with OSHA, we assume employers will provide workers with one quart of water per hour, or 2 gallons of water per day on any days that fall into the initial or high heat triggers. We provide a cost to this water using 2024 billing rates for water from Minneapolis which equates to $0.00503 per gallon.	Minneapolis, 2024[110]
5	Calculate the number of workers in heat exposed industries by county using county-level establishments by sector from County Business Patterns (CBP) (2023) and the USDA Agricultural Census (2022). We select the same industries covered in Neidell et al. 2021 and apply per worker costs to all heat exposed workers.	U.S Census Bureau, 2023[111] USDA, 2022[112] Neidell et al., 2021[113]
6	Combine costs to estimate total costs by county, year, SSP, and GCM.	
7	Sum to state level and average across years in each time period.	

Table B13. Heat/Resilience Planning Costing Methods

Step	Description	Key Data Sources and Models
1	Record heat and resilience planning grants from the Minnesota Pollution Control Agency 2022-2025. Regardless of municipality size, heat/resilience planning grants were ~$50,000. We apply this amount to municipalities across MN.	Minnesota Pollution Control Agency (MPCA), 2025[114]
2	Estimate municipalities in Minnesota. In 2021 there were 912 populated cities or census designated places in the American Community Survey.	U.S Census Bureau, 2021a[115]

[109] U.S. Bureau of Labor Statistics (BLS). Occupational Employment and Wage Statistics (OEWS). State level data downloaded from: https://www.bls.gov/oes/tables.htm
[110] Minneapolis (2024). "Fixed water and sewer charges." https://www.minneapolismn.gov/resident-services/utility-billing/rates-fees/three-year-rate-history/#d.en.108166
[111] U.S Census Bureau. (2023). *All Sectors: County Business Patterns CB2300CBP* [Dataset]. https://data.census.gov/table/CBP2023.CB2300CBP
[112] United States Department of Agriculture (USDA) National Agricultural Statistics Service. (2022). *Census of Agriculture FARM OPERATIONS - NUMBER OF OPERATIONS (Volume 1 Chapter 2: County Level Data) Minnesota* [Dataset]. https://www.nass.usda.gov/Publications/AgCensus/2022/Full_Report/Volume_1,_Chapter_2_County_Level/Minnesota/
[113] Neidell et al., "Temperature and Work."
[114] Minnesota Pollution Control Agency (MPCA), "Climate Grants," 2025, https://data.pca.state.mn.us/views/Climategrantsmap/ClimateGrants?%3Aembed=y&%3AisGuestRedirectFromVizportal=y.
[115] U.S Census Bureau, "American Community Survey 5-Year B01003_001."

Step	Description	Key Data Sources and Models
3	Assess planning frequency. City of Minneapolis updated their initial Climate Action plan after 10 years. We assume this frequency for all cities.	Minneapolis City Coordinator, Sustainability Office, 2013[116] City of Minneapolis, 2023[117]
4	Assume all 912 localities draft a heat/resilience plan every 10 years. Multiply number of municipalities by annualized costs of $5,000 a year.	

Table B14. Urban Tree Watering Costing Methods

Step	Description	Key Data Sources and Models
1	Many urban areas of MN are currently focused on increasing tree canopy for the range of benefits, including heat reduction, trees provide. Because much of that planting may be accomplished by 2040 and is proceeding with multiple goals in mind, we focus this analysis on the increased cost of watering existing and vulnerable urban trees to combat heat stress on high temperature days. To do so, we first identify the current number of public trees in the eight most populous MN cities. 1. Minneapolis: 600,000 2. St. Paul: 500,000 3. Rochester: 100,000 4. Duluth: 12,000 5. Bloomington: 35,000 6. Brooklyn Park: 20,000 7. Plymouth: 40,000 8. Woodbury: 20,000	MN Park and Recreation Board, n.d.[118] City of St. Paul, 2010.[119] City of Rochester, n.d.[120] City of Duluth Minnesota, n.d.[121] City of Bloomington, n.d.[122] City of Brooklyn Park, n.d.[123] CBS News, 2025[124] City of Woodbury, n.d.[125]

[116] Minneapolis City Coordinator, Sustainability Office, *Minneapolis Climate Action Plan* (City of Minneapolis, 2013), https://www2.minneapolismn.gov/media/content-assets/www2-documents/government/Minneapolis-Climate-Action-Plan.pdf.
[117] City of Minneapolis, *City of Minneapolis 2023 Climate Equity Plan* (City of Minneapolis, 2023), https://www.minneapolismn.gov/media/-www-content-assets/documents/Minneapolis-2023-Climate-Equity-Plan.pdf.
[118] Minnesota Park and Recreation Board. "Trees and the Urban Forest." Available at: https://www.minneapolisparks.org/park-care-improvements/trees. Data accessed Nov 2025.
[119] City of St. Paul Minnesota. (2010). "Street and Park Tree Master Plan." https://www.stpaul.gov/DocumentCenter/View/13797.pdf
[120] City of Rochester Minnesota. Rochester Parks and Recreation. "About Us." https://www.rochestermn.gov/departments/parks-and-recreation/forestry/about Data accessed Nov 2025.
[121] City of Duluth Minnesota. Parks and Recreation. "Urban Forestry." https://duluthmn.gov/parks/natural-resources/urban-forestry Data accessed Nov 2025.
[122] City of Bloomington Minnesota. "Urban Forest Master Plan." https://letstalk.bloomingtonmn.gov/urbanforest Data accessed Nov 2025.
[123] City of Brooklyn Park Minnesota. "Community Forestry." https://www.brooklynpark.org/community-forestry/ Data accessed Nov 2025.
[124] CBS News. "Plymouth becomes first Minnesota City to monitor tree health using AI." https://www.cbsnews.com/minnesota/news/plymouth-ai-smart-tree-technology-health-greehill/ Published August 6, 2025.
[125] City of Woodbury Minnesota. "Forestry." https://www.woodburymn.gov/404/Forestry Data accessed 2025.

Step	Description	Key Data Sources and Models
2	Calculate number of vulnerable trees that may require watering during a high heat stress day. Trees typically need watering in the first five years of life, so we estimate the number of these "young" trees in each municipality based on the distribution of young vs. total trees in Minneapolis. • Estimate number of trees in Minneapolis planted each year (~10,000) (MPRB 2022). • Assume ~50,000 new trees need watering in Minneapolis, equivalent to 8.33% of total trees (compare with Step 1). • Apply portion of new/total trees from Minneapolis to all other cities to estimate number of trees in need of water.	MN Park and Recreation Board, 2022[126]
3	Calculate cost of watering per tree. Water costs about $3.76 per 100 cubic feet (equivalent to 748 gallons) in 2024 (Minneapolis 2024). Assume 20 gallons of water per tree per 90 degree day, which equates to ~$0.10 per tree.	Minneapolis, 2024[127]
4	Calculate labor cost of watering per tree. Assume 1 minute of time to water a tree (e.g., filling slow release watering bags). MN median wage rate for "Forest and Conservation Technicians" is $30.98 (OEWS), meaning the labor cost per tree is ~$0.52.	BLS[128]
5	Apply water and labor cost per tree (from Steps 3 and 4) to number of trees that require watering per city (from Step 2) to estimate a total cost to water trees per 90 degree day by city.	
6	Estimate the additional number of days above 90 degrees in the projected period (2040-2099) by county, year, SSP, and GCM over the observed baseline (1995-2014). Assign county-level temperature data to selected cities in Minnesota. If a city is located in multiple counties, then average additional days over the heat index threshold across counties.	Leiss et al. [129]
7	Apply the total cost to water trees per 90-degree day by city to the additional number of days above 90 degrees in the projected period (2040-2099) by city, year, SSP, and GCM.	
8	Sum to state level and average across years in each time period.	

Table B15. Ash Tree Replanting Methods

Step	Description	Key Data Sources and Models
1	Ash trees currently make up a significant part of the shade canopy in urban areas. As Emerald Ash Borer (EAB) results in tree mortality in the future, those trees will need to be replaced to maintain shade cover. First, we identify ash tree populations in 304 select MN cities based on data collected through the Rapid Assessment Community Tree Reports.	Communication with the MN Department of Natural Resources and MNDNR Community Tree Report Viewer[130]

[126] Minnesota Park and Recreation Board. "Investing in our Future. Superintendent's Annual Report 2022." https://www.minneapolisparks.org/wp-content/uploads/2023/04/MPRB22_AnnualReport.pdf
[127] Minneapolis (2024). "Fixed water and sewer charges." https://www.minneapolismn.gov/resident-services/utility-billing/rates-fees/three-year-rate-history/#d.en.108166
[128] U.S. Bureau of Labor Statistics. Occupational Employment and Wage Statistics (OEWS). https://mn.gov/deed/data/data-tools/oes/
[129] Leiss et al., "Fine-Scale Climate Projections over Minnesota for the 21st Century."
[130] https://arcgis.dnr.state.mn.us/portal/apps/experiencebuilder/experience/?id=6fb3082ce97145f1ac41107d50d05a1d

Step	Description	Key Data Sources and Models
2	Identify the historical (1971-2000) extent of EAB. We define extents as areas where the likelihood of occurrence is greater than 50 percent (e.g. more likely than not).	Natural Resources Canada[131]
3	Sum ash trees across 209 cities that fall within the probable EAB suitability areas.	
4	Multiply affected ash trees by tree replacement costs ($1,000 per tree).	MN Shade Tree Advisory Committee[132]
5	Estimate annual costs. Distribute total replacement costs across 35 years (2025-2060), assuming tree replacement is already underway and will be competed by the end of the first period of this study.	

Table B16. Shade Structures at Playgrounds Costing Methods

Step	Description	Key Data Sources and Models
1	Estimate the total number of playgrounds in Minnesota using a report done by the Trust of Public Land (2025), which estimates 2.8 playgrounds per 10,000 people in Minneapolis, MN, and 2.6 playgrounds per 10,000 people in St. Paul, MN. We use the average per 10,000 residents and apply to the total Minnesota population in 2025. We estimate approximately 1,570 playgrounds located across the state.	Trust for Public Land, 2025[133] MN State Demographic Center, 2024a[134]
2	Calculate the cost of one fixed shade structure at a playground using a published price list from the Minnesota Department of Administration. Across all shade structures in the price list, the average cost is approximately $20,675 per structure (2024$). We assess the reasonableness of applying this average estimate by comparing with the costs incurred by municipalities as recorded in files from MPCA Resilient Communities Implementation grants. We find that the average cost of a shade structure described in these grants was $22,479, providing confidence in our estimate.	MN Department of Administration, 2023[135] Implementation Grant Summary, FY 2024 provided by MPCA Resilient Communities Program.
3	Calculate total cost of installing shade structures at all playground in Minnesota. Assume one shade structure per playground. Multiply results of step 1 by step 2. The total estimate cost is $32.4 million (2024$).	
4	We are unable to connect the installation of shade structures on playgrounds to temperature and population trajectories, so we apply an annual cost of installing shade structures considering their approximate 15-year useful life across all SSPs and GCMs. The average annual cost is $2.16 million.	Stanfel, 2025[136]

[131] https://cfs.cloud.nrcan.gc.ca/bmfid/bmfid.php?lang=e
[132] https://www.mnstac.org/uploads/2/0/9/3/20933948/eab_v8.pdf
[133] Trust for Public Land. 2025. City Park Facts 2025 – Facilities and Recreational Amenities Data. https://www.tpl.org/city-park-facts
[134] Minnesota State Demographic Center, "Long-Term Population Projections for Minnesota By Age and Sex," May 2024, https://mn.gov/admin/demography/data-by-topic/population-data/our-projections/.
[135] Minnesota Department of Administration. "Landscape Structures Playground Equipment Price List." Effective June 2023. https://osp.admin.mn.gov/sites/osp/files/2023-09/202310landscapestructuresplaygroundequipmentpricelist.pdf
[136] Stanfel (2025). Choosing the Ideal Shade Solution for Your Playground. Playground Depot. Choosing the Ideal Shade Solution for Your Playground | Playground Depot

Key limitations and uncertainties

Table B17. Sources of Uncertainty in Analysis of Health and Wellbeing Adaptation Costs

Key Assumption or Source of Uncertainty	Direction of Potential Bias on Adaptation Cost	Likely Effect of the Uncertainty on Results
Heat and premature mortality		
We apply the Mills et al. 2015 heat/mortality relationship from urban Minneapolis throughout Minnesota.	**Unknown.** Rural residents may face increased vulnerabilities due to isolation or lack of healthcare access while urban residents may experience greater heat island effects.	**Likely minor.** While vulnerabilities may vary across communities within Minnesota, the relationship between heat and mortality in Minneapolis is unlikely to be an outlier.
Heat and pediatric ED visits		
We only estimate future pediatric ED visits that are specifically recorded as heat related.	**Underestimate impacts.** Children may be treated for other health issues that are not specifically tagged as heat related but that were exacerbated by heat.	**Potentially major.** Bernstein et al. 2022 also identifies a statistically significant relationship between heat and all cause ED visits among children, suggesting an overall increase in ED visits as temperatures warm.
Analysis only considers ED visits among children.	**Underestimate impacts.** ED visits are likely to increase among other vulnerable populations as well, including but not limited to older adults (e.g., Santodomingo et al. 2024[137]).	**Potentially major.** Available literature suggests that adults make up most ED visits on high heat days (e.g., Vaidyanathan et al. 2023[138]).
Heat and lost student learning		
Analysis only considers heat-related learning losses among high school students (ages 14-17), consistent with Park et al. 2020	**Underestimate impacts.** Other research documents that elementary and middle school children in the U.S. also experience learning losses (Roach and Whitney 2022[139]).	**Potentially major.** Learning losses experienced as a younger child may have compounding and longer-term impacts. However, the results from Roach and Whitney cannot readily be combined with the results from Park et al. 2020

[137] Melodie Santodomingo et al., "Extreme Heat Events and Emergency Department Visits among Older Adults in California from 2012–2019," *Medicina* 60, no. 10 (2024): 1593, https://doi.org/10.3390/medicina60101593.
[138] Ambarish Vaidyanathan et al., "Heat-Related Emergency Department Visits — United States, May–September 2023," *MMWR. Morbidity and Mortality Weekly Report* 73, no. 15 (2024): 324–29, https://doi.org/10.15585/mmwr.mm7315a1.
[139] Travis Roach and Jacob Whitney, "Heat and Learning in Elementary and Middle School," *Education Economics* 30, no. 1 (2022): 29–46, https://doi.org/10.1080/09645292.2021.1931815.

Key Assumption or Source of Uncertainty	Direction of Potential Bias on Adaptation Cost	Likely Effect of the Uncertainty on Results
Heat and labor participation		
Labor participation is a suitable proxy for labor productivity.	**Unknown.** Ideally, we would measure changes in worker productivity associated with high heat days, which is a more accurate representation of costs associated with the cognitive burden heat places on workers. Time spent working is a mix of productivity losses as well as a proactive adaptation to limit health and safety risks.	**Unknown.** Existing evidence is insufficient to support a comparison of labor participation and overall labor productivity to inform our understanding of whether this assumption results in a major or minor overall effect on results.
Analysis only considers workers in specific weather exposed industries.	**Underestimate impacts.** Other indoor industries lack sufficient cooling to protect workers from increasing ambient temperatures, including many commercial kitchens, laundry and textile care, etc. As evidence, Minnesota already has a rule that seeks to reduce temperature risks to indoor workers through improved ventilation and other measures. Including those industries in the analysis would increase overall impacts.	**Potentially major.** Available evidence does not document the impact of temperatures on indoor worker participation. However, if the results of Neidell et al. 2021 were extrapolated to all industries that typically lack A/C, the overall magnitude of results would be significantly higher.
A/C in homes		
Available empirical evidence does not support when homes should install A/C to limit adverse impacts, so we rely on multiple sources to suggest that 15 days above 80°F is an appropriate and reasonable threshold.	**Underestimate costs.** Barreca et al. 2015 find that having A/C installed starts being effective at reducing mortality impacts at 80F, therefore it is possible that installing A/C before the 15-day threshold could be desirable.	**Likely minor.** Most counties in Minnesota have already met the 15-day threshold therefore lowering the threshold will have minor effects on the future installation and energy costs we estimate.
Representative example A/C units model costs across the state. Energy prices can be volatile.	**Unknown.** Even within our A/C categories (including window, central, and heat pump) there are a variety of configurations that differ in nameplate capacity and energy efficiency. This analysis also does not project changes in configuration over time. Energy prices can change dramatically given domestic and international policy and resource availability.	**Potentially major.** It is reasonable to assume the average A/C unit will become more efficient over time, reducing costs holding all else constant. Future energy prices are uncertain and could drive large changes in cost.
Costs are estimated for the current housing stock and do not account for costs in new construction.	**Underestimate costs.** New homes are likely to include cooling technologies that are not costed in this analysis.	**Likely minor.** Although the total cost of cooling new homes could be major, it is likely some portion of these homes would have included these technologies even with baseline temperatures.

Key Assumption or Source of Uncertainty	Direction of Potential Bias on Adaptation Cost	Likely Effect of the Uncertainty on Results
A/C in schools		
See first two rows of "A/C in homes" related to A/C adoption assumptions that apply here as well.		
Survey-based responses about school A/C penetration interpreted from a figure from Park et al. 2020.	**Unknown.** Park et al. 2020 rely on survey-based responses from school counselors to determine school A/C coverage across the state. While this is still the best available indicator of A/C available at the county level, the map figure we extract data from presents information in categories (e.g., 70 to 100 percent coverage), and we apply the midpoint of each range to the applicable counties. There is likely substantial within county variation, and it's possible the midpoint is not suitable for some counties.	**Likely minor.** By relying on the midpoint of each range, we expect that our analysis represents average conditions although cannot capture site-specific variability.
Assume an installation cost based on average square footage of schools and an average annual O&M cost based on days above 80°F.	**Unknown.** School size and the associated installation and operation costs may vary based on school type (primary, secondary, public, private, etc.), energy price, or type of unit.	**Potentially major.** Installation costs may differ by contractor and by location in the state. Similar to A/C in homes above, future energy prices are uncertain and could drive large changes in cost, along with differences in type of system.
A/C in commercial and other public buildings		
Energy prices can be volatile.	**Unknown.** Energy prices can also change dramatically given domestic and international policy and resource availability.	Future energy prices are uncertain and could drive large changes in cost.
Public and Commercial buildings that require temperature control are assumed to already have cooling technologies in the baseline; therefore we only cost out increased operating costs.	**Underestimate costs.** Relative to operating costs of existing units, capital costs and operating costs of new units are large. Future capital investment driven by changes in temperature would increase Public/Commercial adaptation costs significantly.	**Potentially major.** In the home A/C analysis additional operating costs of current A/C units were only 30-40% of total costs (depending on scenario). Total Public/ Commercial adaptation cost could more than double if these buildings are driven by temperature to invest in new A/C infrastructure.

Key Assumption or Source of Uncertainty	Direction of Potential Bias on Adaptation Cost	Likely Effect of the Uncertainty on Results
Cooling centers		
Costs of operating a cooling center in Los Angeles are transferrable to Minnesota.	**Unknown.** Demographics and infrastructure differ between the two locations and it is unknown whether costs of operating a cooling center in Minnesota will be greater or less than the costs in Los Angeles. Because Minnesota has experienced few extreme heat days to date, we are unable to compare historical information to adjust accordingly.	**Likely minor.** Even a large percentage change in the per cooling center costs would be unlikely to make this a major cost category relative to other categories.
Number of cooling centers necessary to serve a population can be scaled from Pittsburgh and will not differ over time.	**Overestimate costs.** It is unknown whether the estimate for Pittsburgh is a reasonable proxy for the number of cooling centers Minnesota *should* have available. However, if more homes and other buildings install A/C over time, then the future need for cooling centers may decrease over time.	**Likely minor.** Even as more homes and buildings install A/C, demand for cooling centers is still likely to exist. This is because energy costs may limit some residents from cooling to appropriate levels, and unhoused people will need spaces for cooling.
Worker heat protections		
The proposed OSHA rule represents reasonable expectations for how employers should allocate breaks and water on high heat days.	**Unknown.** We use the break and water requirements from the proposed OSHA rule to guide our cost estimates. It is unknown whether these requirements are sufficient to limit worker health and safety risk.	**Likely minor.** Relative to other state rules that require similar provisions, the OSHA proposed rule is more protective (i.e., rules in Oregon, Washington, and California do not require breaks until 90F and break duration is shorter), suggesting that the OSHA requirements may reach levels that ensure more widespread risk reduction by further limiting exposure.
Offering breaks and water are the main mechanisms through which employers will accrue costs.	**Underestimate costs.** To limit the adverse effects of heat on workers, employers are likely to also invest in planning, training, setting up shade, better monitoring temperatures, generating other means of cooling, etc.	**Likely minor.** Most of the other strategies employers may use to reduce worker risks are one-time investments and may already be in place by 2040.
Heat/climate resilience planning		
Costs covered by resilience planning grants are suitable proxies for the total costs municipalities incur for planning and implementation purposes.	**Underestimate costs.** Conversations with representatives of the Hennepin County Climate and Resiliency team revealed that the grants they receive do not cover their staff time, and that their office has about seven permanent team members.	**Potentially major.** If grants only cover variable programmatic costs but some municipalities also require dedicated staff to plan and implement resiliency projects, then we may significantly underestimate the total costs associated with these administrative oversight activities.

Key Assumption or Source of Uncertainty	Direction of Potential Bias on Adaptation Cost	Likely Effect of the Uncertainty on Results
Urban tree watering		
The number of young vulnerable trees that will require watering will remain constant in the future.	**Underestimate costs.** Some Minnesota, like Hennepin County[140], have established goals for continuing to add tree canopy in the coming years, suggesting there will be more trees to water in the future and potentially a higher rate of newly planted trees in future years.	**Likely minor.** Relative to the cost of planting a tree and typical maintenance, the additional water and labor needs associated with limiting heat stress and tree mortality are likely minor.
Tree watering costs on high heat days are the only climate-related maintenance costs municipalities may incur.	**Underestimate costs.** Climate change may also bring increased pest and disease incidence, requiring additional maintenance costs.	**Potentially major.** Treating pests and diseases can be labor intensive and therefore costly. However, we lack empirical evidence to support linking changing climatic conditions with increased incidence of pest and diseases among urban trees.
Shade structures at playgrounds		
All playgrounds – both public and private – require shade installation in the future.	**Overestimate costs.** Available information about the number of playgrounds per capita is drawn from two MN cities, which we extrapolate throughout the state. Non-urban areas may have fewer playgrounds, or more playgrounds on private property. We also do not have data to estimate the number of playgrounds that may already have sufficient shading.	**Likely minor.** Historically, heat has not been a major threat in Minnesota, so many playgrounds likely remain exposed to the sun in the baseline period and require shade investments.
Playgrounds will install one shade structure each.	**Underestimate costs.** Large playgrounds will require more than one shade structure to provide sufficient protection for children and their caregivers.	**Potentially major.** If playgrounds in the most populous areas add more than one shade structure, then the total costs would at least double.
The cost of the shade structure itself covers most costs incurred by municipalities and private landowners.	**Underestimate costs.** There is likely to be costs associated with installing and maintaining the shade structures.	**Potentially major.** While ongoing maintenance costs may be minor, initial installation costs may be high.

Air Quality

Costs of inaction

The costs of inaction for air quality related health and wellbeing impacts include premature mortality and emergency department visits due to ozone exposure, **school days lost, childhood asthma, and premature mortality due to fine particulate matter ($PM_{2.5}$) exposure.**

[140] Hennepin County, Minnesota. (2021) Climate Action Plan. https://www.hennepin.us/climate-action/-/media/climate-action/Home/hennepin-county-climate-action-plan-final.pdf

Table B18. Costs of Inaction Summary: Air Quality-Related Health and Wellbeing Impacts

Impacts	Cost Measure	CMIP6 Data Used	Spatial Scale	Underlying Study	Methods Table
Wildfire ($PM_{2.5}$) Mortality	VSL	Filter Qiu et al. 2025 to CliMAT-selected GCMs, Annual CONUS Temp	State	Qiu et al., 2025[141]	Table B19
Climate-Induced Ozone Mortality	VSL	Annual CONUS Temp (FrEDI)	State	Fann et al., 2021[142]	Table B20
Climate-Induced Ozone ED Visits	Cost per visit	Annual CONUS Temp (FrEDI)	State	Fann et al., 2021	Table B20
Climate-Induced Ozone School Days Lost	Caregiver costs	Annual CONUS Temp (FrEDI)	State		Table B20
Climate-Induced Ozone Childhood Asthma	Value of avoiding a new onset statistical case of childhood asthma	Annual CONUS Temp (FrEDI)	State		Table B20
*Adjusted FrEDI output					

Table B19. Qiu et al. 2025 Wildfire Premature Mortality Methods

Step	Description	Key Data Sources and Models
1	Author provides baseline (2011-2020) and projected (2046-2055) mortality from wildfire smoke at the county level by SSP and GCM. Projections include all 29 CMIP6 GCMs and three SSPs (SSP1-26, SSP2-45, and SSP3-70).	Qiu et al., 2025[143]
2	Filter projections to Minnesota and MN CliMAT GCMs and SSPs.	
3	Estimate additional projected cases over observed baseline by subtracting baseline period deaths from projections.	
4	Summarize to the state level and average across projection period (2046-2055).	

[141] Qiu, M., Li, J., Gould, C. F., Jing, R., Kelp, M., Childs, M. L., ... & Burke, M. (2025). Wildfire smoke exposure and mortality burden in the US under climate change. Nature, 1-3.
[142] Neal L Fann et al., "Associations between Simulated Future Changes in Climate, Air Quality, and Human Health," *JAMA Network Open* 4, no. 1 (2021): e2032064–e2032064.
[143] Minghao Qiu et al., "Wildfire Smoke Exposure and Mortality Burden in the USA under Climate Change," *Nature*, ahead of print, September 18, 2025, https://doi.org/10.1038/s41586-025-09611-w.

Table B20. Climate-Induced Ozone-Related Premature Mortality, ED Visits, School Days Lost, and Childhood Asthma Methods

Step	Description	Key Data Sources and Models
1	Run FrEDI with CMIP6 temperature projections and MN-specific population projections, for the air quality sector.	FrEDI[144] KNMI Climate Explorer, 2025[145] MN State Demographic Center, 2024a[146]
2	Use standard FrEDI-derived value of statistical life, value of a statistical case of new onset childhood asthma, value of a lost school day, and medical cost of illness estimates for relevant endpoints associated with increased ozone exposure in children and adults.	

Adaptation costs

Air quality impacts are also addressed via air conditioning. See methods under the 'Heat' section.

Table B21. Costs of Adaptation Summary: Air Quality-Related Health and Wellbeing Impacts

Action	Cost Components	Impacts Addressed	Quantified Residual Risks	Spatial scale of Analysis	Methods Table
Air Purifier Investment and Operation	Purchase price and energy costs	PM smoke mortality, PM and aeroallergen morbidity, safety	None	County	Table B22
Air Conditioning – See Heat adaptation measures, summarized in Table 7.					

Table B22. PM-Driven Air Purifier Investment and Aeroallergen-Driven Air Purifier Operation Methods

Step	Description	Key Data Sources and Models
1	An analysis commissioned by Pacific Gas and Electric Company (PG&E) and produced by Evergreen Economics suggests high concentrations of particulate matter (PM) and aeroallergens are common incentives for air purifier purchase and operation. Qui et al. 2025 provides baseline (2011-2020) total and wildfire-driven smoke $PM_{2.5}$ concentrations ($\mu g/m^3$) by 10km grid. Subtract wildfire-driven smoke concentrations from total smoke concentrations to estimate non-wildfire driven smoke concentrations. Qiu et al. 2025 derives concentrations from Childs et al. 2022.	Evergreen Economics, 2022[147] Qiu et al., 2025[148] Childs et al., 2022[149]

[144] https://epa.gov/cira/about-fredi/index.html
[145] KNMI Climate Explorer. (2025). https://climexp.knmi.nl/start.cgi
[146] Minnesota State Demographic Center. (2024). *Long-Term Population Projections for Minnesota By Age and Sex* [Dataset]. https://mn.gov/admin/demography/data-by-topic/population-data/our-projections/
[147] Evergreen Economics, *Air Purifiers National Consumer Survey (1)* (2022), Regulations.gov, https://www.regulations.gov/comment/EERE-2021-BT-STD-0035-0009.
[148] Qiu et al., "Wildfire Smoke Exposure and Mortality Burden in the USA under Climate Change."
[149] Marissa L. Childs et al., "Daily Local-Level Estimates of Ambient Wildfire Smoke PM2.5 for the Contiguous US," *Environmental Science & Technology* 56, no. 19 (2022): 13607–21, https://doi.org/10.1021/acs.est.2c02934.

Step	Description	Key Data Sources and Models
2	Average non-wildfire smoke concentrations across 2016-2020. Exclude 2011-2015 observations following methods from Qiu et al. 2025.	Qiu et al., 2025[150]
3	Qiu et al. 2025 provides projected (2046-2055) wildfire smoke $PM_{2.5}$ concentrations ($\mu g/m^3$) by 10km grid by SSP and GCM. Projections include all 29 CMIP6 GCMs and three SSPs (SSP1-26, SSP2-45, and SSP3-70). Filter projections to Minnesota and MN CliMAT GCMs and SSPs.	Qiu et al., 2025[151]
4	Combine baseline non-wildfire driven smoke concentrations with projected future wildfire smoke concentrations to estimate total $PM_{2.5}$ concentrations 2046-2055 by 10km grid.	
5	Estimate purchase timing. Use the annual 9 $\mu g/m^3$ National Ambient Air Quality Standard (NAAQS) from the EPA to estimate air purifier purchase timing per grid cell. Assume once the NAAQS threshold is reached all households in the grid cell that do not use central or heat pump AC will purchase air purifiers. Central and heat pump AC units purify air during operation.	EPA, 2024[152]
6	Smoke projections are estimated at the 10km grid level and Qui et al. also provide 2050 population at the grid level (based on Stevens et al.). In 2050, MN state population projections from Qiu et al. 2025 are 3.6 percent lower than those provided by the Minnesota State Demographic Center. Household counts are available by county from the Census (averaged 2013-2021). a) Split grid cells by county: Using GIS, overlap 10km grid cells used by Qiu et al. 2025 with MN county boundaries. Estimate the area of each grid-county fragment and the percentage of total grid area within each grid-county fragment. b) Assume, within grid cells that cross county lines, future population is evenly distributed across grids. c) Estimate the share of total county population within each grid-county fragment. d) Multiply the number of households per county by the share of total county population in each grid-county fragment to estimate the number of households in each grid-county fragment	Qiu et al., 2025[153] Stevens et al., 2015[154] MN State Demographic Center, 2024a[155] U.S Census Bureau, 2025[156] Minnesota State Demographic Center, 2024b[157]
7	Estimate the number of new units required per grid-county fragment by multiplying the total households in the grid-county by the percentage of households assumed to not already have air filters (given baseline air purifier assumptions and projections of central and heat pump household AC) and the number of units per household (1.5, also from Evergreen Economics)	Evergreen Economics, 2022[158]

[150] Qiu et al., "Wildfire Smoke Exposure and Mortality Burden in the USA under Climate Change."
[151] Qiu et al., "Wildfire Smoke Exposure and Mortality Burden in the USA under Climate Change."
[152] EPA, "Final Rule to Strengthen the National Air Quality Health Standard for Particulate Matter Fact Sheet," 2024, https://www.epa.gov/system/files/documents/2024-02/pm-naaqs-overview.pdf.
[153] Qiu et al., "Wildfire Smoke Exposure and Mortality Burden in the USA under Climate Change."
[154] Forrest R. Stevens et al., "Disaggregating Census Data for Population Mapping Using Random Forests with Remotely-Sensed and Ancillary Data," *PLOS ONE* 10, no. 2 (2015): e0107042, https://doi.org/10.1371/journal.pone.0107042.
[155] Minnesota State Demographic Center. (2024). *Long-Term Population Projections for Minnesota By Age and Sex* [Dataset]. https://mn.gov/admin/demography/data-by-topic/population-data/our-projections/
[156] U.S Census Bureau, "2025 County TIGER/Line Shapefile," FTP Archive, 2025, https://www2.census.gov/geo/tiger/TIGER2025/COUNTY/.
[157] Minnesota State Demographic Center, "PopFinder For Minnesota, Counties, & Regions."
[158] Evergreen Economics, *Air Purifiers National Consumer Survey (1)*.

Step	Description	Key Data Sources and Models
8	Average across the purchase price of 53 air purifier units from Yang 2022. Annualize purchase price across assumed 10-year lifespan from Yang 2022 and adjust to 2024 dollars.	Yang, 2022[159]
9	Multiply annualized purchase price by the estimated number of units in each grid-county fragment. Assume households purchase units in the first year the NAAQS threshold is reached and replace units once the 10-year lifespan is complete.	EPA, 2024[160] Yang, 2022[161]
10	Ziska et al. 2019 provides observed pollen season length and annual temperature minimum degree days (total degree days temperature minimum is greater than 32°F) 1993-2013 in Minneapolis. Regress pollen season length on temperature minimum degree days. Statistically significant relationship suggests one additional temperature minimum degree day in Minneapolis increases the length of the pollen season by 0.022 days.	Ziska et al., 2019[162]
11	Estimate the number of temperature minimum degree days per year each county/SSP/GCM will experience. Subtract total future degree days from historical observations 1995-2014 to estimate additional future degree days (2040-2099).	Leiss et al. [163]
12	Multiply future and total degree days by the statistical relationship between degree days and pollen season to estimate future pollen season length (in total and net of baseline) by county, SSP, and GCM.	
13	Estimate future operational unit-days per county. Multiply new air purifier units (from Step 7) by total future pollen season length. Multiply current air purifier units by net pollen season length.	
14	Adjust daily energy costs from Yang 2022 given MN energy prices and average across 53 sample air purifier units. Adopt Yang 2022 assumption that units operate for 24 hours a day to estimate cost per pollen season day for each operating unit.	Yang, 2022[164] Minnesota cost per kWh: CEE, 2022[165] U.S. Energy Information Administration (EIA), 2020[166] CEE, 2020[167]
15	Multiply cost per pollen season day by projected operating units per county, SSP, GCM, and year.	

[159] Andrew Yang, "The Cost of Clean Air: A Price Analysis of Air Filtration Technology," *arXiv*, 2022, https://arxiv.org/abs/2208.06041.
[160] EPA, "Final Rule to Strengthen the National Air Quality Health Standard for Particulate Matter Fact Sheet."
[161] Yang, "The Cost of Clean Air: A Price Analysis of Air Filtration Technology."
[162] Lewis H. Ziska et al., "Temperature-Related Changes in Airborne Allergenic Pollen Abundance and Seasonality across the Northern Hemisphere: A Retrospective Data Analysis," *The Lancet Planetary Health* 3, no. 3 (2019): e124–31, https://doi.org/10.1016/S2542-5196(19)30015-4.
[163] Leiss et al., "Fine-Scale Climate Projections over Minnesota for the 21st Century."
[164] Yang, "The Cost of Clean Air: A Price Analysis of Air Filtration Technology."
[165] Center for Energy and Environment, *Investigation of Air Source Heat Pumps as a Replacement of Central Air Conditioning*.
[166] U.S. Energy Information Administration, "Residential Energy Consumption Survey (RECS) Mircodata."
[167] Center for Energy and Environment, *Reconsidering Cooling Loads in Minnesota*.

Step	Description	Key Data Sources and Models
16	Summarize investment and operational costs to counties, and counties to the state level, and average across GCMs.	

Key limitations and uncertainties

Table B23. Sources of Uncertainty in Air Quality

Key Assumption or Source of Uncertainty	Direction of Potential Bias on Adaptation Cost	Likely Effect of the Uncertainty on Results
Climate-Induced Ozone-Related Mortality and Morbidity		
Morbidity endpoints do not capture full extent of potential impacts.	**Underestimate impacts.** Respiratory health is likely to worsen among individuals exposed to air pollution for other climate-induced reasons, including changes in plant pollen production and methane emission induced ozone formation, that also affect respiratory health.	**Potentially major.** The combined effect of multiple stressors may be larger than individual impacts
Wildfire Mortality		
Data from Qiu et al. 2025 does not consider all MN CliMAT SSPs, or all time periods addressed in this study.	**Underestimate costs.** Qiu et al. 2025 only includes data applicable to the mid-century and does not include SSP5-8.5. Excluded temperatures are assumed to result in more extreme wildfires and mortality.	**Potentially major.** Mortality in the late-century, end of century, and under SSP5-8.5 could be far more damaging than mortality in the mid-century under SSP2-4.5 and SSP3-7.0, based on other wildfire and air pollution literature which considers these later years and the higher emissions SSP.
PM-Driven Air Purifier Investment		
Available empirical evidence does not support when homes should install air purifiers to limit adverse impacts, so we rely on NAAQS standards to establish an appropriate and reasonable threshold.	**Unknown.** Air purifier investment behavior has not been thoroughly studied. It is unlikely all households would purchase purifiers once PM concentrations cross NAAQS thresholds.	**Potentially major.** If households air purifier investments are more aggressive than expected the effects of this assumption are minor given our repeat purchase assumption. If household air purifier investments are more cautious than expects, the analysis may overestimate impacts.

Vector-borne Disease and Illness

Costs of inaction

Table B24 provides the costs of inaction associated with increased vector-borne disease, including costs of illness and willingness to pay to avoid fatal risk for Lyme disease and West Nile virus.

Table B24. Costs of Inaction Summary: Vector-borne Disease Health and Wellbeing Impacts

Impacts	Cost Measure	CMIP6 Data Used	Spatial Scale	Underlying Study	Methods Table
Lyme Disease	Cost of illness and WTP to avoid fatal risk (VSL)	Annual CONUS Temp (FrEDI)	State	Yang et al., 2024[168]	Table B25
West Nile Virus	Cost of illness and WTP to avoid fatal risk	Published study uses CMIP5 GCMs and GHG emissions scenarios	State	Belova et al., 2017[169]	Table B26

*Adjusted FrEDI output

Table B25. Vector-borne Disease and Illness Methods (Lyme Disease)

Step	Description	Key Data Sources and Models
1	Run FrEDI with CMIP6 temperature projections and MN-specific population projections.	FrEDI[170] KNMI Climate Explorer, 2025[171] MN State Demographic Center, 2024a[172]
2	For nonfatal outcomes, apply per case lifetime health care cost estimates from Yang et al. (2024) and Aldrion et al. (2015 of $4,282). Cost per case represents an average cost across all severity levels and treatment modes and excludes indirect costs such as lost workdays or productivity.	Yang et al., 2024[173] Adrion et al., 2015[174]
3	Average total costs across years in each time period.	

[168] Yang. H., C.A. Gould, R. Jones, A. St Juliana, M. Sarofim, M. Rissing, M. B. Hahn (2024). By-degree Health and Economic Impacts of Lyme Disease, Eastern and Midwestern United States. *Ecohealth*. 21(1), 56-70, doi:10.1007/s10393-024-01676-9. Available online at https://pubmed.ncbi.nlm.nih.gov/38478199/

[169] 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. https://doi.org/10.4236/ajcc.2017.61010

[170] https://epa.gov/cira/about-fredi/index.html

[171] KNMI Climate Explorer. (2025). https://climexp.knmi.nl/start.cgi

[172] Minnesota State Demographic Center. (2024). *Long-Term Population Projections for Minnesota By Age and Sex* [Dataset]. https://mn.gov/admin/demography/data-by-topic/population-data/our-projections/

[173] Yang. H., C.A. Gould, R. Jones, A. St Juliana, M. Sarofim, M. Rissing, M. B. Hahn (2024). By-degree Health and Economic Impacts of Lyme Disease, Eastern and Midwestern United States. *Ecohealth*. 21(1), 56-70, doi:10.1007/s10393-024-01676-9. Available online at https://pubmed.ncbi.nlm.nih.gov/38478199/

[174] Adrion ER, Aucott J, Lemke KW, Weiner JP (2015) Health care costs, utilization and patterns of care following Lyme disease. PLoS ONE 10(2):e0116767. https://doi.org/10.1371/journal.pone.0116767

Table B26. Vector-borne Disease and Illness Methods (West Nile Virus)

Step	Description	Key Data Sources and Models
1	Study authors provide state level changes in total cases and distribution of cases among fatal and non-fatal outcomes (6.5% and 93.5% respectively), by state for three time periods (baseline, 2050, 2090) and two RCPs (4.5 and 8.5) using a suite of five CMIP5 GCMs	Belova et al., 2017
2	For 2050 and 2090, use MN case counts net of baseline. Assigned RCP 4.5 and 8.5 to SSP2-45 and 5-85 for purposes of this study.	
3	For 2070, linearly interpolated results between the 2050 and 2090 estimates for each RCP.	
4	Applied Belova et al. estimated of cost of medical treatment for non-fatal costs (approximately $41,000 in 2015 dollars, adjusted to 2024 dollars) and used VSL adopted for this study for fatal cases to estimate total cost of inaction.	Belova et al., 2017

Adaptation Costs

Table B27. Costs of Adaptation Summary Vector-borne Disease-Related Health and Wellbeing Impacts

Action	Cost Components	Impacts Addressed	Quantified Residual Risks	Spatial scale of Analysis	Methods Table
Mosquito Control	Control operation expenditures	West Nile Virus morbidity and mortality	None	Metropolitan Counties[175]	Table B28

Table B28. Mosquito Control Adaptation Costs

Step	Description	Key Data Sources and Models
1	CDC provides observed neuroinvasive West Nile Virus (WNV) cases 2016-2023 in Minnesota.	CDC, 2025[176]
2	Compile Metropolitan Mosquito Control District (MMCD) control operation expenditures 2016-2023. MMCD monitor WNV and treat waterbodies for mosquitoes. More treatment is required when higher levels of WNV are observed in the early part of the season.	Metropolitan Mosquito Control Commission, 2023[177] Metropolitan Mosquito Control Commission, 2021[178] Metropolitan Mosquito Control Commission, 2019[179]
3	In 2020 the CDC reported 0 neuroinvasive WNV cases and the Metropolitan Mosquito Control Commission (MMCC) reported	

[175] The Metropolitan Mosquito Control District includes Ramsey, Hennepin, Anoka, Washington, Dakota, Scott, and Carver County.
[176] CDC, "West Nile Virus Historic Data (1999-2024)," 2025, https://www.cdc.gov/west-nile-virus/data-maps/historic-data.html.
[177] Metropolitan Mosquito Control Commission, *Metropolitan Mosquito Control District Budget in Brief For the Fiscal Year Beginning January 1, 2023* (2023), https://mmcd.org/docs/commission/BudgetBrief2023Final.pdf.
[178] Metropolitan Mosquito Control Commission, *Metropolitan Mosquito Control District Budget in Brief For the Fiscal Year Beginning January 1, 2021* (2021), https://www.mmcd.org/docs/commission/BudgetBrief2021Draft.pdf.
[179] Metropolitan Mosquito Control Commission, *Metropolitan Mosquito Control District Budget in Brief For the Fiscal Year Beginning January 1, 2019* (2019), https://www.mmcd.org/docs/commission/BudgetBrief2019.pdf.

Step	Description	Key Data Sources and Models
	control operation expenditures of $13.2 million. We assume the 2020 costs represent typical, baseline operating costs during a low-risk year. For each year 2016 – 2024, we subtract the baseline 2020 low-risk year costs to estimate the variable costs associated with elevated WNV risk.	
4	Combine CDC WNV case data with the annual variable costs from Step 3. Since costs scale with WNV risk (i.e., more treatment needed when risk is higher), we divide variable costs by the number of WNV cases each year, where the number of projected cases serves as a proxy for the risk of WNV. The average risk-driven cost, calculated as variable cost per observed WNV case, across 2016-2023 is ~$175,000 per case.	
5	Utilize projected WNV cases from Belova et al. 2017 (described in Table 26) to represent the relative future risk of WNV in Minnesota.	Belova et al., 2017[180]
6	Apply risk-driven cost developed in Step 4 to the project WNV cases (as a proxy for future risk) by RCP and future time period.	

Key limitations and uncertainties

Table B29. Sources of Uncertainty in Vector-borne Disease and Illness

Key Assumption or Source of Uncertainty	Direction of Potential Bias on Adaptation Cost	Likely Effect of the Uncertainty on Results
Average exposure to vectors is held constant over time.	**Underestimate Costs.** The outdoor recreation analyses presented in this report suggest that people will spend more time outside recreating in warmer future climates which could result in additional risk of vector-borne disease and illness.	**Unknown.** The extent of additional exposure and the potential for counteracting behavioral changes (e.g. better clothing choices or repellant use) is unknown at this time.
To estimate the net effect of climate on West Nile Virus incidence, the Belova et al. (2017) baseline WNV estimate is used for consistency with the Belova et al. projected estimated climate-attributed cases of WNV.	**Underestimate Costs.** Current climate annual average baseline incidence, as estimated by CDC for a recent 20-year period, is about three times larger in Minnesota compared to that in the Belova study. The projected climate influenced incidence is therefore likely underestimated.	**Likely minor.** Projected WNV cases are used to scale mosquito control adaptation costs, however the costs are relatively small compared to other categories of cost.
Mosquito Control		
Variable mosquito control costs tied to WNV risk are not readily available.	**Unknown.** This methodology uses historical WNV cases and mosquito control spending to estimate a relationship between observed cases and spending, though significant variation exists year to year.	**Likely minor.** Variance in unit cost is directly proportional to changes in projected future expenditures, though the total projected costs for this category

[180] Anna Belova et al., "Impacts of Increasing Temperature on the Future Incidence of West Nile Neuroinvasive Disease in the United States," *American Journal of Climate Change* 6, no. 1 (2017): 166–216, https://doi.org/10.4236/ajcc.2017.61010.

Key Assumption or Source of Uncertainty	Direction of Potential Bias on Adaptation Cost	Likely Effect of the Uncertainty on Results
		are relatively small compared to other cost categories.
Mosquito control costs from the metro area are applied statewide.	**Underestimate Costs.** Fixed costs associated with monitoring and setting up mosquito control teams outside of the metro area are not included in this cost. Treatment may be infeasible in these areas, which would mean the residual risk of WNV cases could remain high.	**Unknown.** The fixed costs of opening new districts could be high, though it is not certain this would occur, particularly in sparsely populated parts of the state.

Agriculture and Livestock

This category considers the costs of inaction and adaptation for the main agricultural crops and livestock types in the state. Each subcomponent relies on a different analytical approach and source data, with some relying on existing studies and others on novel modeling conducted for Minnesota.

Crops

Cost of inaction

The analysis considers impacts on the top three crops grown in Minnesota (i.e., corn, soybean, and wheat). Costs of inaction account for changes in yields driven by changes in temperature and precipitation magnitude and seasonality.

Table B30. Costs of Inaction Summary: Crop Impacts

Impact	Cost/Physical Measure	CMIP6 Data Used	Spatial Scale	Underlying Study	Methods Table
Corn Yields Soybean Yields Wheat Yields	Lost revenues	Monthly County Temp and Precipitation	County	FAO33[181]	Table B31

Table B31. Crop Yield Adaptation Costing Methods

Step	Description	Key Data Sources and Models
1	**Crop statistics:** We gather statistics on harvested area, production, yield, irrigation, and revenue for corn, soybeans, and wheat by county, separately. Revenue data is not reported for counties with a small number of farms. For those, we distribute the difference	Crop acres, production, revenues, and farms: USDA 2022 Census[182] CPI: BLS, 2025[183]

[181] J. Doorenbos and A. H. Kassam, *Yield Response to Water*, FAO Irrigation and Drainage Paper 33 (FAO - Food and Agriculture Organization of the United Nations, 1979).
[182] U.S. Department of Agriculture, National Agricultural Statistics Service (USDA-NASS), "QuickStats Database," 2022, https://quickstats.nass.usda.gov/.
[183] U.S. Bureau of Labor Statistics, "Consumer Price Index," 2025, https://www.bls.gov/data/inflation_calculator.htm.

Step	Description	Key Data Sources and Models
	between the county-level sum and the state total using the number of farms. 2022 revenues are converted to 2024 dollars using average consumer price index changes.	
2	**Crop water demand:** Water demand is calculated from potential evapotranspiration (PET) using the modified Hargreaves approach, which incorporates precipitation and temperature data, along with monthly crop-specific demand coefficients, to determine evapotranspiration requirements (ETc). Cropping calendars are obtained from the FAO GAEZ database and crop cycle stage lengths from FAO's Irrigation and Drainage Paper 56. Monthly crop water demand coefficients are obtained from the FAO's Irrigation and Drainage Papers 33 and 56.	PET: Droogers and Allen, 2001[184] Cropping calendar: Fischer et al., 2021[185] Crop cycle stage length: Allen et al., 1998[186] Monthly crop coefficients: Allen et al., 1998[187]; Doorenbos and Kassam, 1979[188]
3	**Crop water supply:** Rainfed water supply is estimated as effective precipitation, which is monthly precipitation adjusted for drainage qualities of the soil and ETc, following the methodology from the FAO's Irrigation Water Management Training Manual no. 3.	Brouwer and Heibloem, 1986[189]
4	**Water stress impacts:** We calculate yield impacts using the annual ratio of effective precipitation to water needs (ETc) and multiplying these by annual crop yield response coefficient (Ky), following the approach from the FAO's Irrigation and Drainage Paper 33. Historical water stress by county is calibrated using reported irrigated and rainfed yields.	Doorenbos and Kassam, 1979[190] Yields: USDA 2018 Survey[191]
5	**Lost revenues:** Crop yield impacts are converted to lost revenues by multiplying by current yield, acreage, and producer prices, for each crop separately. Cropped area and prices are assumed to remain constant over time. Yields are assumed to be affected by climate change-related effects only, excluding changes in input application and agronomic practice over time. Final revenue impacts are calculated as the difference between future and historical average revenues.	
6	**Aggregation:** County-level annual average impacts are calculated for the three eras and all climate scenarios considered in the analysis. Time period-level impacts are calculated by averaging years in each time period. State-level effects are calculated as the sum of county-level revenue impacts.	

[184] Peter Droogers and Richard G Allen, "Estimating Reference Evapotranspiration Under Inaccurate Data Conditions," *Irrigation and Drainage Systems* 16 (2001): 33–45.
[185] Günther Fischer et al., *Global Agro-Ecological Zone v4 – Model Documentation* (FAO - Food and Agriculture Organization of the United Nations, 2021), https://doi.org/10.4060/cb4744en.
[186] Richard G. Allen et al., *Crop Evapotranspiration - Guidelines for Computing Crop Water Requirements*, FAO Irrigation and Drainage Paper 56 (FAO - Food and Agriculture Organization of the United Nations, 1998), https://www.fao.org/3/X0490E/x0490e00.htm#Contents.
[187] Allen et al., *Crop Evapotranspiration - Guidelines for Computing Crop Water Requirements*.
[188] Doorenbos and Kassam, *Yield Response to Water*.
[189] C. Brouwer and M. Heibloem, "Irrigation Water Needs," *Irrigation Water Management* Training Manual 3 (1986), https://www.fao.org/3/s2022e/s2022e00.htm#Contents.
[190] Doorenbos and Kassam, *Yield Response to Water*.
[191] U.S. Department of Agriculture, National Agricultural Statistics Service (USDA-NASS), "QuickStats Database."

Adaptation costs

Adaptation for crop production considers investment in irrigation and tile drainage, as well as a qualitative assessment of cover crops and adjustments to field work and growing season timing. Our analysis considers irrigation investments solely aimed at reducing incremental water stress introduced by climate change. For changes in field trafficability, we evaluate the costs associated with installing tile drainage to maintain baseline design drainage rates under altered future climate conditions.

Table B32. Costs of Adaptation Summary: Crop Adaptation Actions

Action	Cost Components	Impacts Addressed	Quantified Residual Risks	Spatial scale of Analysis	Methods Table
Irrigation	Capital and O&M	Lost revenue (from water stress only)	Yes, from residual water stress	County	Table B33
Tile Drainage	Capital	Reduced field trafficability	No	County	Table B34
Retention Ponds	Capital	Increased field drainage outflows	No	County	Table B35

Table B33. Crop Yield Adaptation Costing Methods

Step	Description	Key Data Sources and Models
1-5	Same as Table 31.	
6	**Adaptation benefits:** Irrigation investments are then considered for an average farm within each county. The introduction of irrigation effectively eliminates the moisture deficit estimated in Step 4 from insufficient rainfall. Modeled yield gains are capped so that yields do not increase beyond observed irrigated yields. We rely on available survey data comparing rainfed and irrigated yields across the country to establish these limits, which range 1.3 to 1.6 times the reported county-level yields in Minnesota. Irrigation is assumed to rely on groundwater, with water resources assumed to be available in all scenarios.	Yields: USDA, 2018 Survey[192]
7	**Investment costs:** We assume investment in sprinkler irrigation systems, based on the average costs of five irrigation systems (e.g., center pivot, pivot with corner, linear move, big gun, and side roll) from NDSU. Costs include annualized capital costs that assume a 25-year infrastructure lifespan and loan payments, as well as operating costs, including maintenance, labor, and energy. Costs are converted to 2024 dollars using average consumer price index changes. For this analysis, annual capital costs are estimated at $129.8 per acre and annual operating costs at $70.8 per acre.	Unit Costs: Scherer, 2022[193] CPI: BLS, 2025[194]
8	**Final investment needs:** Irrigation investments are scaled so that average net benefits are zero, therefore eliminating climate change effects. For each county, we compare average net benefits (i.e., change in revenues minus change in costs) with and without adaptation investments across all GCMs for each SSP within a given time period. Farmers are assumed to make a single investment decision at the beginning of each time period (per SSP) that maximizes the reduction of negative climate change effects, but only if the benefit-cost ratio of the	

[192] U.S. Department of Agriculture, National Agricultural Statistics Service (USDA-NASS), "QuickStats Database."
[193] Tom Scherer, *Selecting a Sprinkler Irrigation System*, no. AE91, NDSU Agriculture (North Dakota State University, 2022), https://www.ndsu.edu/agriculture/extension/publications/selecting-sprinkler-irrigation-system.
[194] U.S. Bureau of Labor Statistics, "Consumer Price Index."

Step	Description	Key Data Sources and Models
	investment is greater than two for the corresponding time period/emissions scenario average. In other words, the average farm will only invest in irrigation if the benefits of irrigating are two times the cost of irrigating. We utilize a ratio of two to account for inefficiencies not captured by our model, such as suboptimal investment due to farm characteristics or nutrient leaching. If the average farm does not meet these thresholds, we assume farmers do not invest and bear the full impact of the climate shock.	
9	**Aggregation:** County-level annual average impacts are calculated for the three eras and all GCMs considered in the analysis, assuming all farmers within a single county make the same investment decision for each time period/emissions scenario. Time period-level impacts are calculated by averaging years in each time period. State-level effects are calculated as the sum of all county-level revenues and costs.	

Table B34. Crop Tile Drainage Adaptation Costing Methods

Step	Description	Key Data Sources and Models
1	**Intersect location of croplands with soil data** to identify major soil types by county. Soils were categorized into 9 key soil types, which together cover about 75% of all cropped areas. The remaining soil types are assumed to need drainage that is consistent with the average cost across the other 9 major soil types.	Cropland: [195] Soils: [196]
2	**Estimate the Design Drainage Rate (DDR) for each county and soil type under historical conditions:** We rely on empirical relationships derived by Ghane et al. (2021) for the northeastern USA to estimate the historical DDR for each county and soil type. DDR (cm/day) is estimated as a function of the long-term average growing season precipitation from one month prior to planting to four months after planning (assumed to be March through August); a drain depth of 1 m for poorly drained soils, 1.25 m for medium-drained soils, and 1.5 m for well-drained soils; the saturated hydraulic conductivity of each soil type; and the estimated depth to the restrictive soil layer in each soil type, which varies for poorly, medium, and well-drained soils.	KNMI Climate Explorer, 2025[197] Design drainage rate equation: [198]
3	**Estimate the DDR for each county and soil type under altered climate conditions, for each time period and GCM:** Using the same equation as in Step 2, estimate the DDR given county level projections of future precipitation. We estimate future growing season precipitation from March through August, but given projected drying in the summer, we assume that any precipitation decreases in June through August will be offset through irrigation.	

[195] U.S. Department of Agriculture, National Agricultural Statistics Service, "Cropland Data Layer," 2025, https://www.nass.usda.gov/Research_and_Science/Cropland/Release/index.php.
[196] U.S. Department of Agriculture, Natural Resources Conservation Service, "Web Soil Survey," n.d., accessed November 15, 2025, https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx.
[197] KNMI Climate Explorer. (2025). https://climexp.knmi.nl/start.cgi
[198] Ehsan Ghane, Manal H. Askar, R. Wayne Skaggs. Design drainage rates to optimize crop production for subsurface-drained fields, Agricultural Water Management, Volume 257, 2021, 107045. https://www.sciencedirect.com/science/article/pii/S0378377421003103

Step	Description	Key Data Sources and Models
4	**Link changes in DDR to changes in optimum drain spacing:** Looking at Waseca county in Minnesota, Ghane et al. (2021) derive a relationship between increases in the DDR under wetter futures and the corresponding decrease in the optimum drain spacing that is required to maintain trafficability. We apply this relationship to derive how the change in DDR from Step 3 translates to an increase in the optimum drain spacing.	Changes in optimum drain spacing: [199]
5	**Estimate investment costs of additional drainage:** Using the change in the optimum drain spacing derived in Step 4, we estimate the investment costs for the incremental additional drainage using unit costs provided in Ghane et al. (2021). This calculation is repeated for each future time period, GCM, soil type, and county. The estimated $/hectare investment cost for a particular soil type are aggregated by multiplying the cost per hectare by the number of hectares of that soil type in that county. Costs across soil types are summed to the county level, with county-level costs summed to reach state totals.	Unit costs per linear meter of drains installed: [200]

Table B35. Crop Retention Ponds Adaptation Costing Methods

Step	Description	Key Data Sources and Models
1-3	Same as Table B34. The Design Drainage Rate (DDR) calculated in these steps provides an indication of the drainage outflow in cm/day for each soil type, county, time period, and climate scenario.	
4	**Estimate required retention pond storage.** Using the DDR from Steps 2 and 3, convert cm/day of drain outflow to a volume of accumulated water per hectare of cropland, with only well- and medium-drained soils assumed to generate high enough volumes of drainage so as to require retention ponds. We assume that retention ponds are sized in order to hold two days' worth of drainage water when the drains are operating at their peak rate (i.e., the DDR).	
5	**Estimate investment costs of retention pond capacity to hold incremental drainage water resulting from climate change:** Find the incremental drain outflow resulting from climate change by subtracting historic outflows from projected outflows under climate change for a single soil and county. We estimate the investment costs for retention pond storage using unit costs provided in EPA (2015), assuming pond sizes of no smaller than 100,000 m^3. County-level costs are summed to reach state totals.	Unit cost per unit volume of retention ponds: [201]

[199] Ehsan Ghane, Manal H. Askar, R. Wayne Skaggs. Design drainage rates to optimize crop production for subsurface-drained fields, Agricultural Water Management, Volume 257, 2021, 107045. https://www.sciencedirect.com/science/article/pii/S0378377421003103

[200] Ehsan Ghane, Manal H. Askar, R. Wayne Skaggs. Design drainage rates to optimize crop production for subsurface-drained fields, Agricultural Water Management, Volume 257, 2021, 107045. https://www.sciencedirect.com/science/article/pii/S0378377421003103

[201] EPA. 2015. Low Impact Development Stormwater Control Cost Estimation Analysis. https://pasteur.epa.gov/uploads/10.23719/1510483/documents/LID%20Cost%20Analysis_Report_National%20SWC_2015.pdf

Key limitations and uncertainties

Table B36. Sources of Uncertainty in Analysis of Cost of Inaction and Adaptation for Crops

Key Assumption or Source of Uncertainty	Direction of Potential Bias on Adaptation Cost	Likely Effect of the Uncertainty on Results
Crop Yields		
The analysis does not consider direct heat and cold stress impacts on crop yields.	**Unknown.** While cold stress is expected to decrease, heat stress is expected to increase with climate change. The net effects on specific cropping calendars and crop attributes.	**Potentially major.** Corn is a generally heat-tolerant crop. Other crops may be significantly affected by heat stress. Globally, the literature suggests these effects can be consequential, potentially leading to crop failure during extreme heat years.
There is a high degree of autonomous adaptation by farmers, who can adjust planting dates, input application, or crop selection to accommodate to predicted weather and environmental changes. Crop insurance can also limit losses during bad years.	**Overestimate impacts.** Autonomous adaptation will result in lower reduction in yields and/or revenues by farmers.	**Potentially major.** If farmers can anticipate weather conditions, they have the ability to significantly limit losses. Moreover, if farms seek profit maximization, then they are likely to adjust their cropping patterns slowly over time. However, their ability to prevent losses is hampered by increased uncertainty in seasonality and variability of climatic conditions with climate change.
The analysis is limited to three commodity crops (corn, soybean, wheat) and therefore does not include other important crops such as hay, potatoes, or sugar beets.	**Underestimate impacts.** Corn, soybean, and wheat account for the vast majority of acres planted and production value, however the combined impact across all other crops may also be significant.	**Potentially major.** Depending on existing irrigation coverage, the impacts of water stress and the potential adaptation costs could be large. It should also be noted that some crops may benefit from the changing climate.
The analysis assumes that groundwater is available for future irrigation demands.	**Underestimate impacts.** Groundwater pumping costs may be underestimated if groundwater levels are lower in the future. In water shortage situations, yield losses may also be underestimated.	**Unknown.** Information on groundwater availability, and how that availability may change in the future, is not readily available.
Drainage and Retention Ponds		
The drainage analysis focuses on changes in precipitation during the spring planting season (i.e., March through May) only.	**Underestimate costs.** While climate projections suggest reductions in precipitation during the fall harvest season, the focus of the analysis on spring planting may miss minor changes in fall trafficability from intense precipitation events.	**Likely minor.** Due to the more sizeable projected precipitation increases in spring months, versus other periods of the year, the focus on March through May likely has a minor overall effect.
Our assessment of drainage of cropland categorized soils into 9 key soil types, which cover about 75% of all cropped areas. The remaining soil types are assumed to need drainage that is consistent	**Unknown.** Impacts of climate change on trafficability of the more minor and less common soil types are not captured in the assessment.	**Likely minor.** While less common soil types may experience trafficability impacts not captured in this assessment, their contribution to the aggregate state level costs of adaptation are anticipated to be minor.

Key Assumption or Source of Uncertainty	Direction of Potential Bias on Adaptation Cost	Likely Effect of the Uncertainty on Results
with the weighted average cost across the other 9 major soil types.		
The retention ponds are sized to hold the additional flows contributed by in-field tile drains (as estimated by the DDR and assuming we need to store two days' worth of drain outflows), but do not take into account changing runoff and flood peaks from altered precipitation patterns under climate change.	**Unknown**. The analysis undertaken does not provide insights about the extent to which these retention ponds may influence pluvial flood attenuation.	**Potentially major.** Depending on the cumulative volume of additional runoff anticipated under climate change, retention ponds are likely to be undersized if there is a need to capture flood flows in addition to tile drain outflows.
We estimate the direct costs of constructing retention ponds for drainage water, but do not account for any additional costs that may be necessary to treat the water further downstream, or to transport the water from small farms to a single more centralized retention pond.	**Underestimate costs.** Removing excess soil moisture from fields may exacerbate pollution concerns downstream, with additional costs associated with treatment. Additionally, we assume that each farm can directly drain to a retention pond, which may underestimate the cost of drainage channels to the pond.	**Potentially major.** Depending on the cumulative volume and pollutant concentration of drainage water, direct retention pond costs may potentially underestimate the total costs.

Livestock

Cost of inaction

Impacts on livestock include the effect of heat stress on cattle milk yields, as well as energy demands on turkey barns. Cattle meat effects consider daily losses in milk production from increasing temperatures surpassing ideal thresholds. The analysis assumes that dairy barns are not equipped to protect cattle from heat stress higher than historical levels. For turkeys, we assume that barns are currently equipped with cooling and heating mechanisms. Impacts are then estimated from changes in net energy consumption for cooling and heating, assuming that the current infrastructure is sufficient to prevent higher temperatures from resulting in any meat yield losses.

Table B37. Costs of Inaction Summary: Livestock Impacts

Impact	Cost Measure	CMIP6 Data Used	Spatial Scale	Underlying Study	Methods Table
Cattle milk	Lost revenues	Daily County level temperature and precipitation	County	St-Pierre, Cobanov, and	Table B38

		Schnitkey, 2003[202]

Table B38. Cattle Milk Impact Methods

Step	Description	Key Data Sources and Models
1	**Dairy statistics:** We gather statistics on headcounts, milk yields, and revenue by county. Revenue data is not reported for counties with a small number of farms. For those, we distribute the missing amount by county using the number of farms. 2022 revenues are converted to 2024 dollars using average consumer price index changes.	Crop acres, production, revenues, and farms: USDA, 2022 Census[203] CPI: BLS, 2025[204]
2	**Temperature humidity index:** A cattle-specific temperature-humidity index (THI) is used to estimate the perceived temperature of an animal based on air temperature, wet-bulb temperature, and relative humidity. THI is calculated for each daily for each climate scenario.	THI equation for cattle: Mauger et al., 2015[205] Leiss et al. [206]
3	**Heat stress:** The direct effects of heat stress are estimated using a cattle-specific impact function for milk that relies on THI as an independent variable, with productivity losses based on heat tolerance thresholds. Production loss begins when the daily maximum THI exceeds a specified threshold, as cattle are subjected to temperatures beyond their ideal thermoneutral zone. Thus, THI is translated into daily impacts on milk yields as liters per head.	Approach and THI thresholds: St-Pierre, Cobanov, and Schnitkey, 2003[207]
4	**Lost revenues.** Annual yield impacts are converted to lost revenues by multiplying the percent change in yield by current revenue. Headcounts and prices are assumed to remain constant over time. Yields are assumed to be affected by climate change-related effects only, excluding changes in feed or management practices. Final revenue impacts are calculated as the difference between future and historical average revenues.	
5	**Aggregation:** County-level annual average impacts are calculated for the three eras and all climate scenarios considered in the analysis. Time period-level impacts are calculated by averaging years in each time period. State-level effects are calculated as the sum of all county-level effects.	

Adaptation costs

Adaptation in the livestock sectors considers investments in heat abatement measures on dairy farms. No adaptation measures are considered for turkeys, as energy costs are expected to see net reductions from a more significant reduction in heating costs than the increase in cooling costs. While increased

[202] N. R. St-Pierre et al., "Economic Losses from Heat Stress by US Livestock Industries," *Journal of Dairy Science* 86 (June 2003): E52–77, https://doi.org/10.3168/jds.S0022-0302(03)74040-5.
[203] U.S. Department of Agriculture, National Agricultural Statistics Service (USDA-NASS), "QuickStats Database."
[204] U.S. Bureau of Labor Statistics, "Consumer Price Index."
[205] Guillaume Mauger et al., "Impacts of Climate Change on Milk Production in the United States," *The Professional Geographer* 67, no. 1 (2015): 121–31, https://doi.org/10.1080/00330124.2014.921017.
[206] Leiss et al., "Fine-Scale Climate Projections over Minnesota for the 21st Century."
[207]

heat may still require additional capital expenditures or upgrades by farmers, such effects are not quantified in this study.

Table B39. Costs of Adaptation Summary: Livestock Adaptation Actions

Action	Cost Components	Impacts Addressed	Quantified Residual Risks	Spatial scale of Analysis	Methods Table
Heat abatement on dairy cattle barns	Capital and O&M	Heat stress on cattle milk	Yes, residual heat stress	County	Table B40
Turkey barn cooling	O&M (change in energy costs)	Turkey production	No	County	Table B41

Table B40. Cattle Barn Adaptation Costing Methods

Step	Description	Key Data Sources and Models
1-4	See Table 38above	
5	**Adaptation benefits:** Investments are then considered for an average farm within each county. We consider three levels of abatement: moderate (fans or forced ventilation), high (fans and sprinklers), and intense (high-pressure evaporative cooling system). Each abatement level has a corresponding heat-stress function that predicts lower heat stress at the same THI.	St-Pierre, Cobanov, and Schnitkey, 2003[208]
6	**Investment costs:** Similarly, each abatement level has a separate cost function that includes capital and operating costs. Capital costs are annualized using rates that consider different maintenance and depreciation requirements, as well as interest, for each adaptation level. All costs are converted to 2024 dollars using average consumer price index changes. For the moderate abatement level, annual capital costs are $426.25 per 3,800 kg of cattle body weight, annualized at 15%, with hourly operating costs of $0.059/hour. For the high abatement level, annual capital costs are $529 per 3,800 kg of cattle body weight, annualized at 25%, with hourly operating costs of $0.069/hour. For the intense abatement level, annual capital costs are $10,230 per 8,865 kg of cattle body weight, annualized at 15%, with hourly operating costs of $0.23/hour. Operating costs include electricity consumption, which is costed at $0.0915/kWh constant electricity price. We assume cattle weigh 1,400 lbs on average. We assume abatement measures are active (i.e., require electricity) only for days when the average temperature exceeds 65˚F.	Capital costs: St-Pierre, Cobanov, and Schnitkey, 2003[209] Energy costs: EIA, 2025[210] CPI: BLS, 2025[211] Cattle weight: MDA, n.d.[212]
7	**Final investment needs:** For each county, we compare average net benefits (i.e., change in revenues minus change in costs) with and without each level of adaptation across all climate scenarios within a given time period. Farmers are assumed to make a single investment decision at the beginning of each time period, preferring the alternative that minimizes costs of inaction while maintaining a net benefit greater than zero (i.e., farmers avoid investing at a level that results in a benefit-cost ratio lower than one). If net benefits are below this	

[209] St-Pierre et al., "Economic Losses from Heat Stress by US Livestock Industries."
[210] EIA, "State Energy Data System," U.S. Energy Information Administration, 2025, https://www.eia.gov/state/seds/.
[211] U.S. Bureau of Labor Statistics, "Consumer Price Index."
[212] Minnesota Department of Agriculture, *Dairy Cattle* (Minnesota Agriculture in the Classroom, n.d.), accessed November 21, 2025, https://cdn.agclassroom.org/mn/edu/card/dairycattle.pdf.

Step	Description	Key Data Sources and Models
	threshold for all levels of adaptation, we assume farmers do not invest and bear the full impact of the climate shock.	
8	**Aggregation:** County-level annual average impacts are calculated for the three eras and all climate scenarios considered in the analysis, assuming all farmers within a single county make the same investment decision for each time period regardless of the climate scenario. State-level effects are calculated as the sum of all county-level effects.	

Table B41. Turkey Adaptation Cost Methods

Step	Description	Key Data Sources and Models
1	**Turkey statistics:** We gather statistics on headcounts and farms by county. Revenue data is not reported for counties with a small number of farms. For those, we distribute the missing amount by county using number of farms. 2022 revenues are converted to 2024 dollars using average consumer price index changes.	Crop acres, production, revenues, and farms: USDA, 2022 Census[213] CPI: BLS, 2025[214]
2	**Barn area:** Floor area requirements vary for toms and hens, with toms needing 4 sqft per bird and hens need 3 sqft per bird. We assume an even distribution and estimate floor area requirements as 3.5 per bird. Then, we multiply by headcounts to estimate the total barn area by county. We assume that at any point in time, all turkeys are housed in a barn.	Minnesota Department of Agriculture, 2005[215]
3	**Current heating demand:** Data on heating (and cooling) energy requirements for turkey barns in the US is limited. We rely on heating requirements for poultry barns in Ireland per unit of area (61.5 kBTU/sqft), which have similar but warmer winters than Minnesota. We validate this estimate by comparing available data on energy demand for broiler production in Arkansas[216,217], which has lower requirements due to its warmer weather (24 kBTU/sqft on average). Minnesota has about 2.4 times more heating degree days than Arkansas on average. Assuming a linear transformation from the Arkansas data, we estimate 59 kBTU/sqft for Minnesota barns, similar to the Ireland figure. We then calculate the total energy requirement by county by multiplying the kBTU per sqft by total barn area.	Caslin and Tierney, 2020[218]
4	**Current cooling demand:** Similar to heating, we utilize the best available proxy to estimate cooling energy needs in Minnesota. We rely on the lowest available	Liang, Costello, and Bautista, 2019[219]

[213] U.S. Department of Agriculture, National Agricultural Statistics Service (USDA-NASS), "QuickStats Database."
[214] U.S. Bureau of Labor Statistics, "Consumer Price Index."
[215] Minnesota Department of Agriculture, *Poultry Your Way: A Guide to Management Alternatives for the Upper Midwest*, ed. Beth Nelson (St. Paul, MN, 2005), https://hdl.handle.net/11299/51841.
[216] G.T. Tabler et al., "Energy Costs Associated with Commercial Broiler Production," *Avian Advice* 5, no. 4 (2004), https://www.thepoultrysite.com/articles/energy-costs-associated-with-commercial-broiler-production.
[217] Yi Liang et al., "Energy Consumption and Conservation Opportunities for Arkansas Broiler Production," *Agriculture and Natural Resources*, 2019.
[218] Barry Caslin and Rebecca Tierney, *Energy Efficiency in Poultry Units*, Fact Sheet Energy 12 (Agriculture and Food Development Authority (Teagasc), 2020), https://teagasc.ie/wp-content/uploads/media/website/rural-economy/rural-development/diversification/Energy-12_Poultry-Energy-Efficiency-in-Poultry-Units.pdf.
[219] Liang et al., "Energy Consumption and Conservation Opportunities for Arkansas Broiler Production."

Step	Description	Key Data Sources and Models
	estimate of electricity needs in the US per unit of area (6.2 kBTU/sqft) from the University of Arkansas, and assume that half of the total electricity demand comes from cooling (i.e., 3.1 kBTU/sqft), consistent with the source study. We then calculate the total cooling energy requirement by county by multiplying the kBTU per sqft by total barn area.	
5	**Current energy costs:** Current energy costs are then calculated by multiplying total energy needs by energy prices. 2023 prices are converted to 2024 dollars using average consumer price index changes. Heating costs rely on Minnesota-specific propane costs for the industry sector ($0.015/kBTU), while cooling costs rely on industrial electricity prices ($0.027/ kBTU).	EIA, 2025[220] CPI: BLS, 2025[221]
6	**Cooling and heating degree days:** To estimate how heating and cooling costs may change in the future, we use climate projections to forecast changes in heating and cooling degree days, metrics commonly used for energy use calculations. Heating degree days are calculated as the total number of degrees below 65 each day. For example, if day 1 is 35 degrees and day 2 is 25 degrees, the heating degree days for those two days would be 70 "degree-days". Cooling degree days are the same calculation, but for degree days above 65 degrees. This metric is widely used in the energy industry to understand the building heating and cooling requirements in a given region.	Leiss et al. [222]
7	**Future energy costs:** Future cooling and heating energy costs are estimated by multiplying current costs by the percent change in cooling degree days and heating degree days in each year relative to historical average values. The calculation is done separately for cooling and heating.	
8	**Aggregation:** Annual average costs are calculated for the three eras and all climate scenarios considered in the analysis. Time period-level impacts are calculated by averaging years in each time period. Lastly, county-level costs are added for each year to estimate net energy cost changes. State-level effects are calculated as the sum of all county-level effects.	

Key limitations and uncertainties

Table B42. Sources of Uncertainty in Analysis of Livestock Costs

Key Assumption or Source of Uncertainty	Direction of Potential Bias on Adaptation Cost	Likely Effect of the Uncertainty on Results
All Livestock Analyses		
The analysis does not consider potential biosecurity from the spread of pests and diseases, which can affect animal mortality and yields.	**Underestimate impacts.** Anecdotal evidence from recent biosecurity risks points to potentially additional impacts rather than reductions in current risks.	**Potentially major.** Turkeys have a frail immune system, and authorities could force farmers to cull the entire population in the event of an outbreak.

[220] EIA, "State Energy Data System."
[221] U.S. Bureau of Labor Statistics, "Consumer Price Index
[222] Leiss et al., "Fine-Scale Climate Projections over Minnesota for the 21st Century."

Key Assumption or Source of Uncertainty	Direction of Potential Bias on Adaptation Cost	Likely Effect of the Uncertainty on Results
Dairy		
The analysis does not consider potential reductions in feed or water availability for livestock, which can further decrease the productivity of animals.	**Underestimate impacts.** While impacts can potentially fluctuate between positive and negative, it is likely that climate change will reduce feed production (hay, fodder crops, pastures) and water availability.	**Likely minor.** Even if resource availability declines, that decline is unlikely to translate into shortages for livestock.
The heat stress model assumes that dairy farms have limited heat abatement measures currently. In reality, some farms are likely better-prepared to cope with increased heat.	**Unknown.** If farmers today have cooling systems that can protect cattle from higher temperatures, those farms will not experience the full extent of the modeled shock. However, they will incur additional energy consumption costs that would offset these effects.	**Likely minor.** The number of farms in Minnesota with improved cooling systems for hotter summers is believed to be small.
Turkey		
The analysis assumes that current barn cooling systems are sufficient to prevent the impact of increased heat. However, these systems may be incapable of cooling barns once temperatures surpass a critical threshold.	**Underestimate impacts.** If cooling systems cannot lower temperatures to safe levels during high heat conditions, yields are expected to decline. Moreover, increased usage of these systems is expected to require farmers to conduct more frequent maintenance and /or reduce their expected lifetime, therefore resulting in incremental costs.	**Potentially major.** We do not have the necessary information to estimate the proportion of barns that would need to install new technology for cooling however these systems could be costly.

Transportation and Electricity Infrastructure

Generally, projections of both impacts and adaptation costs are among the best-developed estimates in the U.S. focused literature. The analyses are based on published studies, with the road and rail work reflecting a decade-long evolution of impact and adaptation life-cycle cost optimization modeling, with multiple supporting lines of research. Data on impacts and adaptation reflect engineering analyses and engineering cost data for the repair cost component, and repair time and/or user re-routing estimates for the user delay time component.

Transportation

The models used for the transportation analyses model costs of inaction and adaptation costs together, therefore both methods are presented together for this category of impacts.

Cost of inaction and adaptation costs

The transportation infrastructure analyses address road and rail infrastructure comprehensively for Minnesota, using a method from the same study and modeling platform, which is incorporated in FrEDI and adjusted for CliMAT scenarios and, where possible for MNDOT infrastructure inventory data. The Cost of inaction estimates for roads incorporate culvert failures. The culvert adaptation cost analysis is a customized methodology based on a method previously developed and applied for the State of

Delaware which uses MNDOT culvert infrastructure data. The culvert adaptation cost analysis does not consider life-cycle optimization but does take a forward looking, flow capacity upgrade approach.

Table B43. Costs of Inaction and Adaptation Cost Summary: Transportation Infrastructure Impacts

Impact	Cost Measure	CMIP6 Data Used	Spatial Scale	Underlying Study	Methods Table
Roads	Repair cost	CONUS Temp (FrEDI)	State and county	Neumann et al., 2021[223]	Table B44
	Delay cost to road users				
Rail	Repair cost	CONUS Temp (FrEDI*)	State and county	Neumann et al., 2021	Table B45
	Delay cost to users				
Culverts – Costs of Inaction	Repair cost	CONUS Temp (FrEDI*)	State and county	Neumann et al. 2021	Table B30
	Delay cost to users				
Culverts – Adaptation Cost	Repair cost after high flow events	Based on CMIP5 GCMs incorporated in Fant et al. (2018)**	Culvert locations (passing under roadways)	IEc, 2021[224]	Table B46
	Delay cost to users during repairs				

*Adjusted FrEDI output for impacts-by-degree and MNDOT inventory
**Gray literature method

Table B44. Road Impact and Adaptation Methods

Step	Description	Key Data Sources and Models
1	Accessed the detailed county-specific, per road mile results from Neumann et al. (2021) for MN (obtained from the author team). Results included disaggregated results by climate stressor (temperature, precipitation, and flooding), along with breakout percentages disaggregated by delay/VOC versus repair (and upgrade) by road type/SSP/year, for all three adaptation response scenarios (Cost of Inaction; Reactive Response; Proactive Adaptation). Culvert results are part of costs of inaction, but replaced with custom analysis for Proactive Adaptation	Neumann et al, 2021[225]
2	Obtained county-level road inventory from publicly available MNDOT roads inventory, with information on road miles by road	MDOT[226]

[223] 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 at: https://link.springer.com/article/10.1007/s10584-021-03179-w

[224] Industrial Economics, Incorporated. 2021. An Economic Analysis of the Impacts of Climate Change in the State of Delaware. Prepared for the Delaware Department of Natural Resources and Environmental Control. Available at: https://documents.dnrec.delaware.gov/energy/Documents/Climate/Plan/Economic-Analysis-of-the-Impacts-of-Climate-Change-in-the-State-of-Delaware.pdf

[225] Neumann, J., 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 at: https://link.springer.com/article/10.1007/s10584-021-03179-w

[226] https://gisdata.mn.gov/dataset/trans-roads-centerlines

Step	Description	Key Data Sources and Models
	type (primary/secondary/tertiary) and surface (paved versus unpaved/gravel).	
3	Adjusted results to reflect differences between CMIP5 GCMs used in Neumann et al. (2021) and CMIP6 results in MN CliMAT. For costs of inaction, all results categories (including culvert impacts) were adjusted using average summer degrees of warming, maintaining dimensions on the proportion of cost by road level (primary, secondary, and tertiary); surface type (paved, gravel, and unpaved). Note: there are no gravel or unpaved primary roads in the inventory. For both the reactive and proactive adaptation scenarios (excluding culverts), results were adjusted by climate stressor: Temperature-influenced impacts are scaled by summer degrees of warming by county with 11-year smoothing. Precipitation-influenced impacts on paved and gravel roads are scaled by the change in maximum monthly precipitation, also with 11-year smoothing. Flooding influenced impacts rely on scaling based on annual average degrees of warming. The scaling is consistent with the generalized relationship between annual degrees of warming and the intensity of high precipitation events, known as the Clausius-Clapeyron equation.	Leiss et al. [227]

Table B45. Rail Impact and Adaptation Methods

Step	Description	Key Data Sources and Models
1	For cost of inaction, run FrEDI with CMIP6 temperature projections and Minnesota specific population projections. The scenario reflects no action by passenger and rail operators to slow trains during heat events, which leads to track buckling events, a higher need for costly track repair, and delays for passengers associated with the need for repair.	FrEDI[228] KNMI Climate Explorer, 2025[229] MN State Demographic Center, 2024a[230]
2	For adaptation costs, run FrEDI with CMIP6 temperature projections. Reactive scenario models operators implementing train speed restrictions during periods of high temperature to avoid track buckling events. Proactive Adaptation scenario models operators using track temperature sensors to optimize their speed restrictions. The analysis estimated the costs of delays and any needed repairs to buckled track sections in each scenario, along with the capital costs of installing sensors in the Proactive Adaptation scenario.	

[227] Leiss et al., "Fine-Scale Climate Projections over Minnesota for the 21st Century."
[228] https://epa.gov/cira/about-fredi/index.html
[229] KNMI Climate Explorer. (2025). https://climexp.knmi.nl/start.cgi
[230] Minnesota State Demographic Center. (2024). *Long-Term Population Projections for Minnesota By Age and Sex* [Dataset]. https://mn.gov/admin/demography/data-by-topic/population-data/our-projections/

Table 46. Culvert Adaptation Methods

Step	Description	Key Data Sources and Models
1	Obtain traffic data and culvert location/design data on culverts in Minnesota from MNDOT	Personal communication with MNDOT personnel who manage the MNDOT Drainage Manual.
2	Identify culverts that have already been replaced and upgraded under existing MNDOT actions and/or policies for replacement prior to mid-century and exclude them from further adaptation analysis. The three criteria used to identify excluded culverts are: 1. All culverts with a "Like New" condition flag in the MNDOT culvert inventory 2. All culverts with a "Inspected and Replaced" flag in the inventory 3. 20 percent of the remaining culverts vulnerable to pre-mid-century high flow conditions.	MNDOT culvert inventory
3	Establish a total failure damage estimate for each culvert, which includes approximate costs of culvert replacement to the same standard as originally built; road reconstruction; and indirect costs of traffic delays	IEc, 2021 for overall method; average costs for culvert repair and replacement from MNDOT 2015,[231] road reconstructions costs from USDOT (2019),[232] indirect costs based on hours of time for repair completion from MNDOT, (2015).
4	Determine three levels of culvert failure, quarter, half, and full damage, triggered when flows exceed required design flows at 50, 100, 200 year flood event for minor roads, and 100, 200, 400 year flood event for major roads.	IEc, 2021
5	Estimate changes in the occurrence of culvert failures using extreme value statistics and daily simulated flows.	Fant et al., 2017[233]
6	Aggregate costs for culvert repair and replacement and indirect costs for each time period and two RCPs (4.5 and 8.5) using a suite of five CMIP5 GCMs.	IEc, 2021

[231] 2015 Maintenance Culvert Cost Data Analysis, conducted by the Minnesota Department of Transportation, http://www.dot.state.mn.us/bridge/hydraulics/culvertcost/2015%20Drainage%20Maintenance%20Data%20Summary%20-%20Final%20Version.pdf

[232] Appendix A-1 of the biennial Status of the Nation's Highways, Bridges, and Transit: Conditions & Performance (23rd Edition), a report from the U.S. Department of Transportation prepares for Congress, 2019. https://www.fhwa.dot.gov/policy/23cpr/

[233] Fant, Charles, Raghavan Srinivasan, Brent Boehlert, Lisa Rennels, Steven C. Chapra, Kenneth M. Strzepek, Joel Corona, Ashley Allen, and Jeremy Martinich. (2017). Climate Change Impacts on US Water Quality Using Two Models: HAWQS and US Basins. Water, 9:118-138), doi:10.3390/w9020118.

Key limitations and uncertainties

Table B47. Sources of Uncertainty in Analysis of Transportation Costs

Key Assumption or Source of Uncertainty	Direction of Potential Bias on Adaptation Cost	Likely Effect of the Uncertainty on Results
Omission of some indirect effects of road and rail damage on local and state economies, productivity, and employment	**Underestimate impacts.** While the analysis does consider road user delay costs, other indirect/secondary costs are omitted. This omission underestimates impacts and may also underestimate the benefits of adaptation, leading to lower adaptation cost estimates.	**Potentially major.** Some prior work suggests that indirect costs on economic productivity can be comparable to direct costs, suggestion an underestimation bias of as large as a factor of two.
Omission of freeze-thaw stressor in roads analysis	**Unknown.** Freeze-thaw events occur during a generally narrow temperature range around freezing. Climate change is likely to both increase and decrease freeze-thaw incidence in different locations, in unknown combinations, but is unlikely to completely eliminate the occurrence of these damaging events.	**Unknown.** Because the direction of effect is uncertain, the magnitude already remains uncertain.
Omission of winter road clearing and maintenance costs	**Overestimate impacts.** Higher winter temperatures should reduce the need for winter road clearing and maintenance, as more snow events could become rain events.	**Likely minor.** Marginal costs of road clearing and maintenance would be reduced, but the capital costs associated with maintaining a fleet of equipment would likely not be significantly reduced.
Damages to vehicles associated with incompletely maintained roads are modeled only in the cost of inaction scenario; the model assumes roads are completed repaired and thus vehicles receive no damage under the reactive and proactive adaptation scenarios.	**Underestimate impacts.** Road damage events are not always immediately or completely repaired, so this omission likely underestimates impacts, and in particular underestimates residual costs.	**Likely minor.** Vehicle damage costs are generally smaller than delay costs, and particularly so if repairs are merely delayed and not permanently put off.
No modeling of derailments in rail analysis	**Underestimate impacts.** Rail buckling events account for only 4 percent of derailments nationwide, but derailments are among the most damaging track buckling events and can also endanger passenger safety.	**Unknown.** No comprehensive estimates of the costs of derailments are yet available.
Culvert analysis relies on riverine flow projections for two RCPs (4.5 and 8.5) using a suite of five CMIP5 GCMs, rather than CMIP6, as proxy for local scale flow through drainage channels typically flowing through smaller culverts	**Unknown.** The lack of availability of more highly resolved flow data may lead to both overestimation and underestimation errors.	**Unknown.** No comprehensive estimates of the frequency and intensity of high flow events in smaller drainage channels are available for Minnesota.

Electricity

The models used for the electricity analyses model costs of inaction and adaptation costs together, therefore both methods are presented together for this category of impacts.

Cost of inaction and adaptation costs

Table B48. Costs of Inaction Summary: Electricity Infrastructure Impacts

Impact	Cost Measure	CMIP6 Data Used	Spatial Scale	Underlying Study	Methods Table
Electricity impact – Transmission and Distribution Infrastructure	Infrastructure repair and replacement cost	CONUS Temp (FrEDI)	State	Fant et al., (2020)[234]	Table B49

Table B49. Electricity Impact – Transmission and Distribution Infrastructure Methods

Step	Description	Key Data Sources and Models
1	Run FrEDI with CMIP6 temperature projections and MN-specific population projections – no adaptation scenario assumes that infrastructure replacement occurs when damaged or reaches end of useful life and is replaced with equipment consistent with baseline climate suitability	FrEDI[235] KNMI Climate Explorer, 2025[236] MN State Demographic Center, 2024a[237]
2	Run FrEDI with CMIP6 temperature projections and MN-specific population projections – reactive and proactive adaptation scenarios. Reactive response scenario assumes that infrastructure replacement occurs when damaged or reaches end of useful life and is replaced with equipment consistent with then current climate suitability. Proactive adaptation scenario assumes that infrastructure replacement occurs when damaged or reaches end of useful life and is replaced with equipment consistent with anticipated projected climate suitability.	FrEDI[238] KNMI Climate Explorer, 2025[239] MN State Demographic Center, 2024a[240] Fant et al., 2020[241]

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

[235] https://epa.gov/cira/about-fredi/index.html

[236] KNMI Climate Explorer. (2025). https://climexp.knmi.nl/start.cgi

[237] Minnesota State Demographic Center. (2024). *Long-Term Population Projections for Minnesota By Age and Sex* [Dataset]. https://mn.gov/admin/demography/data-by-topic/population-data/our-projections/

[238] https://epa.gov/cira/about-fredi/index.html

[239] KNMI Climate Explorer. (2025). https://climexp.knmi.nl/start.cgi

[240] Minnesota State Demographic Center. (2024). *Long-Term Population Projections for Minnesota By Age and Sex* [Dataset]. https://mn.gov/admin/demography/data-by-topic/population-data/our-projections/

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

Key limitations and uncertainties

Table B50. Sources of Uncertainty in Analysis of Electricity Costs

Key Assumption or Source of Uncertainty	Direction of Potential Bias on Adaptation Cost	Likely Effect of the Uncertainty on Results
Power outages that might be caused by the infrastructure failures modeled in this study are not estimated in the underlying study. As a result, direct and indirect costs of outages are not included.	**Underestimate impacts.** The adaptation scenarios assume that repairs to damaged infrastructure happen soon after damage occurs, but supply chain effects in particular can lengthen replacement times and increase the risk of power outages.	**Potentially major.** Power outages have large and wide-ranging effects, meaning their omission could have a large effect on the estimates presented here.
The underlying study's impact model assumes that grid demand is controlled by population change and climatic factors; grid demand is assumed to not be influenced by economic growth. Future changes in the design and structure of electric grids are not considered in this study.	**Underestimate impacts.** Since the study was conducted, substantial increases in grid demand associated with data centers have arisen and do not generally track with population or overall economic growth.	**Unknown.** There are not comprehensive analyses of the increase in grid demand from data centers on grid reliability.

Buildings

Flooding

Costs of inaction

Table B51. Costs of Inaction Summary: Flooding Impacts

Impact	Cost Measure	CMIP6 Data Used	Spatial Scale	Underlying Study	Methods Table
Building damages from pluvial and fluvial flooding	Building damage costs	Fathom's ensemble of High Resolution CMIP-6 GCMs listed as part of the PRIMAVERA project listed here.	1/3 arcseconds	Fathom flood maps	Table B52

Table B52. Building Damages from Pluvial and Fluvial Flooding Impact Methods

Step	Description	Key Data Sources and Models
1	**Estimation of current flood depths**: We rely on flood surfaces from the 2025 Fathom U.S. Flood Maps. These use a high-resolution Digital Elevation Map (DEM) called FABDEM+, integrating openly available LiDAR datasets. • **For fluvial (i.e., riverine) flooding**, flood flows and corresponding return periods are estimated using available river gauges and predictors in ungauged catchments. Flows are evaluated in a bespoke hydrodynamic inundation model to produce estimates of flood depths and extents. • **Pluvial (i.e., precipitation) flooding** relies on rainfall intensities for events of different duration using the BURGER (Bottom Up Regionalised Global Extreme Rainfall) dataset and their associated probabilities to establish a global baseline of Intensity-Duration-Frequency curves. These Intensity-Duration-Frequency curves are then applied to a "rain-on-grid" hydraulic model to estimate inundation depths. Resulting flood surfaces are available at a 1/3 arc-second resolution (about 10 meters).	Fathom U.S. Flood Map[242]
2	**Change in flood depths from climate change:** In addition to the current flood surfaces, we also obtain flood projections under climate change from Fathom. Climate change impacts are modeled as a shift in the current flood frequency for both pluvial and fluvial flooding based on CMIP6 projections. Resulting flood surfaces for a range of return periods (e.g., 10, 20, 50, or 100-year flood events) are available for SSP2-4.5 and 5-8.5 in the CMIP6 ensemble.	
3	**Resources at risk:** The flooding analysis considers damages to buildings, relying on rasterized building footprints from the USGS. We assign value to these building footprints and classify them into residential/commercial/industrial/agricultural/institutional buildings using county-level parcel data from parcel maps. In areas where structure value is unavailable from the parcel maps, we use the American Community Survey (ACS) 5-year, 2019-2023, estimate by census block group, median home value and an average percent of structure value over total value (structure and land) from nearby parcel data.	Building footprints: USGS (2020).[243] Parcel maps: Minnesota IT Services: Geospatial Information Office.[244] U.S. Census Bureau[245]

[242] https://www.fathom.global/product/global-flood-map/us-flood-map/
[243] USGS, "A National Dataset of Rasterized Building Footprints for the U.S.," 2020, https://doi.org/10.5066/P9J2Y1WG.
[244] Minnesota IT Services: Geospatial Information Office, "Land Ownership: Parcels," n.d., https://www.mngeo.state.mn.us/chouse/land_own_property.html.
[245] U.S Census Bureau, "American Community Survey 5-Year B01003_001," 2023. https://www.census.gov/data/developers/data-sets/acs-5year.2023.html#list-tab-1806015614

Step	Description	Key Data Sources and Models
4	**Damage estimation**: Flood depths are ultimately combined with depth-damage functions to estimate the total share of resources that are damaged in a particular flood event. Damage functions describe the relationship between the flooding depth and the level of asset damage. The maximum flood damage to an object can be computed as a certain damage factor multiplied by the total value of the object. Flood depth-damage functions from FEMA's HAZUS model are used for each building use type (e.g., residential, commercial) and the existence of a basement. For this analysis, we assume structures are built 1 ft from the ground level in the baseline. We assume existing building-level protection has been built for all buildings with a benefit-cost ratio of at least 6 and this protection is maintained in the future. Total damage is computed by calculating the damage to each object and location separately for pluvial and fluvial flooding events. These two damage calculations can be added to represent the total flood damage.	FEMA Depth-damage functions[246]

Adaptation costs

Table B53. Costs of Adaptation Summary: Flood Adaptation Actions

Action	Cost Components	Impacts Addressed	Quantified Residual Risks	Spatial scale of Analysis	Methods Table
Elevating structures (two options 2 and 8 ft)	Capital costs (annualized)	Building damages from pluvial and fluvial flooding	Yes, flood damages to structures	Structure	Table B54
Floodproofing existing buildings (up to 1 ft)	Capital costs (annualized)	Building damages from pluvial and fluvial flooding	Yes, flood damages to structures	Structure	Table B54
Basement waterproofing using sump pumps, drainage systems, or exterior waterproofing	Capital costs (annualized)	Basement flooding	No	Structure	Table B54

[246] https://www.fema.gov/sites/default/files/documents/fema_hazus-flood-model-technical-manual-6-1.pdf

Table B54. Building Damages from Pluvial and Fluvial Flooding Costing Methods

Step	Description	Key Data Sources and Models
1	**Adaptation options and costs**: The adaptation options—dry floodproofing and elevating—are based on FEMA's homeowner's guide to retrofitting. Dry floodproofing costs are relative to the length of the outer perimeter of the building which are derived for each building using the building footprint. The cost for elevating structures is relative to the square footage of the ground floor, estimated using the building footprint, and the height elevated. For computational efficiency, we limit the height to two options: two feet and eight feet.	FEMA's Homeowners guide to retrofitting[247]
2	**Thresholds for investments:** For each structure, we estimate the BCR for all three options over a ten-year planning horizon. The benefit is the average annual loss due to repair over the planning horizon without the adaptation subtracted by the average annual loss with the adaptation, similar to other studies.[223,255] The cost of the adaptation used in the BCR is similarly evaluated over the planning horizon including the capital cost as well as an annual maintenance cost. The simulation protects structures if at least one of the BCRs from the three adaptation options is above a specified threshold, depending on the scenario (see step 3 below), and the lowest BCR is chosen among the adaptation options.	Neumann et al. [223]
3	**Adaptation scenarios:** For the impact analysis, we assume no additional flood protection is put in the place in the future, but existing protection is maintained. As alternatives, we evaluate two levels of adaptation: moderate and high. The moderate adaptation adapts with a BCR threshold of six so that a significant proportion of homes are protected but flood damage still increases in the future, just to a lesser degree than the impact analysis. For the high adaptation, we adjust the BCR threshold until the additional damage from climate change is approximately zero such that flood damage repair costs are roughly the same as in the past.	

Table B55. Basement Flooding Adaptation Costing Methods

Step	Description	Key Data Sources and Models
1	**Characterize soil types in urban areas**: We intersect urban areas with soil data to assess the proportions of different soil types in these areas. Soil types were classified into poorly drained, medium-drained and well-drained soils based on their hydraulic conductivity.	Urban areas: [248] Soils: [249]

[247] Federal Emergency Management Agency. (2020). Homeowner's guide to retrofitting: Six ways to protect your home from flooding (PDF). U.S. Department of Homeland Security. https://www.fema.gov/sites/default/files/2020-07/fema_homeowners-guide-to-retrofitting_guide.pdf
[248] U.S. Department of Agriculture, National Agricultural Statistics Service, "Cropland Data Layer."
[249] U.S. Department of Agriculture, Natural Resources Conservation Service, "Web Soil Survey."

Step	Description	Key Data Sources and Models
2	**Changes in peak monthly precipitation to estimate changes in soil moisture:** By county, we calculated the average monthly precipitation experienced in the wettest month of the year historically – this served as the baseline beyond which adaptive action is assumed to be required to address future climate-driven hazards. For each future time period and climate change scenario, we then calculate the average future monthly precipitation to identify the increase in precipitation and soil moisture in the wettest month as a result of climate change in each county.	KNMI Climate Explorer, 2025[250]
3	**Thresholds for investment:** We formulated soil-specific precipitation increase thresholds beyond which investment in additional basement waterproofing measures are considered necessary. Poorly-drained soils have a lower threshold for investment than medium- and well-drained soils, but are also assumed to have a higher baseline level of basement waterproofing (i.e., interior sealing and a sump pump versus just interior sealing in medium- and well-drained soils).	
4	**Investment costs:** We assume that households make at most one major floodproofing investment per time period. Additional investments are assumed to be pursued in order of increasing investment cost, starting with a sump pump, followed by installation of an interior or exterior drainage system, and exterior foundation waterproofing. Costs are annualized capital costs that assume a 20-year infrastructure lifespan. Capital cost values used represent a midpoint of various available estimates at $1,250 for a sump pump, $4,500 for a drainage system, and $11,500 for exterior waterproofing.	
5	**Estimate the number of housing units per urban area:** Using county population data and housing unit counts by county, we estimated the average number of people per dwelling unit by county. We used this result in combination with the population by city to estimate the number of housing units by urban area, and assume that 80 percent of existing housing units have basements.	Population by city: [251] Population by county: [252] Housing unit counts: [253] Share of homes built since 1971 with basements (Midwest): [254]
6	**Final investment needs and aggregation:** We assume an adaptation investment is made when the relevant precipitation increase threshold for a specified soil type is exceeded. The estimated investment cost per household for a particular soil type are aggregated by multiplying the costs per household by the number of households in each city and the proportion of the city area of each soil type. Costs across soil types are summed to the city level, with city-level costs summed to reach state totals.	

[250] KNMI Climate Explorer. (2025). https://climexp.knmi.nl/start.cgi
[251] Minnesota Geospatial Commons. 2024. City, Township, and Unorganized Territory in Minnesota.
[252] Minnesota Demographics. 2025. Minnesota Counties by Population.
[253] Annual Estimates of Housing Units for Counties in Minnesota: April 1, 2020 to July 1, 2024 (CO-EST2024-HU-27). Source: U.S. Census Bureau, Population Division. Release Date: May 2025
[254] United States Census Bureau. 2024. Survey of Construction (SOC). Data for the Midwest from 1971-2024.

Key limitations and uncertainties

Table B56. Sources of Uncertainty in Analysis of Building Flooding

Key Assumption or Source of Uncertainty	Direction of Potential Bias on Adaptation Cost	Likely Effect of the Uncertainty on Results
Building Damages from Pluvial and Fluvial Flooding		
We assume the first floor elevation of all buildings is one foot above the ground. However, if the past flood risk is high enough to result in a benefit-cost ratio of at least 6, and the most cost-effective solution is to elevate the structure, we assume it was elevated.	**Unknown.** Likely structures are built both above and below one foot above the ground elevation.	**Potentially major.** While structures are not likely be significantly above or below this level, first floor elevation directly affects the flood elevation, and as a result the damage calculation.
We assume existing protection is built for structures with a benefit-cost ratio of at least 6. While this is within the range of other findings,[255] there is likely a wide variation in how and where existing protection has been built over time since it depends on individual home-owner decisions.	**Unknown.** Without structure-level information about existing protection, it's not clear if this will increase or decrease the flood damage estimate or adaptation cost. A lower benefit-cost ratio for existing protection will reduce the damage estimate and adaptation costs and vice versa.	**Potentially major.** Existing structure-level protection has a direct effect on the cost of inaction as well as future adaptation cost.
We rely on assessed structure and property values to estimate damage repair costs. While this is a common approach to damage calculations, these assessed values may be inaccurate.	**Unknown.** Higher structure values will result in a higher damage estimate and adaptation cost, and vice versa.	**Likely moderate.** Since the majority of the structure values were derived from the parcel data, these are not likely to be significantly different from actual values.
Basement Flooding from Increased Soil Moisture		
We assume that in the historic baseline, existing houses on medium- and well-drained soils have interior basement sealing, and that houses on poorly-drained soils have both interior sealing as well as sump pumps to prevent basement floods.	**Unknown.** Existing structures may have more or less basement floodproofing than assumed.	**Likely minor.** Since repeated and damaging basement flooding historically would likely have been addressed by some kind of floodproofing investment, the assumption that most basements can withstand historic baseline levels of soil moisture is considered realistic.

[255] Lorie, Mark, James Neumann, Marcus Sarofim (corresponding), Russell Jones, Radely Horton, Robert E. Kopp, Charles Fant, Cameron Wobus, Jeremy Martinich, Megan O'Grady, 2019, Modeling Coastal Flood Risk and Adaptation Choices under Future Climate Conditions, Climate Risk Management 29 https://doi.org/10.1016/j.crm.2020.100233

Key Assumption or Source of Uncertainty	Direction of Potential Bias on Adaptation Cost	Likely Effect of the Uncertainty on Results
Building Damages from Pluvial and Fluvial Flooding		
Based on data for the Midwest, we assume that 80 percent of housing in urban areas has useable basements that can be damaged from flooding.	**Unknown.** It is unclear what fraction of existing homes in Minnesota have a basement and which portion of existing basements are considered "finished" basements, such that floodproofing investments would be conducted in response to water damage. These uncertainties can result in either over- or underestimation of adaptation investments.	**Potentially moderate.** Given the importance of the number of structures for which basement flood proofing is assumed to be needed on the estimated costs, uncertainty in the number of homes with basements can drive potentially moderate variance in the investment needs.
We assume that basement flooding outside of urban areas is minimal.	**Underestimate costs.** This assumption may result in the exclusion of additional basement adaptation costs in rural areas.	**Likely minor.** As the majority of Minnesotans reside in urban areas, the adaptation costs for possible basement flooding in rural areas are likely minor in comparison.

Wind and wildfire

Wildfire affects buildings in Minnesota which are located within the wildland-urban interface. This risk has been increasing in recent years. Costs of inaction include increases in damage to structures as the risk of burning increases, associated with dryer and hotter conditions in future years, as well as the need to increase wildfire suppression efforts in response to fires. Adaptative actions include hardening of structures and vegetation management near homes, as well as increased pre-suppression activity such as prescribed burning of forests to reduce fuel load.

We currently have no basis to estimate the potential for a change in the risk of wind damage to structures associated with climatic changes, though recent trends suggest climate change may lead to an increase in the severity if not the frequency of damaging "derecho" wind events.[256]

Costs of inaction

Table B57. Costs of Inaction Summary: Wildfire and Buildings

Impact	Cost Measure	CMIP6 Data Used	Spatial Scale	Underlying Study	Methods Table
Wildfire damage to structures	Property damage	New estimate from available data	Statewide	Gao et al. 2021[257]	Table B58

[256] S. Lasher-Trapp, S.A. Orendorf, and R.J. Trapp (2023). Investigating a Derecho in a Future Warmer Climate. Bulletin of the American Meteorological Association, 104(10): E1831–E1852, https://doi.org/10.1175/BAMS-D-22-0173.1

[257] Peng Gao, Adam J. Terando, John A. Kupfer, J. Morgan Varner, Michael C. Stambaugh, Ting L. Lei, J. Kevin Hiers, Robust projections of future fire probability for the conterminous United States, Science of The Total Environment, Volume 789, 2021, 147872, https://doi.org/10.1016/j.scitotenv.2021.147872 .

Impact	Cost Measure	CMIP6 Data Used	Spatial Scale	Underlying Study	Methods Table
Wildfire suppression costs	Wildfire emergency response costs	New estimate from available data	Statewide	MN DNR, 2025[258] and Gao et al., 2021	Table B59

Table B58. Wildfire and Buildings - Building Damage Methods

Step	Description	Key Data Sources and Models
1	Estimate baseline annual wildfire damage to buildings. Baseline estimate generated by reference to historical reported estimates of damage by St Louis County assessors from the 2025 Brimson Complex Fire, as well as weighted average of number of structures, annual risk of burn, and quantified risk level from USDA HURisk estimates, and median value of structure outside of Hennepin and Ramsey counties from assessor's database used in flood risk analysis (median structure value is $224,000)	Dillon et al. 2024, Wildfire Risk to Communities[259]
2	Scale future building damage risk from baseline to SSPs 2-45 and 5-85 in mid and end century periods using incremental estimated percentage increase in total acreage burned in Minnesota from Gao et al. (2021) for the Minnesota pyrome.	Gao et al. 2021[260]
3	Interpolate estimates for late century and SSP 3-70 from available estimates	

Table 59. Wildfire and Buildings – Suppression and Emergency Wildfire Response Costs Methods

Step	Description	Key Data Sources and Models
1	Estimate baseline annual MN DNR Suppression Costs from MNDNR (2025) by taking 10-year average over the 2015-2024 period. Estimate USFS estimates for Superior and Chippewa National Forests from disaster preparedness and response estimates in U.S. Office of Management and Budget Climate Financial Risk Report (2024)	MN DNR, 2025[261] OMB, 2024[262]
2	Scale future suppression activity/costs from baseline to SSPs 2-45 and 5-85 in mid and end century periods using incremental estimated percentage increase in suppression activity total acreage burned in Minnesota from Gao et al. (2021) for the Minnesota pyrome.	Gao et al. 2021[263]

[258] MN DNR Annual Report on Emergency Firefighting Expenditures, Fiscal Year 2024, 01/15/2025. Available at: https://files.dnr.state.mn.us/aboutdnr/reports/legislative/2024/fy24-emergency-firefighting-fund-report.pdf

[259] Dillon, Gregory K.; Lazarz, Mitchell T.; Karau, Eva C.; Story, Scott J.; Pohl, Kelly A. 2024. Wildfire Risk to Communities: Community Wildfire Risk Reduction Zones for the United States. Updated 27 May 2025. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2024-0030, Available at: https://www.fs.usda.gov/rds/archive/catalog/RDS-2024-0030

[260] Peng Gao, Adam J. Terando, John A. Kupfer, J. Morgan Varner, Michael C. Stambaugh, Ting L. Lei, J. Kevin Hiers, Robust projections of future fire probability for the conterminous United States, Science of The Total Environment, Volume 789, 2021, 147872, https://doi.org/10.1016/j.scitotenv.2021.147872 .

[261] MN DNR Annual Report on Emergency Firefighting Expenditures, Fiscal Year 2024, 01/15/2025. Available at: https://files.dnr.state.mn.us/aboutdnr/reports/legislative/2024/fy24-emergency-firefighting-fund-report.pdf

[262] U.S. Office of Management and Budget, March 2024. Climate Financial Risk: The Federal Government's Budget Exposure to Financial Risk Due to Climate Change, available at: https://www.srs.fs.usda.gov/pubs/ja/2024/ja_2024_prestemon_003.pdf

[263] Peng Gao, Adam J. Terando, John A. Kupfer, J. Morgan Varner, Michael C. Stambaugh, Ting L. Lei, J. Kevin Hiers,

Step	Description	Key Data Sources and Models
3	Interpolate estimates for late century and SSP 3-70 from available estimates	

Adaptation costs

Table B60. Costs of Adaptation Summary: Wildfire Risks

Action	Cost Components	Impacts Addressed	Quantified Residual Risks	Spatial scale of Analysis	Methods Table
Forest Thinning and Prescribed Burning	Annual treatment costs	Wildfire risk to buildings (co-benefits for forest ecosystem health)	None	Statewide	Table B61
Prescribed Burning	Annual treatment costs	Wildfire risk to buildings (co-benefits for forest ecosystem health)	None	Statewide	Table B61
Structure Hardening	Structure and landscaping improvements	Wildfire risk to buildings	None	Statewide	Table B62

Table B61. Forest Thinning and Prescribed Burning Adaptation Costing Methods

Step	Description	Key Data Sources and Models
1	Estimate baseline annual MN DNR Pre-Suppression Costs from MNDNR (2025) by taking 10-year average over the 2015-2024 period. Identify acres of prescribed burns for MNDNR and USFS using Minnesota Incident Command System (MNICS) 2024 annual report. Scale costs of per acre activity from state to federal partners to estimate total baseline costs.	MN DNR, 2025[264] MNICS Annual Report, 2024[265]
2	For low estimate (reactive), scale future Pre-suppression activity/costs from baseline to SSPs 2-45 and 5-85 in mid and end century periods using incremental estimated percentage increase in acreage burned in Minnesota from Gao et al. (2021) for the Minnesota pyrome.	Gao et al. 2021[266]
3	For high estimate (proactive), use same procedure as in Step 2 but scale acreage activity level required to twice as large as projected increase in area burned from Gao et al (2021), to account for uncertainty in location of needs for prescribed burns	

Robust projections of future fire probability for the conterminous United States, Science of The Total Environment, Volume 789, 2021, 147872, https://doi.org/10.1016/j.scitotenv.2021.147872 .

[264] MN DNR Annual Report on Emergency Firefighting Expenditures, Fiscal Year 2024, 01/15/2025. Available at: https://files.dnr.state.mn.us/aboutdnr/reports/legislative/2024/fy24-emergency-firefighting-fund-report.pdf

[265] Minnesota Incident Command System 2024 Annual Report, available at: https://mnics.org/wpress/wp-content/uploads/2025/02/2024-MNICS-Annual-Report.pdf

[266] Peng Gao, Adam J. Terando, John A. Kupfer, J. Morgan Varner, Michael C. Stambaugh, Ting L. Lei, J. Kevin Hiers, Robust projections of future fire probability for the conterminous United States, Science of The Total Environment, Volume 789, 2021, 147872, https://doi.org/10.1016/j.scitotenv.2021.147872 .

Step	Description	Key Data Sources and Models
4	Interpolate estimates for late century and SSP 3-70 from available estimates	

Table B62. Structure Hardening Adaptation Costing Methods

Step	Description	Key Data Sources and Models
1	Use estimates of unit cost for hardening of $15,000 for "acceptably safe" measures from MN DNR Firewise program, using cost estimates from Headwater Economics report (2024).	Headwaters Economics, 2024[267]
2	For all SSPs in mid century period, assume all Minnesota homes within the High HURisk category (Dillon et al. 2024) adopt the unit cost of hardening of $15,000, with 1/10 of costs incurred annually. Assume that all structures in Very High HURisk category are hardened in baseline (Note: only 12 Minnesota structures are in the Very High risk category).	Dillon et al. 2024, Wildfire Risk to Communities[268]
3	Scale future hardening costs from mid-century to SSPs 2-45 and 5-85 in end century period using incremental estimated percentage increase in total acreage burned in Minnesota from Gao et al. (2021) for the Minnesota pyrome.	Gao et al. 2021[269]
4	Interpolate estimates for late century and SSP 3-70 from available estimates	

[267] Headwaters Economics (2024). Retrofitting a Home for Wildfire Resistance: Costs and Considerations. Spring 2024. Available at: https://headwaterseconomics.org/wp-content/uploads/2024/06/Wildfire_Retrofit_Report_R5.pdf

[268] Dillon, Gregory K.; Lazarz, Mitchell T.; Karau, Eva C.; Story, Scott J.; Pohl, Kelly A. 2024. Wildfire Risk to Communities: Community Wildfire Risk Reduction Zones for the United States. Updated 27 May 2025. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2024-0030, Available at: https://www.fs.usda.gov/rds/archive/catalog/RDS-2024-0030

[269] Peng Gao, Adam J. Terando, John A. Kupfer, J. Morgan Varner, Michael C. Stambaugh, Ting L. Lei, J. Kevin Hiers, Robust projections of future fire probability for the conterminous United States, Science of The Total Environment, Volume 789, 2021, 147872, https://doi.org/10.1016/j.scitotenv.2021.147872 .

Key limitations and uncertainties

Table B63. Sources of Uncertainty in Analysis of Wildfire Risk to Buildings

Key Assumption or Source of Uncertainty	Direction of Potential Bias on Adaptation Cost	Likely Effect of the Uncertainty on Results
Damage to Buildings and Costs of Hardening		
Limited data on current and future damage to buildings, which generally excludes indirect costs such as disposal of debris.	**Underestimate impacts.** Available data on impacts is limited to a few recent, large, and well-publicized events in St. Louis County, from among hundreds of fires annually. Data to simulate the annual occurrence of losses is based on broad categories of risks with attached annual frequency of occurrence, but little information on which to base the percentage of structure loss. Assumptions are conservative at this time.	**Unknown.** Estimates could underestimate current and future risks by a wide margin, or a small margin. The nature of extreme events such as wildfires which are relatively rare complicates all analysis of their annualized impacts.
Analysis of hardening is based on a simple model of measures that could be employed to reduce risk, applied to a single risk class of homes.	**Underestimate impacts.** Historical fire damage has occurred to Minnesota homes in the lower risk classes.	**Potentially major.** The number of homes in the High risk class is roughly 4,000, but over 100,000 homes are in the Moderate risk class, and historical damage has occurred to structures in that class.
Assumption that no homes in the High risk class have been upgraded with fire hardening measures	**Overestimate impacts. I**f homes have been upgraded already, the marginal costs of hardening may be lower than estimated here.	**Likely minor.** Most measures (e.g., landscaping or roofs) require period re-installation or major maintenance over time, so even if there is some existing hardening it is likely the costs assumed needed in future years are only slightly overestimated.
The analyses rely on an indirect measure of future structure risk, the statewide extent of burned acres, to project damages.	**Unknown.** The basis of projection may overestimate or underestimate adaptation cost, depending on the proximity of future fires from potentially vulnerable structures.	**Unknown.** There is currently no basis for estimating the likely error margin for the use of this indirect measure of structure risk.
Suppression and Pre-suppression Costs		
Incomplete information exists on the current and future extent of these measures, which are also limited to public entities and exclude all activity conducted by private actors.	**Underestimate costs.** Private sector activity by private foresters may be practiced within the state.	**Unknown.** There is currently no basis for estimating the likely error margin for the omission of private suppression and pre-suppression activity.

Key Assumption or Source of Uncertainty	Direction of Potential Bias on Adaptation Cost	Likely Effect of the Uncertainty on Results
Unit costs for both thinning and prescribed burning vary widely by location and a range of site-specific factors.	**Underestimate costs.** The estimate for prescribed burning reflects actual costs in Minnesota from the FACTS database, but the costs are lower than in other locations. In addition, the unit costs for thinning assume that only 20% of the acreage designated for treatment will require thinning; the actual percentage could be higher.	**Potentially major.** Thinning costs per acre are as much as five times as large as prescribed burning costs per acre, which implies that an underestimate of the requirement for thinning prior to burning could have a large effect of the cost estimates presented here.
The analyses rely on an indirect measure of future structure risk, the statewide extent of burned acres, to project costs.	**Unknown.** The basis of projection may overestimate or underestimate adaptation cost, depending on the proximity of future fires from potentially vulnerable structures.	**Unknown.** There is currently no basis for estimating the likely error margin for the use of this indirect measure of structure risk.

Ecosystems

Ecosystems are integrated into all other categories of impacts and adaptation actions (e.g., urban trees for shade/cooling and forest thinning for building protection from wildfires). Cost of inaction for ecosystems are difficult to quantify at the scale of this analysis, therefore we are limited in the costs of inaction quantifiable for this section. The main report discusses the many important aspects of ecosystems and the services they provide that are at risk due to climate change. Similarly, for adaptation, the right action is often a site-specific decision. The adaptation costs quantified for this study provide a sense of the order of magnitude of potential cost, but as is the case in all sections of this report, they do not represent specific recommended actions.

Terrestrial Ecosystems

Costs of inaction and adaptation costs for the Terrestrial Ecosystems subsector are considered in aggregate for quantifiable categories – that is, the costs of inaction do not always align directly with adaptation costs, in part because the costs of inaction for most ecosystem services (beyond timber value and carbon sequestration) are challenging to quantify.

Costs of inaction

The costs of inaction for the Terrestrial Ecosystems sub-sector are both nuanced and incompletely quantified for timber-related impacts. The nuance is owing to the intricate interconnections of forest health with both natural and working lands ecosystem service flows. Year-round outdoor recreation activities contribute both economically and culturally to the state of Minnesota. Participation in these activities are estimated change in relation to changes in temperature and precipitation.

Table B64. Costs of Inaction Summary: Terrestrial Ecosystems Impacts

Impact	Cost Measure	CMIP6 Data Used	Spatial Scale	Underlying Study	Methods Table
Timber Carbon Flux (net effect across all timber species)	CO2 sequestered (physical) and Social Cost of Carbon (SCC) (valuation)	Annual CONUS Temp (FrEDI)	State	Baker et al., 2023[270]	Table B66
Timber Production Losses (net of species changes, with market adjustment)	Producer surplus	Annual CONUS Temp (FrEDI*)	State	Baker et al., 2023[271]	Table B65
Lost Other Activity Opportunities (bike, hunt, hike, run)	Consumer Surplus	Annual CONUS Temp (FrEDI)	State	Willwerth et al., 2023[272]	Table B67
Lost Snow Sport Opportunities					
Lost Alpine Skiing Opportunities	Ticket sales	Annual CONUS Temp (FrEDI)	State	Wobus et al., 2017[273]	Table B68
Lost Cross-Country Skiing Opportunities					
Lost Snowmobiling Opportunities					
*Adjusted FrEDI output					

[270] Justin S. Baker et al., "Projecting U.S. Forest Management, Market, and Carbon Sequestration Responses to a High-Impact Climate Scenario," *Forest Policy and Economics* 147 (February 2023): 102898, https://doi.org/10.1016/j.forpol.2022.102898.
[271] Baker et al., "Projecting U.S. Forest Management, Market, and Carbon Sequestration Responses to a High-Impact Climate Scenario."
[272] Willwerth, J., Sheahan, M., Chan, N., Fant, C., Martinich, J., & Kolian, M. (2023). The Effects of Climate Change on Outdoor Recreation Participation in the United States: Projections for the Twenty-First Century. Weather, Climate, and Society, 15(3), 477-492.
[273] Wobus, C., Small, E. E., Hosterman, H., Mills, D., Stein, J., Rissing, M., Jones, R., Duckworth, M., Hall, R., Kolian, M., Creason, J., & Martinich, J. (2017). Projected climate change impacts on skiing and snowmobiling: A case study of the United States. Global Environmental Change, 45, 1-14. https://doi.org/10.1016/j.gloenvcha.2017.04.006

Table B65. Timber Production Loss Methods

Step	Description	Key Data Sources and Models
1	The Forestry sector in FrEDI draws upon Baker et al. (2023), which combines bottom-up estimates of forest productivity responses to climate inputs with dynamic economic modeling of the U.S. forest sector. Baker et al. use the FASOM-GHG (Forestry and Agricultural Sector Optimization Model - Greenhouse Gas) intertemporal dynamic optimization model of the U.S. land use sectors to model maximizing consumer and producer surplus measures accounting for physical resource constraints and heterogeneity in forest productivity by site class, forest type, and region. The published version of FrEDI reports a combined producer and consumer surplus. For this analysis, we first separate these two components of the FrEDI input data to only reflect Producer Surplus, rather than the sum of Producer and Consumer Surplus.	FrEDI[274] Baker et al., 2023[275]
2	Run the adjusted FrEDI tool (i.e. producer surplus only) with CMIP6 temperature projections and MN-specific population projections. Adjust dollar year from 2015$ (FrEDI default) to 2024$.	KNMI Climate Explorer, 2025[276] MN State Demographic Center, 2024a[277] BEA, 2025[278]
3	Average across years in each time period.	

Table B66. Timber Carbon Flux Methods

Step	Description	Key Data Sources and Models
1	See Step 1 in Table 45 above. Carbon flux is not a default FrEDI impact however for this analysis, we process carbon flux data from Baker et al. 2023 alongside Producer Surplus.[279] See FrEDI Technical Documentation for full data processing description. We also adjust the dollar year from 2015$ (FrEDI default) to 2024$.	Baker et al., 2023[280] U.S. Environmental Protection Agency, 2024[281] BEA, 2025[282]

[274] https://epa.gov/cira/about-fredi/index.html
[275] Baker et al., "Projecting U.S. Forest Management, Market, and Carbon Sequestration Responses to a High-Impact Climate Scenario."
[276] KNMI Climate Explorer. (2025). https://climexp.knmi.nl/start.cgi
[277] Minnesota State Demographic Center. (2024). *Long-Term Population Projections for Minnesota By Age and Sex* [Dataset]. https://mn.gov/admin/demography/data-by-topic/population-data/our-projections/
[278] U.S. Bureau of Economic Analysis (BEA). (2025). *Table 1.1.9. Implicit Price Deflators for Gross Domestic Product* [Dataset]. https://apps.bea.gov/iTable/?ReqID=19&step=4&isuri=1&1921=flatfiles
[279] There is one difference in processing between Producer Surplus and Carbon Flux. Carbon flux is not divided by GDP/capita in data processing and it is not multiplied by GDP/capita in FrEDI.
[280] Baker et al., "Projecting U.S. Forest Management, Market, and Carbon Sequestration Responses to a High-Impact Climate Scenario."
[281] U.S. Environmental Protection Agency, "2024 Technical Documentation for the Framework for Evaluating Damages and Impacts (FrEDI)," EPA, 2024, Science Inventory, https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=360384&Lab=OAP&simplesearch=0&showcriteria=2&sortby=pubDate&searchall=fredi&timstype=&datebeginpublishedpresented=11/20/2023.
[282] U.S. Bureau of Economic Analysis, "Table 1.1.9. Implicit Price Deflators for Gross Domestic Product."

Step	Description	Key Data Sources and Models
2	Run the adjusted FrEDI with CMIP6 temperature projections and MN-specific population projections.	FrEDI[283] KNMI Climate Explorer, 2025[284] Minnesota State Demographic Center, 2024a[285]
3	Following Baker et al., CO_2 sequestration is valued using the Social Cost of Carbon from the Minnesota Department of Transportation.	Minnesota Department of Transportation, 2024[286]
4	Average across years in each time period.	

Table B67. Lost Snow Sports and Other Outdoor Recreation Methods

Step	Description	Key Data Sources and Models
1	FrEDI includes estimates of changes in outdoor recreation participation drawn from Willwerth et al. (2023), which derives an empirical relationship between weather conditions (temperature and precipitation) with participation in outdoor recreation as tracked in the American Time Use Survey (ATUS). Outdoor recreation types are group based on category descriptions in ATUS. Willwerth et al. values changes in outdoor recreation by assigning "value per trip" estimates the Oregon Statewide Comprehensive Outdoor Recreation Plan (Rosenberger 2018), a recent application of the Oregon State University Recreation Use Value Database (Rosenberger 2016).	FrEDI[287] Willwerth et al., 2023[288] Rosenberger, 2016[289] Rosenberger, 2018[290]
2	Run FrEDI with MN CliMAT temperature projections and MN-specific population projections. Adjust dollar year from 2015$ (FrEDI default) to 2024$.	FrEDI[291] KNMI Climate Explorer, 2025[292] MN State Demographic Center, 2024[293] BEA, 2025[294]
3	Sum to state level and average across years in each time period.	

[283] https://epa.gov/cira/about-fredi/index.html
[284] KNMI Climate Explorer. (2025). https://climexp.knmi.nl/start.cgi
[285] Minnesota State Demographic Center, "Long-Term Population Projections for Minnesota By Age and Sex."
[286] Minnesota Department of Transportation, "Recommended Standard Values for Use in Cost-Effectiveness & Benefit-Cost Analysis in SFY 2025," Minnesota Department of Transportation, Office of Transportation System Management, 2024, https://www.dot.state.mn.us/planning/program/appendix_a.html.
[287] https://epa.gov/cira/about-fredi/index.html
[288] Jacqueline Willwerth et al., "The Effects of Climate Change on Outdoor Recreation Participation in the United States: Projections for the Twenty-First Century," Weather, Climate, and Society, *Weather, Climate, and Society* 15, no. 3 (2023): 477–92, https://doi.org/10.1175/WCAS-D-22-0060.1.
[289] Rosenberger, R. S., 2016. Recreation Use Values Database. College of Forestry, Oregon State University, accessed 17 June 2021, http://recvaluation.forestry.oregonstate.edu/.
[290] Rosenberger, R.S., *2019-2023 Oregon Statewide Comprehensive Outdoor Recreation Plan Supporting Documentation. Part B: Total Net Economic Value from Residents' Outdoor Recreation Participation in Oregon*, 2018.
[291] https://epa.gov/cira/about-fredi/index.html
[292] KNMI Climate Explorer. (2025). https://climexp.knmi.nl/start.cgi
[293] Minnesota State Demographic Center. (2024). *Long-Term Population Projections for Minnesota By Age and Sex* [Dataset]. https://mn.gov/admin/demography/data-by-topic/population-data/our-projections/
[294] U.S. Bureau of Economic Analysis (BEA). (2025). *Table 1.1.9. Implicit Price Deflators for Gross Domestic Product* [Dataset]. https://apps.bea.gov/iTable/?ReqID=19&step=4&isuri=1&1921=flatfiles

Table B68. Lost Alpine Skiing, Lost Cross-Country Skiing, and Lost Snowmobiling Methods

Step	Description	Key Data Sources and Models
1	FrEDI additionally includes estimate of lost days of alpine skiing, Nordic skiing (cross-country skiing), and snowmobiling from Wobus et al. 2017. Lost trips are valued using forgone ticket sales by activity type. The output from FrEDI only includes the total lost revenue. We calculate the number of trips associated with this lost revenue by dividing the total lost revenue by the activity-specific ticket price as reported in Wobus et al.	FrEDI[295] Wobus et al., 2017[296]
2	Run FrEDI with MN CliMAT temperature projections and MN-specific population projections. Adjust dollar year from 2015$ (FrEDI default) to 2024$.	FrEDI[297] KNMI Climate Explorer, 2025[298] MN State Demographic Center, 2024[299] BEA, 2025[300]
3	Sum to state level and average across years in each time period.	

Adaptation Costs

Table B69. Costs of Adaptation Summary: Terrestrial Ecosystems Adaptation Actions

Action	Cost Components	Impacts Addressed	Quantified Residual Risks	Spatial scale of Analysis	Methods Table
Invasive Species Management in Forests	Treatment of affected areas	Forest disturbances	None	Statewide	Table B70

Table B70. Invasive Species Management Adaptation Costing Methods for Oak Wilt, Mountain Pine Beetle, and Emerald Ash Borer

Step	Description	Key Data Sources and Models
1	Select important terrestrial invasive plants and pests in Minnesota to include in the analysis.	Venette, 2020[301]

[295] https://epa.gov/cira/about-fredi/index.html
[296] Wobus, C., Small, E. E., Hosterman, H., Mills, D., Stein, J., Rissing, M., Jones, R., Duckworth, M., Hall, R., Kolian, M., Creason, J., & Martinich, J. (2017). Projected climate change impacts on skiing and snowmobiling: A case study of the United States. Global Environmental Change, 45, 1-14. https://doi.org/10.1016/j.gloenvcha.2017.04.006
[297] https://epa.gov/cira/about-fredi/index.html
[298] KNMI Climate Explorer. (2025). https://climexp.knmi.nl/start.cgi
[299] Minnesota State Demographic Center. (2024). *Long-Term Population Projections for Minnesota By Age and Sex* [Dataset]. https://mn.gov/admin/demography/data-by-topic/population-data/our-projections/
[300] U.S. Bureau of Economic Analysis (BEA). (2025). *Table 1.1.9. Implicit Price Deflators for Gross Domestic Product* [Dataset]. https://apps.bea.gov/iTable/?ReqID=19&step=4&isuri=1&1921=flatfiles
[301] R. C. Venette, *Minnesota's Top Terrestrial Invasive Plants and Pests for Research: An Expanded Prioritization*, January 2020, https://hdl.handle.net/11299/241447.

Step	Description	Key Data Sources and Models
2	Identify the historical (1971-2000) and future extents of the invasive species selected in Step 1, limiting the list to species where extent information is available. Future extents are provided for two RCPs (RCP4.5 and RCP8.5) and two time periods relevant to this analysis (2041-2070: assigned to mid-century; and 2071-2100: assigned to end of century). Selected species are: • *Agrilus planipennis* (Emerald ash borer) • *Dendroctonus ponderosae* (Mountain pine beetle) • *Bretziella fagacearum* (Oak wilt) Extents are identified by likelihood of potential distribution. We define extents as areas where the likelihood of occurrence is greater than 50 percent (e.g. more likely than not).	Natural Resources Canada[302]
3	Overlay historical and future extents from Step 2 to identify the areas newly exposed under future climates and calculate the incremental new acres in each time period for each SSP.	
4	Use the current extent of the host species to limit the newly exposed areas from Step 2 to the incremental areas requiring treatment in the future (e.g. only areas with oak trees will require treatment for Oak wilt.	MNDNR Forest Stand Inventory[303]
5	Based on a MN study of oak wilt treatment, we apply a 57 percent adjustment factor to account for the proportion of forests that will likely be treated versus left untreated.	Haight et al., 2011[304]
6	Estimate the number of trees that require treatment by applying estimates of trees per acre by species from the literature to the calculated acres requiring treatment.	Oak: Indiana Division of Forestry[305] Pine: UMN[306] Ash: UMN[307]
7	Apply costs per tree (or per acre, depending on the source) of treatment costs from the literature to get the total treatment costs by future eras	Oak: Haight et al., 2011 Pine: Price et al., 2010[308] Ash: MN Shade Tree Advisory Committee[309]

[302] https://cfs.cloud.nrcan.gc.ca/bmfid/bmfid.php?lang=e
[303] https://gisdata.mn.gov/dataset/biota-dnr-forest-stand-inventory
[304] Robert G. Haight et al., "Assessing the Cost of an Invasive Forest Pathogen: A Case Study with Oak Wilt," *Environmental Management* 47, no. 3 (2011): 506–17, https://doi.org/10.1007/s00267-011-9624-5.
[305] https://www.in.gov/dnr/forestry/files/underplantingoak.pdf
[306] https://extension.umn.edu/managing-woodlands/managing-eastern-white-pine-forests
[307] https://silvlib.cfans.umn.edu/kettle-lake-ash-reforestation-tree-planting-advance-emerald-ash-borer-mn-dnr
[308] James I. Price et al., "Insect Infestation and Residential Property Values: A Hedonic Analysis of the Mountain Pine Beetle Epidemic," *Forest Policy and Economics* 12, no. 6 (2010): 415–22, https://doi.org/10.1016/j.forpol.2010.05.004.
[309] https://www.mnstac.org/uploads/2/0/9/3/20933948/eab_v8.pdf

Key limitations and uncertainties

Table B71. Sources of Uncertainty in Analysis of Terrestrial Ecosystems Costs

Key Assumption or Source of Uncertainty	Direction of Potential Bias on Adaptation Cost	Likely Effect of the Uncertainty on Results
Timber		
Estimates of species-specific timber growth in Baker et al. 2023 likely underestimate tree mortality associated with disturbance (e.g., pests and wildfire).	**Underestimate impacts.** Recent analyses by MFRC indicate an increasing historical trend of tree mortality from disturbance connected to climate change, including decreased pest mortality associated with milder winters and increased fire risk associated with summer drying.	**Potentially major.** MFRC analyses suggest that tree mortality from disturbance now exceeds timber harvest volumes by a factor of roughly 10 times. It is not yet clear, however, whether the species affected by climate-associated disturbance are likely to be those most valuable as a timber source.
Results from Baker et al. 2023 are estimated for the Lake States Forest and Agricultural Sector Optimization Model (FASOM) region (MN, WI, MI). Estimates are disaggregated to states based on county-level mill capacity and forest supply.	**Unknown.** Timber processing capacity and forest productivity are imperfect representatives of relative timber production between states. Bias towards a specific state, if present, is unknown.	**Likely minor.** MN, WI, and MI have similar dominant timber species and ecological zones. Timber resources and mill capacity across the three states are comparable.
Results from Baker et al. 2023 treat imports and exports as fixed and exogenous.	**Unknown.** The U.S is important to the global forest sector, but it is not the sole producer. Global market dynamics are difficult to predict.	**Potentially major.** As climate change alters forest growth dynamics, the global timber market, which depends on sensitive ecological processes, may undergo substantial long-term shifts.
Terrestrial invasive treatment options and associated costs vary widely and are site specific.	**Unknown.** Tree pest management can involve a range of treatment options including marginal changes to harvest and planting schedules or more intensive management and actions. Costs per acre, by treatment, vary significantly.	**Potentially major.** The large areas identified as at risk from the various pests means that any change in treatment cost will result in large magnitude changes in total cost.
Forest treatment costs are only quantified for three potential pests.	**Underestimate impacts.** Forest ecosystems in Minnesota face a number of potential disturbance threats, including additional pests, wildfire, and windstorms. We only quantify costs associated with three modeled pest habitat ranges.	**Potentially major.** Forest areas make up a large portion of the Minnesota landscape. Costs to manage various threats could be significantly higher than the costs quantified in this analysis.

Key Assumption or Source of Uncertainty	Direction of Potential Bias on Adaptation Cost	Likely Effect of the Uncertainty on Results
Forest treatments are only costed for forestlands owned or maintained by MNDNR.	**Underestimate impacts.** MNDNR is a major forestland owner and the state is most able to effectuate action on this land, however private lands and other public lands are also vulnerable to the same stressors.	**Potentially major.** MNDNR owns approximately 25 percent of forested land in Minnesota[310], meaning there is a large portion of land potentially requiring treatment that is not included in this analysis.
Outdoor Recreation		
Minnesota residents will continue to respond to the changes in temperature and precipitation conditions similar to how other residents in the northern regions of the United States have responded in the past.	Overestimate impacts. If Minnesota residents acclimatize as climatic conditions change and alter their outdoor recreation participation accordingly, then we likely overestimate impacts.	Likely minor. While acclimatization may reduce the magnitude of impacts, other countervailing forces, like the availability of infrastructure of certain types of recreation will likely constrain the magnitude of impacts.

The winter recreation industry in Minnesota is also incurring costs associated with increased needs to make snow. Publicly available information on this topic is limited, and we are currently in touch with the Minnesota Ski Area Association to determine if we can use their data to project future costs to this industry.

With increases in demand for activities typically associated with warmer weather, it is likely that both public and private entities will also incur costs to install and upgrade infrastructure that supports these activities. However, available data and models limit our ability to project those future costs.

Aquatic Ecosystems

Costs of Inaction

Table B72. Costs of Inaction Summary: Aquatic Ecosystems Impacts

Impact	Cost Measure	CMIP6 Data Used	Spatial Scale	Underlying Study	Methods Table
Water Quality	WTP	Lake surface temperatures	Region	Chapra et al., (2017)[311]	Table B73
Harmful Algal Blooms	Lost Recreation	Lake surface temperatures	Region	Clark et al. (in review)[312]	Table B74
Lost Recreational Fishing Opportunities	Consumer Surplus	Annual CONUS Temp (FrEDI)	State	Willwerth et al., 2023[313]	Table B75
Lost Water Sport Opportunities					

[310] DNR Forest Management - Summary

[311] Steven C Chapra et al., "Climate Change Impacts on Harmful Algal Blooms in US Freshwaters: A Screening-Level Assessment," *Environmental Science & Technology* 51, no. 16 (2017): 8933–43.

[312] Suzanna Clark et al., *Projected Effects of Climate Change and Warming Lake Temperatures on Microsystis Blooms in Minnesota's Inland Lakes*, In Review.

[313] Willwerth, J., Sheahan, M., Chan, N., Fant, C., Martinich, J., & Kolian, M. (2023). The Effects of Climate Change on Outdoor Recreation Participation in the United States: Projections for the Twenty-First Century. Weather, Climate, and Society, 15(3), 477-492.

Table B73. Recreational Opportunities Due to Water Quality Methods

Step	Description	Key Data Sources and Models
1	FrEDI includes a water quality impact estimate from Fant et al. (2017) that measures the lost welfare (willingness to pay) associated with changes in water quality, measured by a composite water quality index.	Fant et al., (2017)[314]
2	Run FrEDI with CMIP6 temperature projections and MN-specific population projections.	FrEDI[315] KNMI Climate Explorer, 2025[316]

Table B74. Microcystin Concentration Due to HABs Methods

Step	Description	Key Data Sources and Models
1	Similar to above, harmful algal bloom concentrations are driven by lake surface temperatures (LSTs). Projections of changes in LSTs are derived from Clark et al. (in review), an estimation of lake surface temperature for MN using the CLIMAT climate scenarios for SSP2-4.5 and SSP5-8.5.	Clark et al. (in review)[317]
2	An ensemble of simulated cyanobacteria concentrations and lake surface temperature from Chapra et al. (2017), which accounts for nutrient and light limitations as well as temperature effects on cyanobacteria growth, are used to develop an envelope of probabilistic cyanobacteria concentrations for each integer degree for lakes across the state. For example, given a lake surface temperature of 30° C, we estimate a range of exceedance probabilities of cyanobacteria concentrations from the 1st to 99th percentiles.	Chapra et al., 2017[318]
3	Using the LST estimate from step 1 and the probabilistic envelope of cyanobacteria concentrations from step 2, we project future possibilities of harmful algal blooms in MN lakes.	
4	Following Chapra et al. (2017), we estimate that lakes used for recreation will need to close if cyanobacteria concentrations exceed 10,000 cells/ml based on WHO guidelines for recreational exposure that presents a "very high" risk to human health.	WHO, 1999[319]
5	Each day of closure results in lost visitor-days and lost revenues. The number of visitors to lakes and reservoirs as well as average revenues per visit were derived from a 2022 Minnesota State Park Visitor Study.	MN DNR, 2022[320]

[314] Charles Fant et al., "Climate Change Impacts on US Water Quality Using Two Models: HAWQS and US Basins," *Water* 9, no. 2 (2017): 118.
[315] https://epa.gov/cira/about-fredi/index.html
[316] KNMI Climate Explorer. (2025). https://climexp.knmi.nl/start.cgi
[317] Clark et al., *Projected Effects of Climate Change and Warming Lake Temperatures on Microsystis Blooms in Minnesota's Inland Lakes*.
[318] Chapra et al., "Climate Change Impacts on Harmful Algal Blooms in US Freshwaters: A Screening-Level Assessment."
[319] World Health Organization (WHO). Toxic Cyanobacteria in Water: A guide to their Public Health Consequences, Monitoring and Management; E & FN Spon, 1999: London, http://www.who.int/water_sanitation_health/resourcesquality/toxcyanobacteria.pdf?ua=1
[320] 2022 Minnesota State Park Visitor Study. Available: https://files.dnr.state.mn.us/aboutdnr/reports/parks/2022-state-parks-visitor-study.pdf

Table B75. Lost Recreational Fishing and Lost Water Sports Methods

Step	Description	Key Data Sources and Models
1	FrEDI includes estimates of changes in outdoor recreation participation drawn from Willwerth et al. (2023), which derives an empirical relationship between weather conditions (temperature and precipitation) with participation in outdoor recreation as tracked in the American Time Use Survey (ATUS). Outdoor recreation types are group based on category descriptions in ATUS. Willwerth et al. values changes in outdoor recreation by assigning "value per trip" estimates the Oregon Statewide Comprehensive Outdoor Recreation Plan (Rosenberger 2018), a recent application of the Oregon State University Recreation Use Value Database (Rosenberger 2016).	FrEDI[321] Willwerth et al., 2023[322] Rosenberger, 2016[323] Rosenberger, 2018[324]
2	Run FrEDI with MN CliMAT temperature projections and MN-specific population projections. Adjust dollar year from 2015$ (FrEDI default) to 2024$.	FrEDI[325] KNMI Climate Explorer, 2025[326] MN State Demographic Center, 2024[327] BEA, 2025[328]
3	Sum to state level and average across years in each time period.	

Adaptation Costs

Table B76. Costs of Adaptation Summary: Aquatic Ecosystems Adaptation Actions

Action	Cost Components	Impacts Addressed	Quantified Residual Risks	Spatial scale of Analysis	Methods Table
Alum Treatment		Harmful Algal Blooms	None	Region	Table B77
Wetlands Restoration		Water quality	None	Region	Table B78
Restocking Brook Trout	Replacement Fish Costs	Lost Freshwater Fishing Recreation Trips	None	State	Table B79

[321] https://epa.gov/cira/about-fredi/index.html
[322] Willwerth et al., "The Effects of Climate Change on Outdoor Recreation Participation in the United States."
[323] Rosenberger, R. S., 2016. Recreation Use Values Database. College of Forestry, Oregon State University, accessed 17 June 2021, http://recvaluation.forestry.oregonstate.edu/.
[324] Rosenberger, R.S., *2019-2023 Oregon Statewide Comprehensive Outdoor Recreation Plan Supporting Documentation. Part B: Total Net Economic Value from Residents' Outdoor Recreation Participation in Oregon*.
[325] https://epa.gov/cira/about-fredi/index.html
[326] KNMI Climate Explorer. (2025). https://climexp.knmi.nl/start.cgi
[327] Minnesota State Demographic Center. (2024). *Long-Term Population Projections for Minnesota By Age and Sex* [Dataset]. https://mn.gov/admin/demography/data-by-topic/population-data/our-projections/
[328] U.S. Bureau of Economic Analysis (BEA). (2025). *Table 1.1.9. Implicit Price Deflators for Gross Domestic Product* [Dataset]. https://apps.bea.gov/iTable/?ReqID=19&step=4&isuri=1&1921=flatfiles

Table B77. Alum Treatment for HABs Adaptation Costing Methods

Step	Description	Key Data Sources and Models
1	Identify the lakes with HABs-related closures at least one day a year on average across each time period.	
2	Estimate the cost of alum treatment relative to lake surface area using project cost data from the Minnesota Legacy Project Database to estimate linear relationship between lake surface area and project costs (assuming some fixed costs as well).	Minnesota's Clean Water and Legacy Amendment and Environment and Natural Resources Trust Fund Project Database[329]
3	Estimate cost by time period using data from Step 1 and Step 2 above and divide by years in each time period to calculate the average annual cost per time period.	

Table B78. Wetland Restoration for General Water Quality Adaptation Methods

Step	Description	Key Data Sources and Models
1	Similar to above, nitrogen and phosphorus (nutrient) harmful algal bloom concentrations are driven by lake surface temperatures (LSTs). Projections of changes in LSTs are derived from Clark et al. (in review), an estimation of lake surface temperature for MN using the CLIMAT climate scenarios for SSP2-4.5 and SSP5-8.5.	Clark et al. (in review)[330]
2	An ensemble of simulated nitrogen and phosphor and lake surface temperature from Chapra et al. (2017), which accounts for a number of nutrient sources and sinks as well as temperature effects on nutrient concentrations, are used to develop an envelope of probabilistic nutrient concentrations for each integer degree for lakes across the state. For example, given a lake surface temperature of 30° C, we estimate a range of exceedance probabilities of nutrient concentrations from the 1st to 99th percentiles.	Chapra et al., 2017[331]
3	Using the LST estimate from step 1 and the probabilistic envelope of nutrient concentrations from step 2, we project future possibilities of nutrient concentrations in MN lakes.	
4	We estimate the number of lakes that exceed the EPA's maximum contaminant level (MCL) for nitrate, one of the nutrient concentrations tracked in the model, of 10 mg/L	EPA limits[332]
5	Using the Minnesota Legacy Project Database and identify projects with at least 20 acres to calculate a	Minnesota's Clean Water and Legacy Amendment and Environment and Natural Resources Trust Fund Project Database [333]

[329] https://www.legacy.mn.gov/projects?search_api_fulltext=Alum%20Treatment
[330] Clark et al., *Projected Effects of Climate Change and Warming Lake Temperatures on Microsystis Blooms in Minnesota's Inland Lakes*.
[331] Chapra et al., "Climate Change Impacts on Harmful Algal Blooms in US Freshwaters: A Screening-Level Assessment."
[332] https://www.epa.gov/nutrientpollution/estimated-nitrate-concentrations-groundwater-used-drinking
[333] https://www.legacy.mn.gov/projects?search_api_fulltext=Wetland+restoration

Step	Description	Key Data Sources and Models
	cost to restore wetlands per acre. We estimate a cost of $4,869 per acre.	
6	Using the Watershed pollutant load reduction calculator, we find wetlands reduce load by 7-48 lbs / acre / year. We use the average of that range, 27 lbs / acre / year to reduce total nitrogen load until it is below the EPA limit in Step 4.	https://data.pca.state.mn.us/views/Watershedpollutantloadreductioncalculator/Calculator?%3Aembed=y&%3AisGuestRedirectFromVizportal=y
7	Estimate the acres of wetlands per basin required in step 3 and use the cost from step 2 to estimate the cost to reduce the load below the EPA standard.	

Table B79. Lost Brook Trout Restocking Costing Methods

Step	Description	Key Data Sources and Models
1	Using a study focused on projecting the impacts of the changing climate on various recreation activities, we estimate the average annual decrease in the percentage of Minnesota streams with brook trout due to a loss of habitable conditions. The study provide the current and future (in 20 years, or ~2040) percent of streams with brook trout. The percentage decrease in streams (and therefore brook trout population) is linearly interpolated from 2015 to 2040, and extrapolated to future years. We assume that brook trout are evenly distributed among the river miles in which they occupy. Therefore, the percent decrease in habitable streams translates into an equivalent reduction in the brook trout population. For example, a 1 percent loss in MN streams with brook trout is equivalent to a 1 percent decrease in the population.	McCreary et al.[334]
2	Estimate the total baseline population of brook trout using the number of river miles of habitable conditions applicable for trout (Explore Minnesota (2025)), as well as the average trout population per river mile from a 2017 MN Department of Natural Resources (DNR) population assessment (Hoxmeier et al. (2017)).	Explore Minnesota, 2025[335] Hoxmeier et al., 2017[336]
3	Project annual decrease in brook trout population between 2017-2100 by combining Step 1 and Step 2.	
4	To reduce the impacts of decreased trout stocks on recreational fishing, we estimate the cost to restock brook trout up to the baseline population levels. To assess the reasonableness of our restocking projections, we compared with annual historical restocking rates of brook trout in streams from the MN DNR LakeFinder stocking data. Since 2016, the MN DNR has restocked about 38,500 individuals annually.	MN DNR, 2025[337]

[334] A McCreary et al., *North Shore Community Climate Readiness: Understanding Visitor Behaviors and Responses to Climate Change Projections | NC State Extension Publications* (NC State Extension, 2017), https://content.ces.ncsu.edu/north-shore-community-climate-readiness.
[335] Explore Minnesota. 2025. "Where to Fish for Trout in Minnesota." https://www.exploreminnesota.com/outdoors/fishing/where-to-fish-trout-minnesota Website accessed November 2025.
[336] R John H Hoxmeier et al., *Spatial Distribution of Apparent Native Brook Trout Populations and Their Characteristics in Southeastern MN Streams* (2017), https://files.dnr.state.mn.us/areas/fisheries/lanesboro/research/675_spatia_distribution_brook_trout_populations_southeastern_minnesota_streams.pdf.
[337] Minnesota Department of Natural Resources (MN DNR). (2025). *LakeFinder Stocking Data web application* [Dataset].

Step	Description	Key Data Sources and Models
5	Calculate the restocking cost per fish in the Great Lakes region. We assume 75 percent of the restocked fish are fingerling size (2-4 inches), and 25 percent of the restocked fish are a catchable size (10-13 inches).	Southwick and Loftus, 2017[338]
6	Apply cost per fish to the number of fish restocked each year, then adjust from 2017$ to 2024$.	BEA, 2025[339]
7	Average annual estimates to the MN eras. We are unable to link brook trout restocking to the MN SSP/GCMs, so we apply the average physical restocking amounts and associated costs across all SSP/GCMs.	

Key limitations and uncertainties

Table B80. Sources of Uncertainty in Analysis of Aquatic Ecosystems Costs

Key Assumption or Source of Uncertainty	Direction of Potential Bias on Adaptation Cost	Likely Effect of the Uncertainty on Results
Alum Treatment and Wetland Restoration		
Water quality measures do not account for increased extreme precipitation.	**Underestimate impacts.** Increased extreme precipitation can increase siltation and runoff and further degrade water quality.	**Unknown.** The magnitude of this impact is dependent on a number of complex hydrological factors that are not yet explored in this analysis.
Representative lakes / reservoirs are modeled instead of modeling each individually	**Uncertain.** Since these are representative impoundments, the reality is more complex, but it is not clear if the impact will be higher or lower overall.	**Unknown.** Without modeling each lake/reservoir individually, it is not clear if the magnitude of this assumption is minor or more significant.
The effectiveness of the wetland restoration adaptation varies across a fairly wide range, depending on what vegetation is used, where it is constructed, and other factors. The effectiveness will also vary over time depending on the overall health of the wetland.	**Uncertain.** If the wetland is more effective than assumed, it would require less of an investment and vice versa.	**Likely significant.** Given the wide range in effectiveness, this is likely a significant factor in determining the adaptation cost.
Harmful algal blooms have potential to impact drinking water. This was not evaluated due to the uncertainty and many unknown factors.	**Underestimate impacts.** Since this impact was not included, the impact is likely underestimated.	**Unknown.** If toxins from cyanobacteria did enter the drinking water, the impacts have the potential to be significant if unaware but the likelihood of that occurring are probably low.

[338] R I Southwick and A J Loftus, *Investigation and Monetary Values of Fish and Freshwater Mollusk Kills*, Special Publication 35 (American Fisheries Society, n.d.).
[339] U.S. Bureau of Economic Analysis (BEA). (2025). *Table 1.1.9. Implicit Price Deflators for Gross Domestic Product* [Dataset]. https://apps.bea.gov/iTable/?ReqID=19&step=4&isuri=1&1921=flatfiles

Key Assumption or Source of Uncertainty	Direction of Potential Bias on Adaptation Cost	Likely Effect of the Uncertainty on Results
Brook Trout Restocking		
Measurements of brook trout density in Southeastern MN streams are a reasonable proxy for average brook trout density per stream mile across trout-suitable waterways in the state.	**Unknown.** There is limited available data describing the distribution of brook trout densities in the state.	**Unknown.** There is limited available data describing the distribution of brook trout densities in the state.
The cost per fish, which represents the hatchery production costs, captures most costs associated with restocking.	**Underestimate impacts.** Restocking also involves labor and travel.	**Potentially major.** The per fish costs we leverage may be small compared to the total cost of restocking and other climate-related related operations.

Appendix C. Contributors and acknowledgements

Contributors

This study was guided by a Project Management Team at MPCA led by Kate Knuth. The Project Management Team and other contributors to the report included the following MPCA staff: Mindy Granley, Amanda Gorton, Sharon Stephens, and Liz Wiese.

The MCPA Project Management Team and the Consultant Team together formed the overall Project Team. Industrial Economics (IEc) was the lead consultant for the Consultant Team. Directed by Jacqueline Willwerth and James Neumann, IEc staff designed the overall study methodology, conducted most of the costs of inaction and costs of adaptation analyses, drafted the report, prepared report graphics and visualizations, curated project data, and participated as lead subject matter experts in stakeholder engagement activities.

The University of Minnesota Climate Adaptation Partnership, directed by Heidi Roop, provided observed and projected climate data including the data from the Minnesota Climate Mapping and Analysis tool, contributed to the cost of adaptation analyses, contributed to drafting many sections of the overall report, led development of Chapter 3, prepared report graphics, and participated as subject matter experts in the stakeholder engagement activities.

Two Degrees Adapt, led by Sharai Lewis-Gruss and Brian Smoliak, played a lead role in recruiting the stakeholder engagement participants, served as primary contacts with stakeholders, arranged and participated in follow-up interviews, facilitated stakeholder meetings, supported survey drafting and administration, drafted Appendix A on the stakeholder engagement activities and results, and reviewed the overall report.

Consensus Building Institute (CBI), directed by Elizabeth Cooper, developed the Stakeholder Engagement Plan, provided stakeholder engagement meeting logistics, facilitated stakeholder meetings, developed survey formats and administered surveys, and reviewed the overall report.

The Consultant team was advised by two professional economists, Stephen Polasky and Justin Johnson, and a flood risk engineer, Sami Shokrana. All three are affiliated with universities but contributed to the project in an Independent Advisory role and not as representatives of their respective universities.

Full list of contributors (organizational leads in italics)

IEc

- *Jacqueline Willwerth*
- *James Neumann*
- Gabriel Bendat
- Brent Boehlert
- Diego Castillo
- Hugh Easton
- Charles Fant
- Anthony Gardella
- Benjamin Jeweler
- Stefani Penn
- Megan Sheahan
- Kenneth Strzepek
- Kim Smet
- Janusz Strzepek
- Laura Taylor

Communications and Graphics Team

- Lena Flannery
- Erin Lyons

UMN Climate Adaptation Partnership

- *Heidi Roop*
- Dena Coffman
- Ryan Harp
- Stefan Liess
- Samuel Potter
- Kristen Schmitt

Two Degrees Adapt

- *Sharai Lewis-Gruss*
- *Brian Smoliak*

CBI

- *Elizabeth Cooper*
- Meira Downie
- Sam Haas
- Sofia Soto Reyes

Independent Advisors

- Stephen Polasky, Fesler-Lampert Professor of Ecological/Environmental Economics, University of Minnesota
- Justin Johnson, Associate Professor of Applied Economics, University of Minnesota
- Sami Shokrana, Post-Doctoral Associate, Massachusetts Institute of Technology

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The Project Team made efforts to ensure that a broad range of stakeholder perspectives are reflected in the analysis and report, and regrets if any errors or omissions are subsequently identified. Any errors or omissions remain the sole responsibility of IEc.