United States Environmental Protection Agency

Multi-Model Framework for Quantitative Sectoral Impacts Analysis

A Technical Report for the Fourth National Climate Assessment

May 2017

FRONT MATTER

CONTRIBUTORS

The Climate Change Impacts and Risk Analysis (CIRA) project is coordinated by the U.S. Environmental Protection Agency's (EPA), with significant contributions from a number of Federal agencies, including the Department of Energy (DOE), U.S. Forest Service (USFS), and Centers for Disease Control and Prevention (CDC); academic experts; and consultants, including Industrial Economics, Inc., Abt Associates Inc., and RTI International. Support for the report's production was provided by Industrial Economics, Inc.

Individual Contributors and Modelers[1] (listed in alphabetical order):

Ashley Allen (EPA)
Susan C. Anenberg (Env. Health Analytics)
Justin Baker (RTI International)
Chris Barker (U. of California Davis)
Matthew Baumann (Industrial Economics)
Robert Beach (RTI International)
Anna Belova (Abt Associates)
Charlotte Benishek (Industrial Economics)
Victor Bierman Jr. (LimnoTech)
Britta Bierwagen (EPA)
Margaret Black (Industrial Economics)
Brent Boehlert (Industrial Economics)
Alexandra Bothner (Industrial Economics)
Yongxia Cai (RTI International)
Karen Carney (Abt Associates)
Steven C. Chapra (Tufts University)
Paul S. Chinowsky (Resilient Analytics)
Stuart Cohen (National Renewable Energy Lab)
Jefferson Cole (EPA)
Joel Corona (EPA)
Jared Creason (EPA)
Allison Crimmins (EPA)
Pat Dolwick (EPA)
Michael Duckworth (Abt Associates)
Rebecca Eisen (CDC)
Xavier Espinet (Resilient Analytics)
Neal Fann (EPA)
Charles Fant (Industrial Economics)
Josh Graff-Zivin (U. of California San Diego)
Sahil Gulati (Industrial Economics)
Ethan Gutmann (Nat. Ctr. Atmos. Research)
Micah Hahn (CDC)
Ron Hall (Abt Associates)
Petr Havlik (Int'l Inst. Applied Systems Analysis)
Jacob Helman (Resilient Analytics)
Jim Henderson (Abt Associates)
Russell Horowitz (Pacific Northwest National Lab)
Heather Hosterman (Abt Associates)
Gokul Iyer (Pacific Northwest National Lab)
Lesley Jantarasami (EPA)
Russ Jones (Abt Associates)
Michael Kolian (EPA)
John Kim (USFS Pacific Northwest Res. Station)
Patrick L. Kinney (Columbia University)
Peter Larsen (Independent Consultant)
Claire Lay (Abt Associates)
Jia Li (EPA)
Mark Lorie (Abt Associates)
Lindsay Ludwig (Industrial Economics)
Hardee Mahoney (Abt Associates)
Sergey S. Marchenko (U. of Alaska Fairbanks)
Jeremy Martinich (EPA)
Diane M.L. Mas (Fuss & O'Neill)
James McFarland (EPA)
April Melvin (American Assoc. for the Adv. Sci.)
Karen Metchis (EPA)
Dave Mills (Abt Associates)
Naoki Mizukami (Nat. Ctr. Atmos. Research)

[1] Specific technical and modeling contributions by these individuals does not necessarily represent endorsement of material appearing in this Technical Report.

Christopher Moore (EPA)
Philip Morefield (EPA)
Matthew Neidell (Columbia University)
James E. Neumann (Industrial Economics)
Dmitry J. Nicolsky (U. of Alaska Fairbanks)
Christopher Nolte (EPA)
Sara Ohrel (EPA)
Hans W. Paerl (U. of North Carolina)
Stefani Penn (Industrial Economics)
Jason Price (Industrial Economics)
Lisa Rennels (Industrial Economics)
Matthew Rissing (Abt Associates)
Henry A. Roman (Industrial Economics)
Marcus Sarofim (EPA)
Rebecca Schultz (EPA)
Kate Shouse (EPA)
Eric Small (U. of Colorado Boulder)
Tanya Spero (EPA)
Alexis St. Juliana (Abt Associates)
Justin Stein (Abt Associates)
Ken Strzepek (Industrial Economics & MIT)
Nicole Thompson (Industrial Economics)
Hugo Valin (Int'l Inst. Applied Systems Analysis)
Stephanie Waldhoff (Pacific Northwest Nat. Lab)
Chris Weaver (EPA)
Kate R. Weinberger (Brown University)
Brittany Whited (EPA)
Jacqueline Willwerth (Industrial Economics)
Cameron Wobus (Abt Associates)
Raghavan Srinivasan (Texas A&M University)
Xuesong Zhang (Pacific Northwest National Lab)
Pearl Zheng (Abt Associates)

PEER REVIEW

The methods and results of the climate change impacts analyses described herein have been peer reviewed in the scientific literature. In addition, this Technical Report was peer reviewed by seven external and independent experts in a process independently coordinated by Eastern Research Group.

EPA gratefully acknowledges the following peer reviewers for their useful comments and suggestions: Anna Alberini, Mikhail Chester, Helene Margolis, Michael Meyer, Timothy Randhir, Matthias Ruth, and Susanna T.Y. Tong. The information and views expressed in this report do not necessarily represent those of the peer reviewers, who also bear no responsibility for any remaining errors or omissions. Details describing this review, and a comprehensive reference list for the CIRA peer-reviewed literature, can be found in the Technical Appendix to this report.

RECOMMENDED CITATION

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

DATA AVAILABILITY

Figures and metadata are being made available in the Global Change Information System (https://data.globalchange.gov).

TABLE OF CONTENTS

INTRODUCTION

ABOUT THIS REPORT

This Technical Report summarizes and communicates the results of the second phase of quantitative sectoral impacts analysis under the Climate Change Impacts and Risk Analysis[2] (CIRA) project (for information on the first phase, see the CIRA Project Background section). This effort is intended to inform the fourth National Climate Assessment[3] (NCA4) of the U.S. Global Change Research Program (USGCRP).[4] The goal of this work is to estimate climate change impacts and economic damages to multiple U.S. sectors (e.g., human health, infrastructure, and water resources) under different scenarios. Though this report does not make policy recommendations, it is designed to inform strategies to enhance resiliency and protect human health, investments, and livelihoods.

Each sectoral analysis is part of the CIRA multi-model framework which uses consistent inputs (e.g., socioeconomic and climate scenarios) to enable comparison of sectoral impacts across time and space. In addition, the role of adaptation is modeled for some of the sectors to explore the potential for risk reduction and, where applicable, to quantify the costs associated with adaptive actions.

The methods and results of the CIRA project have been peer-reviewed in the scientific literature, including a special issue of *Climatic Change* entitled, "A Multi-Model Framework to Achieve Consistent Evaluation of Climate Change Impacts in the United States."[5] The research papers underlying the modeling and results presented herein are cited throughout this report and are listed in Section A.2 of the Appendix to this Technical Report.

The Executive Summary follows this brief Introduction. The Modeling Framework (including climate change projections, metrics modeled, and sources of uncertainty), further CIRA project background, and commonly used terms and acronyms are described in the subsequent introductory chapters. The results of 25 modeling analyses are reported in six chapters on Health, Infrastructure, Electricity, Water Resources, Agriculture, and Ecosystems. The final chapter provides a synthesis of results at national and regional (sub-national) scales as well as a summary of the analyses that modeled adaptation responses. Additional resources can be found in the Technical Appendix or in the underlying research papers cited throughout.

---

[2] www.epa.gov/cira

[3] www.globlachange.gov/NCA4

[4] For a detailed assessment of the physical science basis for climate change, as well as a glossary of climate change terms, see the U.S. Global Change Research Program (USGCRP)'s Climate Science Special Report (CSSR), which is similarly developed to inform the NCA4, and the fifth assessment report of the Intergovernmental Panel on Climate Change. USGCRP, 2017 (*In Press)*: Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA. IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

[5] Martinich, J., J. Reilly, S. Waldhoff, M. Sarofim, and J. McFarland, Eds, 2015: Special Issue on "A Multi-Model Framework to Achieve Consistent Evaluation of Climate Change Impacts in the United States." *Climatic Change*, **131**, 1-181.

INTERPRETING THE RESULTS

This Technical Report presents results from a large set of sectoral impact models that quantify and monetize climate change impacts in the U.S., with a primary focus on the contiguous U.S., under moderate and severe future climates. The CIRA analyses are intended to provide insights about the potential direction and magnitude of climate change impacts. However, none of the estimates presented in this report should be interpreted as definitive predictions of future impacts at a particular place or time. Instead, the intention is to produce preliminary estimates of future effects using the best available data and methods, which can then be revisited and updated over time as science and modeling capabilities continue to advance.

The CIRA analyses do not evaluate or assume specific mitigation or adaptation policies in the U.S. or in other world regions. Instead, they consider scenarios (Representative Concentration Pathways or RCPs[6]) to illustrate potential impacts and damages of alternative future climates. The results should not be interpreted as supporting any particular domestic or global mitigation policy or target. In addition, the costs of reducing greenhouse gas (GHG) emissions, and the health benefits associated with co-reductions in other air pollutants, are well-examined elsewhere in the literature and are beyond the scope of this report. For this reason, the analysis presented in this Technical Report does not constitute a cost-benefit assessment of climate policy.

Furthermore, only a small portion of the impacts of climate change are estimated, and therefore this Technical Report captures just a fraction of the potential risks and damages that may be avoided or reduced when comparing the alternative scenarios. To better estimate impacts, this ongoing project continues to add new sectors, measures of economic damages, and adaptation scenarios, and to improve methods and assumptions within existing sectoral modeling. Impacts that are not covered by the modeling analyses and other important considerations or limitations are described in the discussion sections of each individual sector chapter.

[6] The RCPs are identified by their approximate total radiative forcing (not emissions) in the year 2100, relative to 1750: 2.6 W/m^2 (RCP2.6), 4.5 W/m^2 (RCP4.5), 6.0 W/m^2 (RCP6.0), and 8.5 W/m^2 (RCP8.5). RCP8.5 implies a future with continued high emissions growth with limited efforts to reduce GHGs, whereas the other RCPs represent mitigation pathways of varying stringency; none of these scenarios represent any particular national nor global policy.

EXECUTIVE SUMMARY

This report quantifies potential physical and economic damages to multiple U.S. sectors (nationally and within U.S. regions) using a consistent set of climate and socioeconomic scenarios and assumptions (see following Modeling Framework section). Importantly, only a small portion of the impacts of climate change are estimated. Looking across the large number of sectoral impacts described in this report, a number of key findings emerge:

Under both atmospheric greenhouse gas (GHG) concentration scenarios modeled (Representative Concentration Pathways or RCP4.5 and RCP8.5), climate change is projected to significantly affect human health, the U.S. economy, and the environment. These climate change impacts will not be uniform across the U.S., with most sectors showing a complex pattern of regional-scale impacts.

For example, under RCP8.5, almost 1.9 billion labor hours across the national workforce are projected to be lost annually by 2090 due to the effects of extreme temperature on suitable working conditions, totaling over $160 billion in lost wages per year. More than a third of this national loss is projected to occur in the Southeast ($47 billion lost annually by 2090).

In almost all sectors, projected physical and economic damages are significantly larger under RCP8.5 than under RCP4.5. Lower global atmospheric GHG concentrations under RCP4.5 substantially reduce damages associated with extreme weather, such as extreme temperature, heavy precipitation, drought, and storm surge events.

For example, twice as many "100-year" flood events are projected across the contiguous U.S. under RCP8.5 compared to RCP4.5 by the end of the century. By 2100, the difference between projected damages from inland flooding under RCP8.5 and RCP4.5 is approximately $4 billion per year.

Avoided or reduced damages under the lower atmospheric GHG concentration scenario (RCP4.5) are projected to increase over the course of the 21st century. Risks and damages over the 21st century will not be avoided without significant reductions in GHG emissions.

For example, compared to RCP8.5, RCP4.5 avoids nearly 800 premature deaths from extreme temperatures (both extreme heat and cold) per year by 2050, and more than 5,400 premature deaths per year by 2090 in 49 U.S. cities —a reduction of temperature-related mortality of 24% by 2050, and nearly 60% from the 9,300 premature deaths projected to occur each year under RCP8.5 by 2090.

Adaptation actions, especially in the infrastructure sectors, are projected to substantially reduce climate change impacts. Proactive adaptation measures implemented in anticipation of future climate change risks are generally more cost-effective in reducing damages than reactive adaptation responses implemented after impacts have already occurred. For several infrastructure sectors, a combined portfolio of global mitigation and regional adaptation strategies can eliminate a large portion of the economic impacts that are otherwise projected to occur this century.

For example, average cumulative discounted reactive adaptation costs for roads are estimated at $230 billion through 2100 under RCP8.5 and $150 billion under RCP4.5. Across all road types and climate stressors, proactive adaptation to protect roads from climate change-related impacts is projected to decrease costs over the century by more than 75% under both RCPs.

The rate and timing of climate change impacts, and actions to reduce them, are important. While some impacts increase in frequency or magnitude in a gradual manner, others exhibit threshold- type responses to climate change, as large changes manifest over a short period of time.

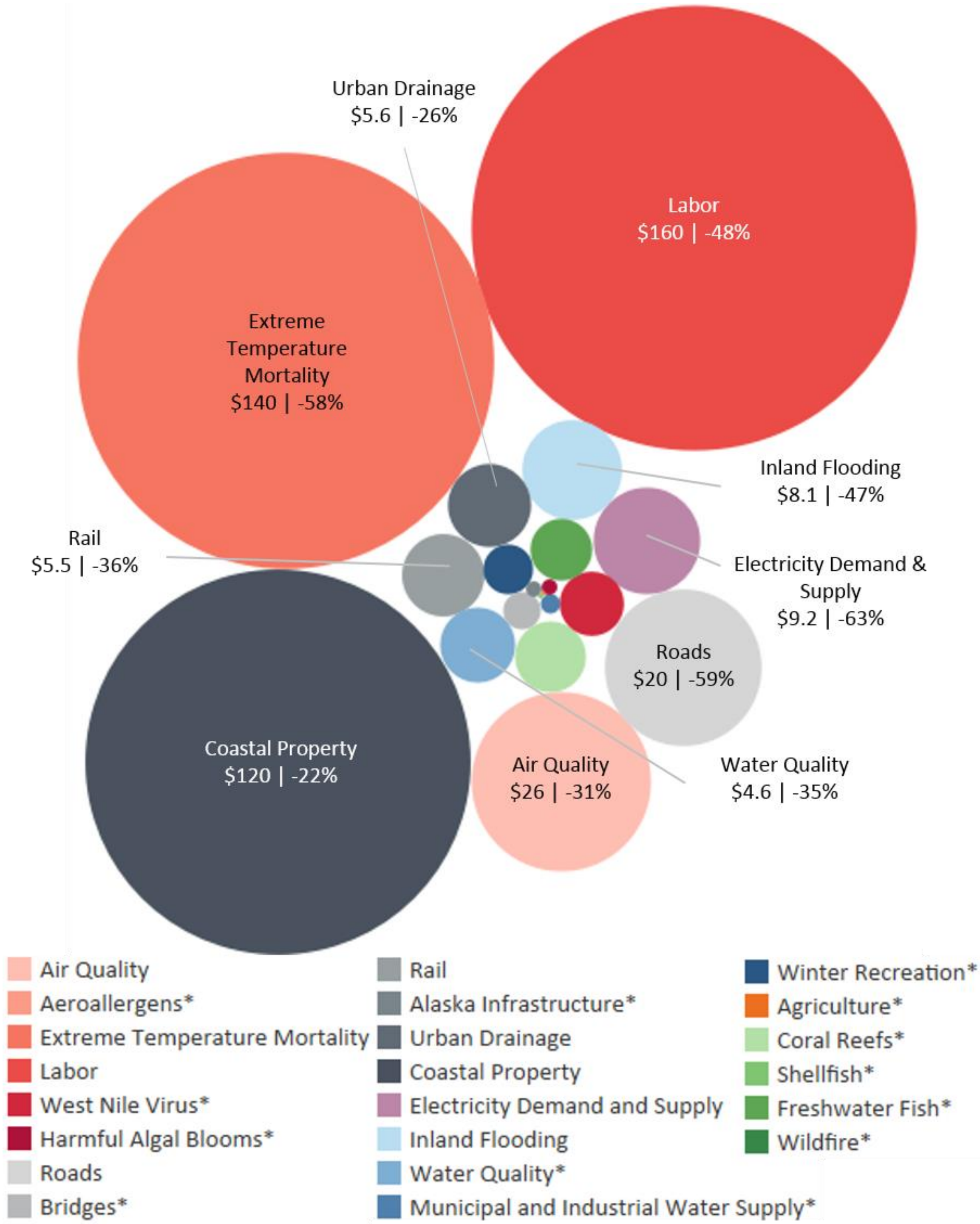
For example, high-temperature bleaching events in coral (expulsion of symbiotic algae) occurred infrequently in the past, but are projected to occur with greater frequency by 2030, resulting in significant losses of U.S. coral reefs in Hawai'i and the Caribbean.

The figure on the next page provides an overview of the national-scale results presented throughout this Technical Report, and shows that climate change is projected to cause economic impacts across most of the sectors analyzed. Importantly, many of the sectoral methodologies do not estimate and monetize the full extent of potential impacts from climate change on that sector, and as such, the results should be treated as conservative. For example, the Air Quality analysis only estimates economic damages from mortality caused by changes in ozone, omitting effects from changes in other air pollutants and morbidity effects. In another example, the Extreme Temperature Mortality analysis only includes 49 major cities, covering about one third of the population. Although not available for all sectors, cumulative impacts for the entire 21st century would very likely be much larger than the annual estimates presented in the figure below. Please refer to the sectoral sections of this report describing the individual modeling efforts for detailed information on the results, a summary of the methodologies used, key sources of uncertainty, and references to the supporting peer-reviewed literature.

Annual damages are projected to increase over time and are generally larger under RCP8.5 compared to RCP4.5. Projected impacts on Extreme Temperature Mortality, Labor, and Coastal Property are the most economically significant under both RCPs in 2050 and 2090. Estimated impacts on Air Quality and Road infrastructure are also large. For Wildfire, climate change is projected to generally have a beneficial economic effect at a national level in the timeframes shown. It is important to note that while the magnitude of estimated economic impacts for some of the sectors is relatively small, many of the corresponding physical impacts have significant societal or iconic values that are generally not captured in the estimates. For example, while damages associated with the loss of freshwater fishing days ($3.1 billion per year in 2090 under RCP8.5) is projected to be orders of magnitude less than coastal property damages ($120 billion per year by 2090 under RCP8.5), this important recreational activity contributes significantly to local economies, with more than 27 million people in the U.S. spending a total of $25 billion on over 365 million freshwater recreational fishing trips in 2011 alone.

Annual Economic Damages from Climate Change

Relative area represents projected economic damages under RCP8.5 in 2090. Sectors with estimated damages larger than $5 billion per year are labeled (first number shown in $billions), and include the percent decrease in damages under RCP4.5 compared to RCP8.5 in 2090 (second number shown in %). Projected damages in 2050 and 2090 under both RCP8.5 and RCP4.5 for all sectors can be found in Table 28.2 of the National Summary section, including sectors with less than $5 billion annual damages in 2090 under RCP8.5, which are noted with asterisks in the legend but may not be visible at this figure scale.



MODELING FRAMEWORK

1. SCENARIOS AND PROJECTIONS

As this second phase of the CIRA project was undertaken to inform the development of NCA4, the selection of scenarios and projections has been made consistent, to the maximum extent possible, with the USGCRP-recommended inputs to the forthcoming assessment. These inputs have the benefits of being well-known and commonly used by others in the climate change impacts modeling community.

1.1. SELECTION OF INPUTS

This section describes the selected scenarios and projections, as well as details regarding how they were processed for use in the modeling framework.

Scenarios of GHG Emissions and Radiative Forcing

As described in the 2015 guidance from the USGCRP Scenarios and Interpretive Science Coordinating Group,[7] the NCA4 will rely on climate scenarios generated for the Intergovernmental Panel on Climate Change's (IPCC's) Fifth Assessment Report (AR5). The scenarios are based on four "representative concentration pathways" (RCPs) that capture a range of plausible emission futures. The RCPs are identified by their approximate total radiative forcing (not emissions) in the year 2100, relative to 1750: 2.6 W/m^2 (RCP2.6), 4.5 W/m^2 (RCP4.5), 6.0 W/m^2 (RCP6.0), and 8.5 W/m^2 (RCP8.5). RCP8.5 implies a future with continued high emissions growth with limited efforts to reduce GHGs, whereas the other RCPs represent mitigation pathways of varying stringency; none of these scenarios represent any particular national or global policy.

As in many sectoral impact analyses, the analyses presented in this Technical Report use a subset of the RCPs due to computational, time, and resource constraints. Based on USGCRP guidance, the analyses utilize RCP8.5 as a high-end scenario and RCP4.5 as a low-end scenario.[8] Comparing outcomes under RCP8.5 and RCP4.5 captures a range of uncertainties and plausible futures and provides perspectives on

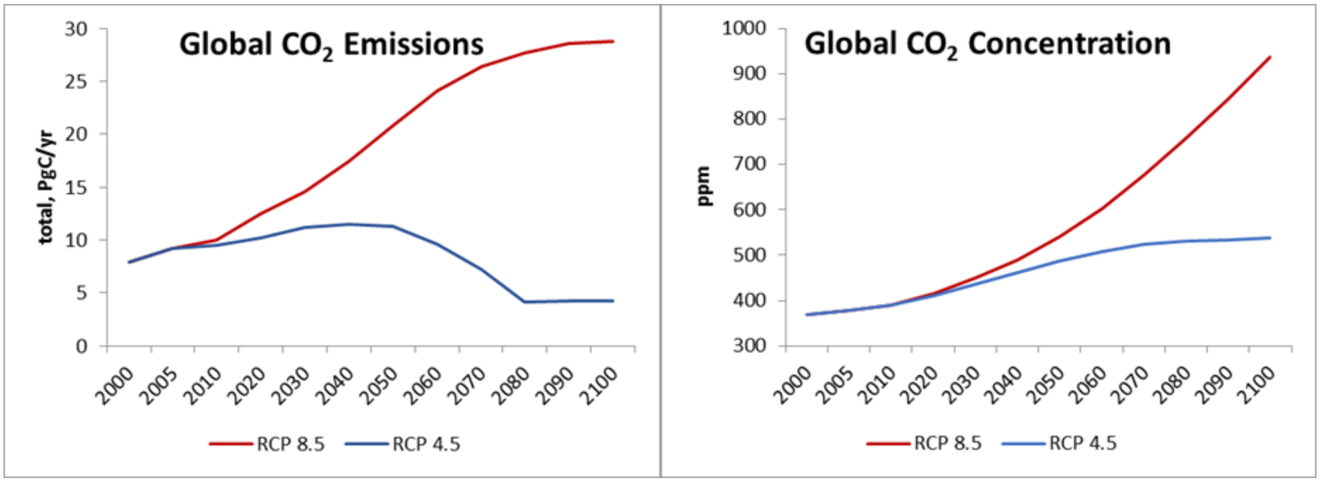
---

[7] U.S. Global Change Research Program, 2015: U.S. Global Change Research Program General Decisions Regarding Climate-Related Scenarios for Framing the Fourth National Climate Assessment. USGCRP Scenarios and Interpretive Science Coordinating Group. Available online at https://scenarios.globalchange.gov/accouncement/1158

[8] See the Third National Climate Assessment (2014) and Climate Impacts Group (2013) for useful descriptions of how the RCPs compare to other common scenarios. References: Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossinet al., 2014: Ch. 2: OurChanging Climate. Climate Change Impacts in the United States: The Third National Climate Assessment, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 19-67. doi:10.7930/J0KW5CXT; Climate Impacts Group, 2013. Making sense of the new climate change scenarios. University of Washington, available at: http://cses.washington.edu/db/pdf/snoveretalsok2013sec3.pdf.

the potential differences between scenarios.[9,10] Figure 1.1 shows differences between RCP8.5 and RCP4.5 in terms of global GHG emissions and atmospheric CO_2 concentration. Under RCP8.5, global atmospheric CO_2 levels rise from current-day levels of approximately 400 up to 936 parts per million (ppm) by 2100 relative to the 1986–2005 average. Under the RCP4.5, atmospheric CO_2 levels at the end of the century remain below 550 ppm. For more information on RCP projections, see Appendix section A.4 and the USGCRP Climate Science Special Report (CSSR).[11]

Figure 1.1. Global GHG Emissions and Atmospheric CO_2 Concentrations for RCP8.5 and RCP4.5[12]



Selection of Global Climate Model (GCM) Projections

To support development of the IPCC's AR5, over 20 climate modeling groups from around the world agreed to a coordinated climate modeling experiment called the fifth phase of the Coupled Model Intercomparison Project (CMIP5).[13] More than 60 models from these groups were run with the RCPs described above, and the resulting data archive has been made available for use by the scientific community over the past several years.

Statistical Downscaling

The results of these global climate model simulations are displayed in coarse geographic grid cells (roughly 2.5˚x2.0˚). This coarse spatial resolution can encompass disparate areas; for instance, a single grid cell of a global climate model can cover the distance from San Francisco to Sacramento.[14] To provide more localized projections of climate changes—important for local impact assessment and adaptation planning—and to provide more consistency with historical observations, downscaling

---

[9] Ibid.

[10] As described in the Coordinating Group's guidance, RCP4.5 is consistent with the SRES-B1 scenario used in NCA3, whereas RCP2.6 would represent a significant departure.

[11] USGCRP, 2017 (*In Press)*: Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA.

[12] Data from: Meinshausen, M., S.J. Smith, K. Calvin, J. S. Daniel, M. L. T. Kainuma, J-F. Lamarque, K. Matsumoto, S.A. Montzka, S.C.B. Raper, K. Riahi, A. Thomson, G.J.M. Velders, and D.P.P. van Vuuren, 2011: The RCP Greenhouse Gas Concentrations and their extension from 1765va to 2500. *Climatic Change*, **109**, 213, doi: 10.1007/s10584-011-0156-z. Data available at: http://www.pik-potsdam.de/~mmalte/rcps/.

[13] Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2012: An overview of CMIP5 and the experiment design. *Bull. Amer. Meteor. Soc.*, **93**, 485-498, doi:10.1175/BAMS-D-11-00094.1.

[14] http://loca.ucsd.edu/what-is-loca/

methodologies are typically employed. The approach used in this report is statistical downscaling, which develops statistical relationships between local climate variables (e.g., temperature or precipitation) and large-scale predictors (e.g., pressure fields) and applies those relationships to the GCM output. While many downscaled products using the CMIP5[15] archive are available, the modeling in this Technical Report uses two of the highest-quality, publicly-available, and peer-reviewed downscaled primary datasets:

Contiguous U.S.: A 2016 dataset of downscaled CMIP5 climate projections was commissioned by the U.S. Bureau of Reclamation and Army Corps of Engineers and developed by the Scripps Institution of Oceanography with a number of collaborators.[16] This dataset, called LOCA (which stands for Localized Constructed Analogs), is used in USGCRP's CSSR, which provides the physical climate science basis for the upcoming NCA4. The LOCA dataset has many advantages; notably, the statistical approach produces improved estimates of extremes, constructs a more realistic depiction of the spatial coherence of the downscaled field, and reduces the problem of producing too many light-precipitation days.[17] LOCA projections have been developed for both RCP8.5 and RCP4.5 using 32 GCMs from the CMIP5 archive.[18] However, as of the finalization date of this Technical Report, the LOCA dataset has only been downscaled for the contiguous U.S. Finally, the LOCA dataset provides daily projections through 2100 at a 1/16th degree resolution for three variables: daily maximum temperature (tmax), daily minimum temperature (tmin), and daily precipitation. Some of the sectoral models of this Technical Report require additional variables, such as solar radiation, wind speed, and relative humidity. Appendix A.4 describes the historical binning approach used to develop internally-consistent projections for these variables based on the LOCA projections.

Alaska: The Scenarios Network for Alaska + Arctic Planning (SNAP), a part of the International Arctic Research Center at the University of Alaska Fairbanks, developed a downscaled climate dataset for Alaska,[19] which as described above, is not covered in the LOCA dataset. The commonly used SNAP dataset focuses on five climate models from the CMIP5 ensemble that have the most skill for Alaska and the Arctic.[20] These five models, all of which were run using RCP8.5 and RCP4.5, are:

---

[15] The CMIP5 climate data are widely available now, whereas products from the next phase of the project (CMIP6) are not envisioned to be available in time to support the analyses of this project.

[16] U.S. Bureau of Reclamation, Climate Analytics Group, Climate Central, Lawrence Livermore National Laboratory, Santa Clara University, Scripps Institution of Oceanography, U.S. Army Corps of Engineers, and U.S. Geological Survey, 2016: Downscaled CMIP3 and CMIP5 Climate Projections: Release of Downscaled CMIP5 Climate Projections, Comparison with Preceding Information, and Summary of User Needs. Available online at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/downscaled_climate.pdf. Data available at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/.

[17] University of California San Diego, cited 2017: LOCA statistical downscaling. Scripps Institution of Oceanography. Available online at http://loca.ucsd.edu/

[18] The LOCA projections were released in September 2016. For timing reasons, a pre-release version of the LOCA dataset was obtained and used in the analyses of this Technical Report. This earlier version contained some very minor differences that have no significant impact on the sectoral modeling results. Specifically, temporal discontinuities (jumps) in the time-series were found for a small number of grid cells on the 1/16th degree grid. Compared to the publicly available version, the earlier dataset contains a slight increase in noise of the precipitation field, and slightly less agreement between the original model-predicted climate change signal and the change seen after downscaling with LOCA.

[19] University of Alaska Fairbanks, cited 2017: SNAP: Scenarios Network for Alaska and Arctic Planning. International Arctic Research Center. Available online at: https://www.snap.uaf.edu/

[20] Model skill is a criterion to select a subset of GCMs that are able to best re-create historical climate in a region (e.g., see Rupp et al. 2013, McSweeney et al. 2015, Vano et al. 2015). In the SNAP context, skill is measured based on the degree to which each GCM's output aligned with observed climate data from 1958 to 2000 for precipitation, sea level pressure, and surface air temperature. Note that due to nonstationarity, skill at matching historical observations may not always lead to superior representation of future climate conditions. References:
McSweeney, C.F., Jones, R.G., Lee, R.W. and Rowell, D.P., 2015. Selecting CMIP5 GCMs for downscaling over multiple regions. Climate Dynamics, 44(11-12), pp.3237-3260.

CCSM4	National Center for Atmospheric Research
GFDL-CM3	Geophysical Fluid Dynamics Laboratory (NOAA)
GISS-E2-R	Goddard Institute for Space Studies (NASA)
IPSL-CM5A-LR	Institut Pierre-Simon Laplace
MRI-CGCM3	Meteorological Research Institute

While it would be preferable to use one downscaled product to maximize consistency, neither dataset covers all geographic areas needed for all analyses, and the strengths of each dataset offer significant advantages over other available downscaled products.

Selection of GCMs

As in many sectoral impact analyses in the literature, the selection of a subset of GCMs is necessary due to computational, time, and resource constraints. Table 1.1 presents the five GCMs that are used in the sectoral analyses of this Technical Report. These GCMs were chosen based on: 1) the ability to leverage existing dynamically-downscaled GCM data, 2) their availability in the SNAP and LOCA downscaled datasets, 3) their ability to capture variability in temperature and precipitation outcomes, and 4) their demonstrated independence and quality. A detailed description of the criteria used to select GCMs can be found in the Technical Appendix (see section A.4).

Rupp, D.E., Abatzoglou, J.T., Hegewisch, K.C. and Mote, P.W., 2013. Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. Journal of Geophysical Research: Atmospheres, 118(19).

Vano, J.A., Kim, J.B., Rupp, D.E. and Mote, P.W., 2015. Selecting climate change scenarios using impact-relevant sensitivities. Geophysical Research Letters, 42(13), pp.5516-5525.

Table 1.1. CMIP5 GCMs Used in the Analyses of this Technical Report

Center (Modeling Group)	Model Acronym	Availability		References
		LOCA	SNAP	
Canadian Centre for Climate Modeling and Analysis	CanESM2	X		Von Salzen et al. 2013[21]
National Center for Atmospheric Research	CCSM4	X	X	Gent et al. 2011[22] Neale et al. 2013[23]
NASA Goddard Institute for Space Studies	GISS-E2-R[24]	X	X	Schmidt et al. 2006[25]
Met Office Hadley Centre	HadGEM2-ES	X		Collins et al., 2011[26] Davies et al. 2005[27]
Atmosphere and Ocean Research Institute, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC5	X		Watanabe et al. 2010[28]

Use of Eras and Control Scenarios

The LOCA and SNAP datasets, which are based on GCM projections from CMIP5, provide data for the 1950-2100 time period.[29] In order to reduce the effects of inter-annual variability and obtain results that are better representative of a particular point in the future, the analyses described in this Technical Report use 20-year eras centered on specific years of interest. The selected timeframes provide sufficient coverage of time periods across the century, including a reasonable estimation of late century impacts (i.e., getting as close to 2100 as possible).

---

[21] von Salzen, K., J.F. Scinocca, N.A. McFarlane, J. Li, J.N. Cole, D. Plummer, D. Verseghy, M.C. Reader, X. Ma, M. Lazare, and L. Solheim, 2013: The Canadian fourth generation atmospheric global climate model (CanAM4). Part I: representation of physical processes. *Atmosphere-Ocean*, **51**, 104-125.

[22] Gent, P.R., G. Danabasoglu, L.J. Donner, M.M. Holland, E. Hunke, S. Jayne, D. Lawrence, R.B. Neale, P.J. Rasch, M. Vertenstein, and P.H. Worley, 2011: The community climate system model version 4. *Journal of Climate*, **24**, 4973-4991.

[23] Neale, R.B., J. Richter, S. Park, P.H. Lauritzen, S.J. Vavrus, P. Rasch, and M. Zhang, 2013: The mean climate of the community Atmosphere Model (CAM4) in forced SST and fully coupled experiments. *Journal of Climate*, **26**, 5150-5168.

[24] Some of the GCMs in the CMIP5 archive were run multiple times to develop individual initializations for each climate model. In general, the LOCA dataset provides projections using the first initialization of each GCM. However, for the GISS-E2-R model, the LOCA dataset provided data for RCP4.5 using run #r6i1p1 and run #r2i1p1 for RCP8.5. The main reasoning for this difference is that the GCM initializations (raw data from CMIP5) did not provide all of the climate data necessary for doing the LOCA constructed analog and bias correction technique. While the usage of different initializations for the GISS-ER-R model could introduce inconsistency, the statistical differences across runs of the same GCM are dramatically lower than across models, and those differences are further dampened by the LOCA bias correction. To evaluate the potential that these alternative initializations could introduce inconsistencies, an analysis was completed comparing the raw #r6i1p1 runs for both RCPs and the raw #r2i1p1 runs for both RCPs. The results of this comparative analysis confirmed that the differences are minimal and that it is reasonable to use the LOCA projections.

[25] Schmidt, G.A., R. Ruedy, J.E. Hansen, I. Aleinnov, N. Bell, M. Bauer, S. Bauer, B. Cairns, V. Canuto, Y Cheng, and A. Del Genio, 2006: Present-day atmospheric simulations using GISS ModelE: Comparison to in situ, satellite, and reanalysis data. *Journal of Climate*, **19**, 153-192.

[26] Collins, W.J., N. Bellouin, M. Doutriaux-Boucher, N. Gedney, P. Halloran, T. Hinton, J. Hughes, C. D. Jones, M. Joshi, S. Liddicoat, G. Martin, F. O'Connor, J. Rae, C. Senior, S. Sitch, I. Totterdell, A. Wiltshire, and S. Woodward, 2011: Development and evaluation of an Earth system model– HadGEM2. *Geoscience Model Development*, **4**, 1051-1075.

[27] Davies, T., M. J. P. Cullen, A. J. Malcolm, M. H. Mawson, A. Staniforth, A. A. White, N. Wood, 2005: A new dynamical core for the Met Office's global and regional modelling of the atmosphere. *Quarterly Journal of the Royal Meteorological Society*, **131**, 1759-1782.

[28] Watanabe, M., T. Suzuki, R. O'ishi, Y. Komuro, S. Watanabe, S. Emori, T. Takemura, M. Chikira, T. Ogura, M. Sekiguchi, and K. Takata, 2010: Improved climate simulation by MIROC5: mean states, variability, and climate sensitivity. *Journal of Climate*, **23**, 6312-6335.

[29] Two of the five GCMs used in this project only provide data through the end of calendar year 2099. Therefore, the inclusion of the year 2100 data is not included in the eras used in the analyses of this Technical Report.

- Historic (1986-2005), typically referred to as the 'reference period'[30]
- 2030 (2020-2039)
- 2050 (2040-2059)
- 2070 (2060-2079)
- 2090 (2080-2099)

All the sectoral analyses in this Technical Report provide results for the 2050 and 2090 eras. Further, results for some sectors are provided using a full time-series of results through 2100, as the outputs of those models provide monthly or annual projections for the entire century.

For some sectors, it is necessary to compare projected climate change impacts with future 'control scenarios' that do not include changes in climate. This is done to isolate the effects of climate change from impacts occurring due to changes in non-climate effects, such as increasing population or economic growth (see descriptions of these socioeconomic variable selections below). The Approach sections for each sector describe where these 'control scenarios' are used and what they represent.

Sea Level Rise Scenarios

This Technical Report uses sea level rise scenarios described in the 2017 NOAA sea level rise technical report for NCA4[31] and the CSSR of the USGCRP.[32] The global mean sea level rise estimates underlying these scenarios are based on the rates described in Kopp et al. (2014).[33]

To generate the global mean sea level rises estimates, the NOAA (2017) projections are stratified based on rates in 2100, and the median[34] for each subset of projections was identified to be consistent with the 2100 global mean sea levels. These six values of global mean sea level change in 2100 are shown in the first column of Table 1.2. After developing annual time series consistent with these 2100 sea levels, these projections are used in the Coastal Property analysis described in this report. To account for the differences in probabilities that each sea level trajectory could occur under each RCP, scenarios weights based on NOAA (2017) are then applied to the Coastal Property sector results for each of the six levels (Table 1.2).

---

[30] While the 1986-2005 reference period was used across most sectors of this Technical Report, there are some where alternative periods were defined due to model or data-specific needs and constraints. Each reference period used is defined in the sectors of the report.

[31] National Oceanographic and Atmospheric Administration. 2017. Global and regional sea level rise scenarios for the United States. NOAA Center for Operational Oceanographic Products and Services, Technical Report NOS CO-OPS 083.

[32] Sweet, W.V., R. Horton, R.E. Kopp, and A. Romanou, 2017 (*In Press)*: Sea level rise. In: Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA.

[33] Kopp, R.E., R.M. Horton, C.M. Little, J.X. Mitrovica, M. Oppenheimer, D.J. Rasmussen, B.H. Strauss and C. Tebaldi, 2014: Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future*, **2**, 383–406, doi:10.1002/2014EF000239.

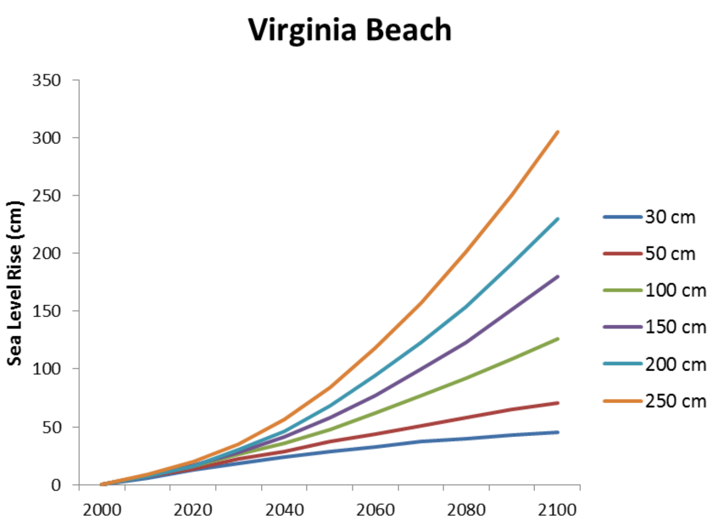
[34] These medians represent projections in which global mean sea level rise in 2100 is 28-32 cm, 48-52 cm, 98-102 cm, 145-155 cm, 195-205 cm, or 245-255 cm.

Table 1.2. Global Mean Sea Level Rise in 2100 with Scenario Weights

Global Mean Sea Level Rise in 2100 (cm)	RCP8.5		RCP4.5	
	Exceedance Probability	Scenario Weight	Exceedance Probability	Scenario Weight
30	0.9997	0.0069	0.9814	0.0948
50	0.9607	0.4064	0.7296	0.7197
100	0.1670	0.5464	0.0330	0.1746
150	0.0133	0.0352	0.0045	0.0087
200	0.0026	0.0038	0.0012	0.0014
250	0.0009	0.0013	0.0005	0.0008

Projections of location-specific differences in relative (or local) sea level change are also taken from NOAA (2017), which account for land uplift or subsidence, oceanographic effects, and responses of the geoid and the lithosphere to shrinking land ice. The probabilistic sea level rise estimates by location from NOAA (2017) are not adopted; instead the mean values for each tide gauge location are used. A distance weighting procedure for interpolating between tide gauge locations is used to attribute tide gauge-level results to each coastal county. Figure 1.2 presents an example of the relative sea level rise rates over the course of the century for Virginia Beach, VA.

Figure 1.2. Local Sea Level Rise Rates for Virginia Beach



Atmospheric Carbon Dioxide Concentrations

For the CMIP5 project, most climate model simulations used prescribed atmospheric CO_2 concentrations, and therefore did not interactively include the effect of carbon cycle feedbacks.[35] The analyses in this Technical Report therefore assume that CO_2 concentrations in each of the GCM

[35] Friedlingstein, P., M. Meinshausen, V. K. Arora, C. D. Jones, A. Anav, S. K. Liddicoat, and R. Knutti, 2013: Uncertainties in CMIP5 climate projections due to carbon cycle feedbacks. *J. Clim.,* **27**, 511–526.

simulations are consistent, with reported values for each RCP taken from the Potsdam Institute for Climate Impact Research (Meinshausen et al., 2011).[36]

Socioeconomic Projections

To capture the effects increasing population and income can have on impact estimates, the analyses in this Technical Report use a single trajectory of socioeconomic change under each RCP. Using a single control population projection isolates the differences in climate change impacts between the two RCPs, such that the results will not be influenced by differing pathways of socioeconomic change.

The analyses in this Technical Report use the Median Variant Projection of the United Nation's (UN) 2015 *World Population Prospects* dataset to project future U.S. population for 2015-2100.[37] This scenario was chosen as it represents a reasonable, mid-range population projection, and allows for the reasonable incorporation of future population growth. [38] For historical U.S. population data for the period 1986-2014, U.S. census data was used.[39] As shown in Figure 1.3, the projected change in U.S. population under the UN Median (shown in solid blue) lies between the U.S. Census High and Low projections through 2060,[40] and by 2100 lies in the middle of the range of scenarios from the UN and the Shared Socioeconomic Pathways (SSPs).[41] The UN Median projection is also similar to the population trajectory used in the first phase of the CIRA project (Paltsev et al., 2013).[42] The impacts of climate change on future U.S. population are not factored into the projections used throughout this Technical Report, with the exception of the domestic migration sector. As such, the population projection does not include important feedbacks that may lead to higher or lower populations at regional levels.

As the UN Median population projection is only available at a national scale, disaggregated population projections were produced at the county-level using EPA's Integrated Climate and Land Use Scenarios version 2 (ICLUSv2) model.[43,44] The spatial pattern of population change in ICLUS is dependent upon

[36] M. Meinshausen, S. Smith, S. J. Smith, K. Calvin, J. S. Daniel, M. L. T. Kainuma, J-F. Lamarque, K. Matsumoto, S. A. Montzka, S. C. B. Raper, K. Riahi, A. Thomson, G. J. M. Velders, and D.P. P. van Vuuren, 2011: The RCP Greenhouse Gas Concentrations and their extension from 1765 to 2500, *Climatic Change* (Special Issue on RCPs), **109**, 213, doi: 10.1007/s10584-011-0156-z. Data available at: http://www.pik-potsdam.de/~mmalte/rcps/

[37] United Nations, 2015: World Population Prospects: The 2015 Revision. United Nations, Department of Economic and Social Affairs, Population Division.

[38] The choice of this particular population scenario versus another could have significant influence on the estimated impacts across sectors, particularly those most influenced by changes in population and economic growth. The use of other population scenarios, such as SSP5 (713 million by 2100) or the UN High Variant (647 million), were determined to be less ideal for this analysis, as they would have a large effect in inflating late-century impact estimates due to the large increase in national population. In addition, recent demographic trends in the U.S. suggest that population growth lie closer to the mid-range scenarios presented in Figure 1.3. Given that the purpose of this analysis is to focus on understanding the difference between the two RCPs, the exploration of uncertainty surrounding this particular population projection is deferred to future work, and the robust literature exploring the differences amongst scenarios.

[39] U.S. Census Bureau, cited 2017: Population Estimates Program. Available online at https://www.census.gov/programs-surveys/popest.html

[40] Hollmann, F.W., T.J. Mulder, and J.E. Kallan, 2000: Methodology and Assumptions for the Population Projections of the United States: 1999 to 2100. U.S. Department of Commerce, Bureau of the Census, Population Division, Population Projections Branch. Population Division Working Paper No. 38. Available online at https://www.census.gov/population/www/documentation/twps0038/twps0038.html

[41] O'Neill, B. C., E. Kriegler, K. Riahi, K. L. Ebi, S. Hallegatte, T. R. Carter, R. Mathur, and D. P. v. Vuuren, 2014: A new scenario framework for climate change research: the concept of shared socioeconomic pathways, *Climatic Change*, doi:10.1007/s10584-013-0905-2.

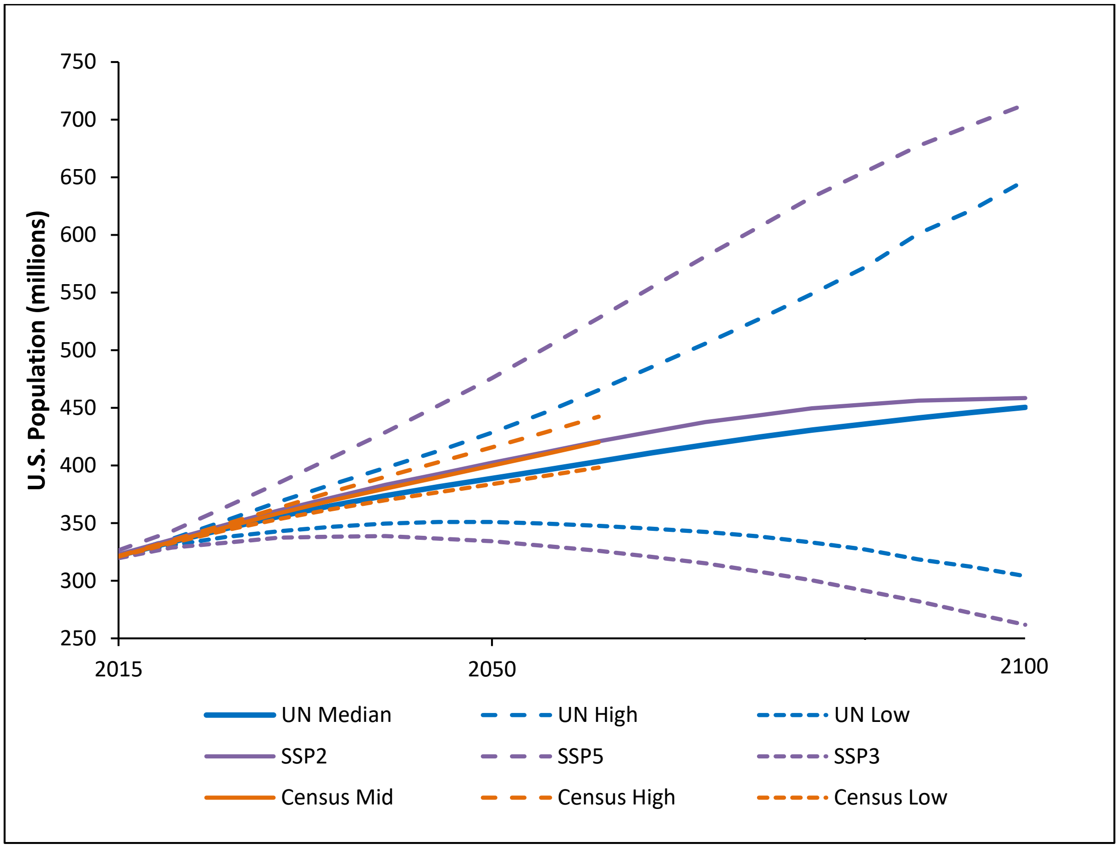
[42] Paltsev, S., E. Monier, J. Scott, A. Sokolov, and J. Reilly, 2013: Integrated economic and climate projections for impact assessment. *Climatic Change*, doi:10.1007/s10584-013-0892-3.

[43] Bierwagen, B., D.M. Theobald, C.R. Pyke, A. Choate, A.P. Groth, J.V. Thomas, and P. Morefield, 2010: National housing and impervious surface scenarios for integrated climate impact assessments. *Proc Natl Acad Sci USA*, **107**, 20887-20892. See http://www.epa.gov/iclus for more information.

[44] EPA, 2017: Updates to the Demographic and Spatial Allocation Models to Produce Integrated Climate and Land Use Scenarios (Iclus) (Version 2). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-16/366F. Available online at https://cfpub.epa.gov/ncea/iclus/recordisplay.cfm?deid=322479

underlying assumptions regarding fertility, migration rate, and international immigration. These assumptions were parameterized using the storyline of SSP2,[45] which suggests medium levels of fertility, mortality, and international immigration.[46] Figure 1.4 shows these county-scale population projections (absolute and percent change from the reference period). The ICLUS model was also used to develop county-scale demography projections (i.e., age, gender, and race),[47] a developed-lands (municipal and industrial development) map layer, and county-scale population projections driven by the future climate patterns of the five LOCA GCMs described above.

Figure 1.3. Comparison of UN, U.S. Census, and the SSPs Population Projections

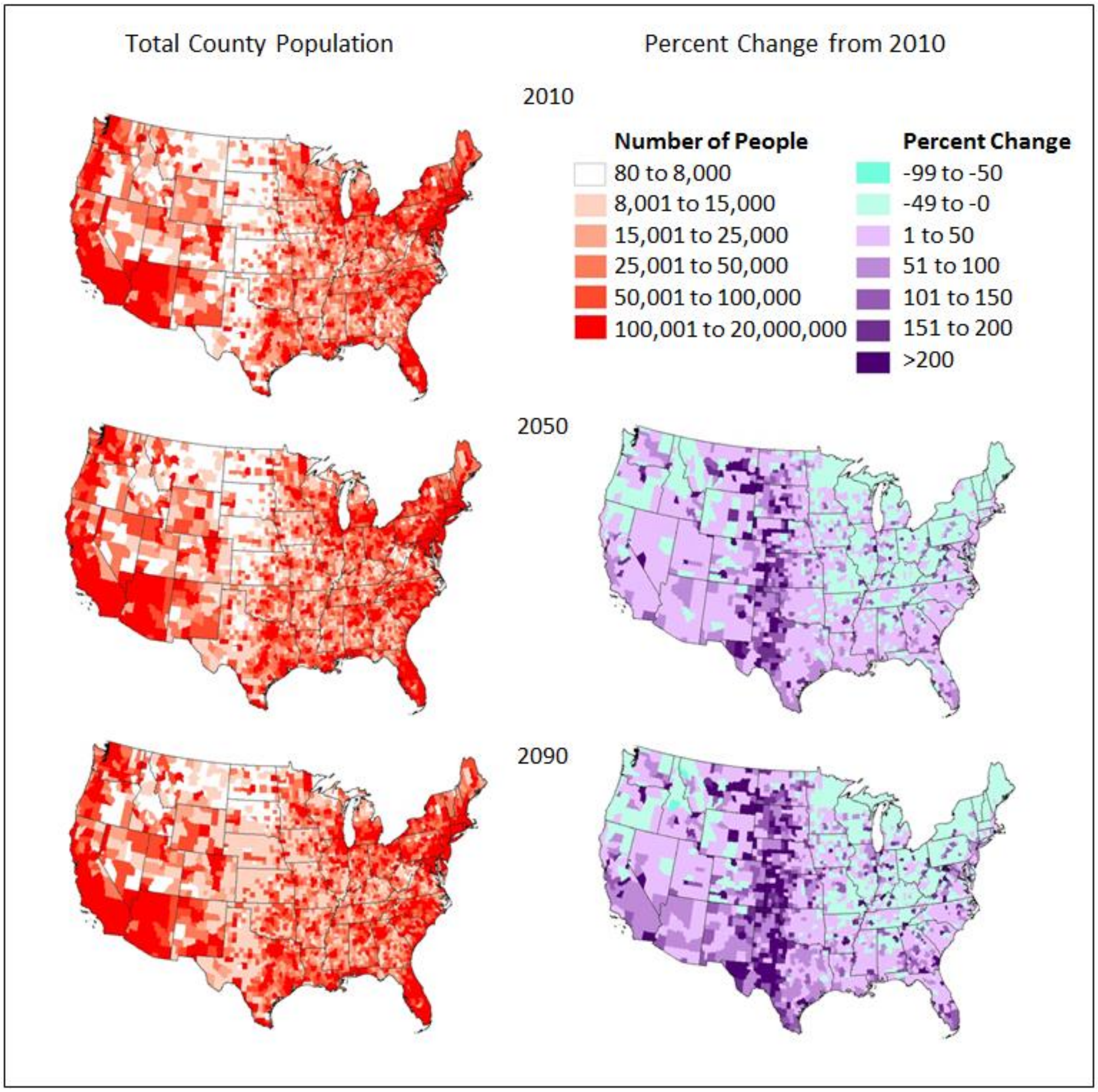


[45] O'Neill, B. C., E. Kriegler, K. Riahi, K. L. Ebi, S. Hallegatte, T. R. Carter, R. Mathur, and D. P. v. Vuuren, 2014: A new scenario framework for climate change research: the concept of shared socioeconomic pathways, *Climatic Change*, doi:10.1007/s10584-013-0905-2.

[46] The ICLUSv2 model, as well as the assumptions used in this particular run of the model, represent one framework for projecting population and demographic change across the U.S. Alternative models or specifications could lead to different outcomes than those reported in this Technical Report.

[47] Projected changes in age distribution by county over time from ICLUSv1 were scaled by the projected change in total county population using the CIRA2.0 ICLUSv2 dataset.

Figure 1.4. Projected County-Scale Population Change



Using the UN Median population projection for the U.S., the Emissions Predictions and Policy Analysis (EPPA, version 6) model[48] was run to generate a projection of economic growth (i.e., gross domestic product, or GDP). This approach is similar to the one used in the first phase of CIRA modeling.[49] The projection of GDP growth through 2040 for the U.S. was taken from the 2016 Annual Energy Outlook reference case,[50] combined with EPPA-6 baseline assumptions for other world regions and time periods (Figure 1.5). The impacts of climate change on economic activity (e.g., losses to labor supply or increased capital expenditures for adaptation) are not accounted for in the macroeconomic input projections used

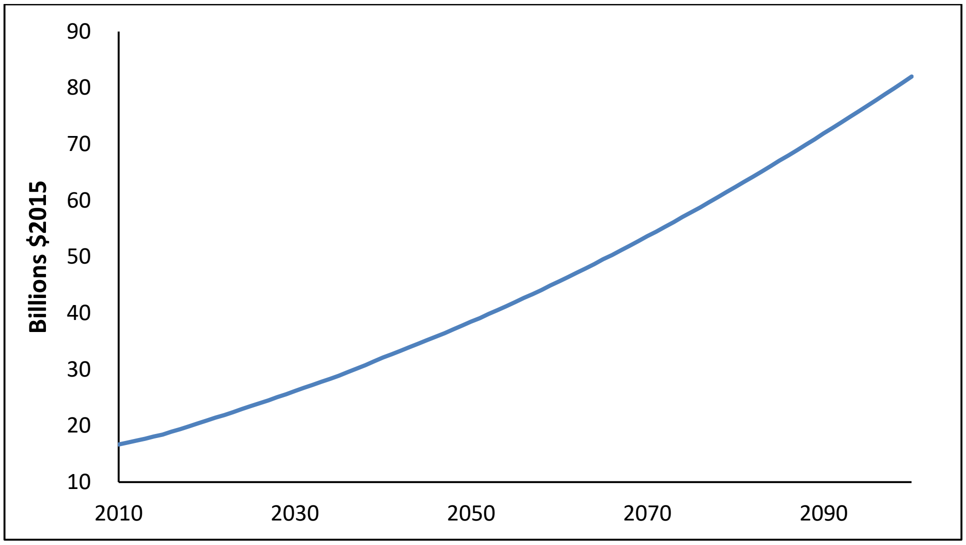
[48] Chen, Y.-H. H., S. Paltsev, J. Reilly, J. Morris, and M. Babiker, 2015: The MIT EPPA6 Model: Economic Growth, Energy Use, and Food Consumption. MIT Joint Program on the Science and Policy of Global Change, Report 278, Cambridge, MA. Available online at http://globalchange.mit.edu/research/publications/2892

[49] Paltsev, S., E. Monier, J. Scott, A. Sokolov, and J. Reilly, 2013: Integrated economic and climate projections for impact assessment. *Climatic Change*, doi:10.1007/s10584-013-0892-3.

[50] U.S. Energy Information Administration, 2016: Annual Energy Outlook.

throughout this Technical Report. As such, the economic growth projection may be overestimated when considering the multi-sector damages, and the use of a single national-scale economic growth projection that omits region-specific socioeconomic changes may lead to different results than those reported.

Figure 1.5. Projected Change in U.S. Gross Domestic Product



Treatment of Discounting

When presenting annual economic results for future years (e.g., 2050 or 2090), results are not discounted. When presenting cumulative economic results in present day value, defined as the year 2015, this report uses a 3% discount rate.[51] In all cases, economic estimates are presented in $2015.[52]

Regional Summaries of Results

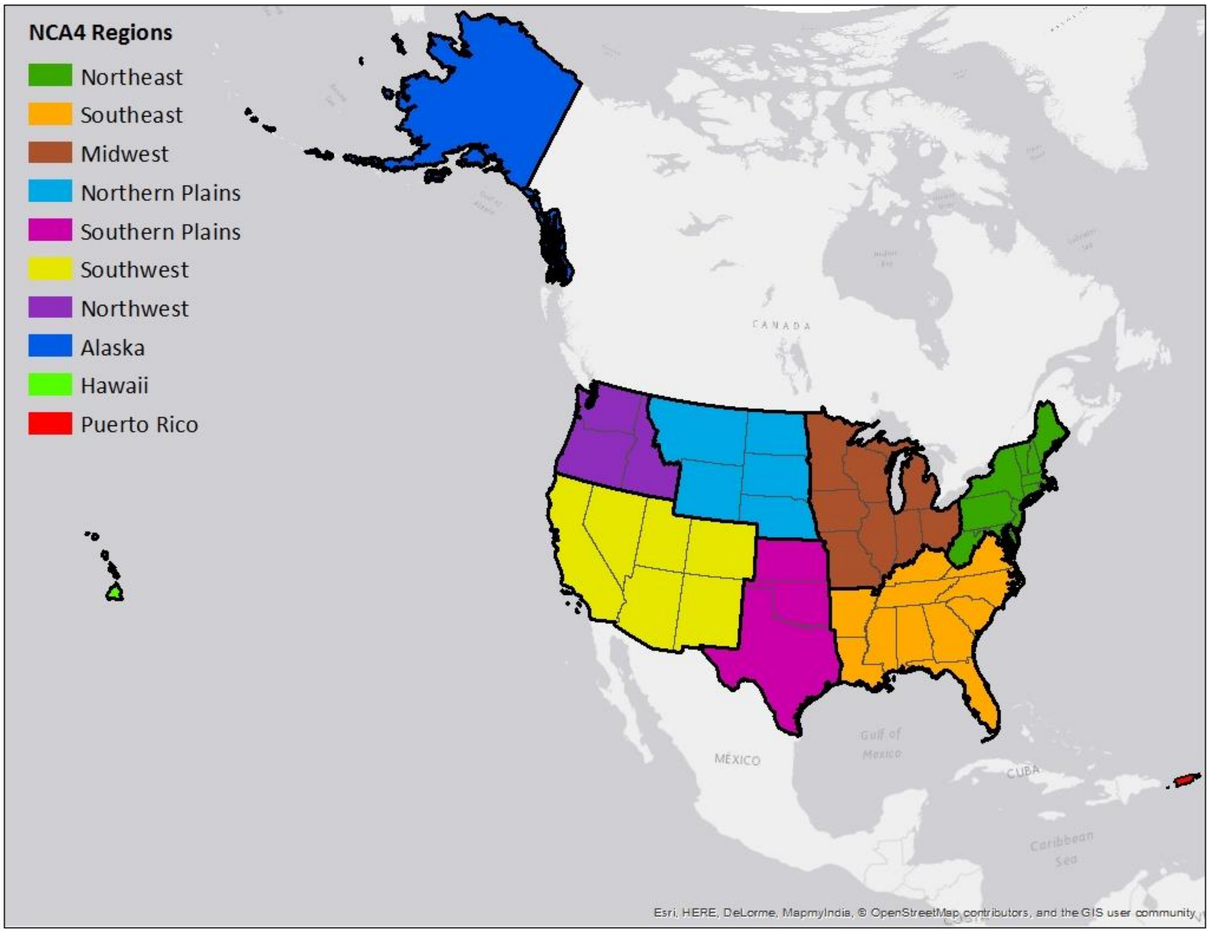
The sectoral sections of this report estimate impacts at various spatial scales (e.g., city-level, county, 8-digit hydrologic unit code). To enable the development of regional (sub-national) comparisons and summaries, results are aggregated to the scale of the NCA4 regions, which are shown in Figure 1.6. See the Regional Summaries section of this Technical Report for estimated physical and economic impacts across sectors.

---

[51] In short, discounting provides an equal basis to compare the value of economic impacts that occur in different time periods. The discount rate itself reflects the trade-off between consumption today and consumption tomorrow, meaning that with a positive discount rate, benefits that occur today are worth more than they would be tomorrow. There are many ways to select a discount rate and little consensus about which discount rate is most appropriate, particularly when assessing economic impacts that span generations. Therefore, this Technical Report uses 3%, a commonly employed rate in the climate impacts literature (e.g., see Goulder and Williams (2012)). This rate is also consistent with the consumption rate of interest recommended by federal guidance for benefit cost analysis, known as OMB Circular A-4, to capture "the rate at which 'society' discounts future consumption flows to their present value." OMB based this rate on the real rate of return on long-term government debt averaged over a 30-year period prior to the issuance of Circular A-4 (2003). Goulder, Lawrence H. and Roberton C. Williams III, "The Choice of Discount Rate for Climate Change Policy Evaluation," Climate Change Economics. Volume 4, Issue 3, November 2012, http://dx.doi.org/10.1142/S2010007812500248.

[52] Dollar years are adjusted using the U.S. Bureau of Economic Affairs' Implicit Price Deflators for Gross Domestic Product, Table 1.1.9. See "National Income and Product Accounts Tables" at https://bea.gov/national/index.htm

Figure 1.6. NCA4 Regional Aggregations[53]



[53] The NCA4 regions align with the NCA3 regions except that: 1) the Great Plains is split into two regions, with the Northern Plains encompassing North Dakota, South Dakota, Nebraska, Montana, and Wyoming, and the Southern Plains encompassing Kansas, Oklahoma, and Texas, and 2) Hawai'i and the Pacific Islands, as well as the Caribbean, are separate regions in NCA4.

1.2. PROJECTIONS OF FUTURE CLIMATE

This section provides a general overview of the characteristics of the climate projections driving the sectoral analyses described in this Technical Report. Projections of secondary or indirect physical impacts, such as runoff or water supply, are described in the relevant sector chapters.

Temperature Change in the U.S.

Figure 1.7 presents the change in mean temperature across the lower 48 states (averaged across the five LOCA GCMs described in the previous section), and Figure 1.8 shows the change in mean temperature across Alaska (averaged across the two SNAP GCMs that are also included in the LOCA set – CCSM4 and GISS-E2-R). As shown, the models project significant warming by the end of the century under RCP8.5 compared to RCP4.5, particularly in parts of the Northeast, Midwest, and Northern Plains of the contiguous U.S. In Alaska, the projected temperature increase is highest along the North Slope, and the increase under RCP8.5 is significantly higher than that under RCP4.5. Section A.4 of the Appendix to this Technical Report presents the results for each GCM.

Figure 1.7. Change in Mean Annual Temperature Relative to the Reference Period (1986-2005) across the Contiguous U.S. (Average across the Five LOCA GCMs)

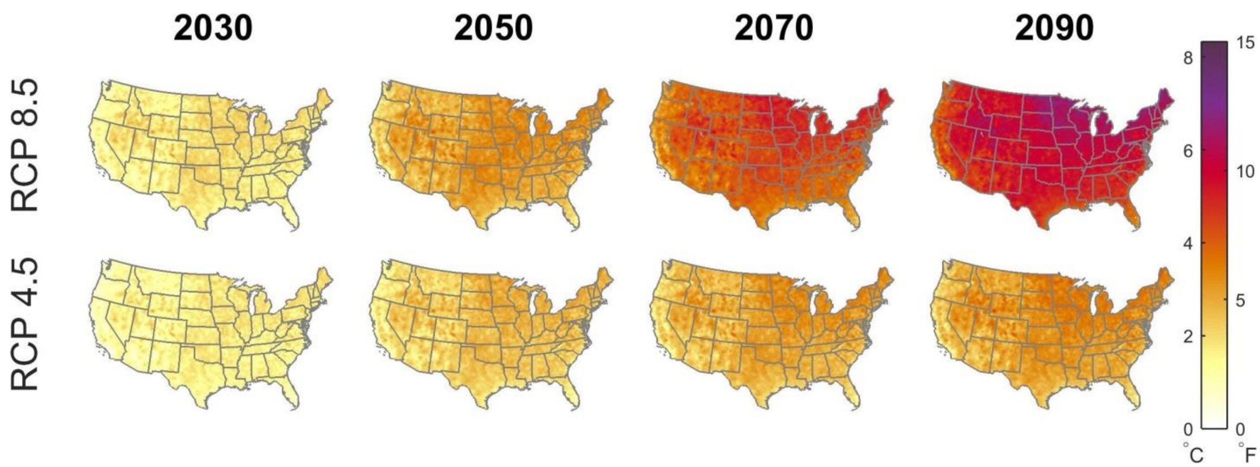
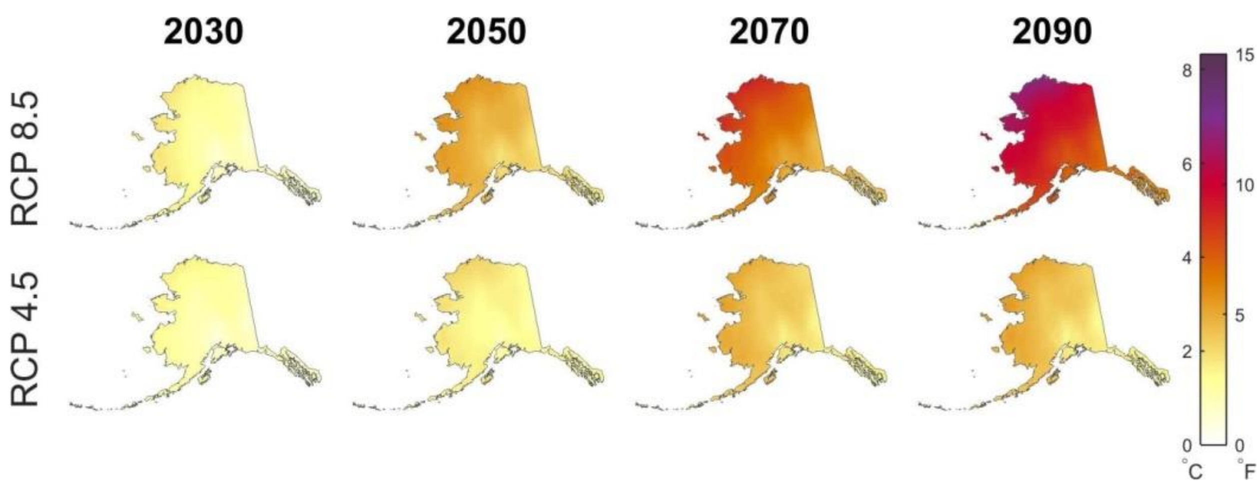


Figure 1.8. Change in Mean Annual Temperature Relative to the Reference Period (1986-2005) across Alaska (Average across Two SNAP GCMs)



In addition to increasing average temperatures, climate change is projected to result in an increase in extreme temperatures. Figure 1.9 presents the projected number of days above 90°F across the contiguous U.S., as well as the number of days above 90°F for the reference period (1986-2005). As shown, the models project a significant increase in the number of days above 90°F by the end of the century under RCP8.5 compared to RCP4.5, particularly in areas of the Southwest, Southern Plains, and Southeast, where the number of days above 90°F reaches as high as 160 days per year. Figure 1.10 shows the projected number of days above 80°F across Alaska in future periods, as well as the reference. The models project a significant increase in the number of days above 80°F, particularly in the central part of the state, and the number of days above 80°F is greater under RCP8.5 than RCP4.5. Section A.4 of the Appendix to this Technical Report presents the results for each GCM.

Figure 1.9. Number of Days above 90°F across the Contiguous U.S. (Average across the Five LOCA GCMs)

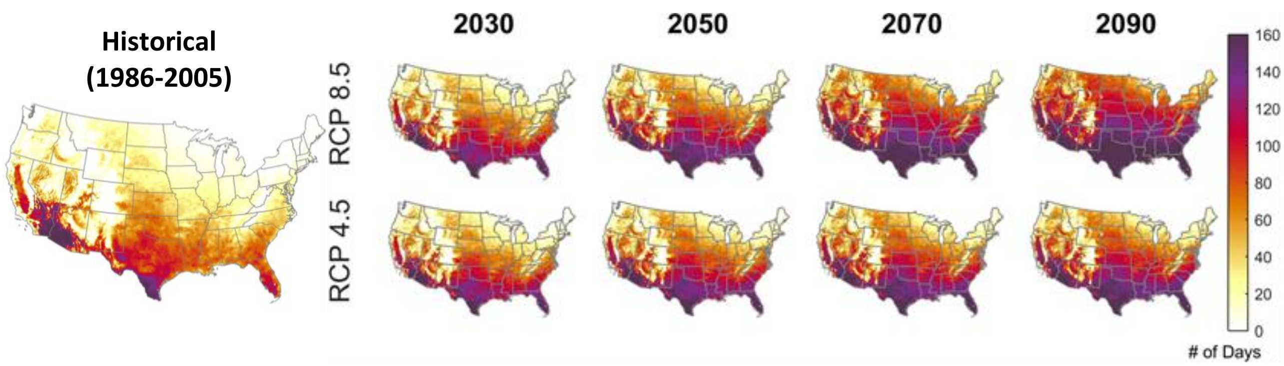
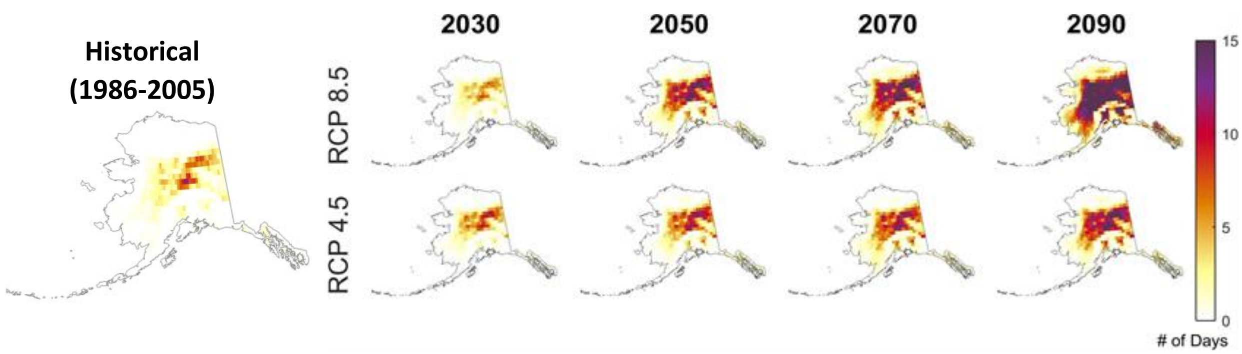


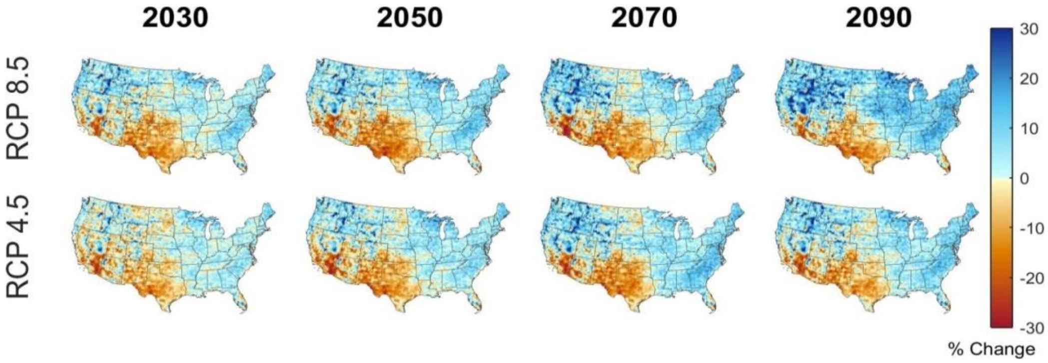
Figure 1.10. Number of Days above 80°F across Alaska (Average across the Two SNAP GCMs)



<u>Precipitation Change in the U.S.</u>

Figure 1.11 presents the percent change in mean annual precipitation across the lower 48 states, and Figure 1.12 shows the percent change in mean annual precipitation across Alaska. As shown, the models project significant changes in precipitation by the end of the century under RCP8.5 compared to RCP4.5. Some regions, particularly the Southwest, are projected to receive less annual rainfall while other regions, particularly the Northwest, receive more annual rainfall. In Alaska, the projected increase in precipitation is generally highest in the eastern parts of the state, but the projections under RCP8.5 for the end of the century show extreme wetting across the majority of the state. Section A.4 of the Appendix to this Technical Report presents the results for each GCM.

Figure 1.11. Percent Change from Reference Period in Mean Annual Precipitation across the Contiguous U.S. (Average across the Five LOCA GCMs)



In addition to changes in mean annual precipitation, climate change is projected to result in periods of more intense rainfall. Figure 1.13 presents the percent change in the maximum daily precipitation across the contiguous U.S, and Figure 1.14 presents the percent change in the maximum monthly precipitation across Alaska. As shown, the models project more intense rainfall events by the end of the century under RCP8.5 compared to RCP4.5. Across Alaska, the models project significant increases in the maximum monthly precipitation by the end of the century in eastern areas of the state under RCP8.5, while western and southwestern areas are projected to experience drying under RCP4.5. Section A.4 of the Appendix to this Technical Report presents the results for each GCM.

Figure 1.12. Percent Change from Reference Period in Mean Annual Precipitation across Alaska (Average across Two SNAP GCMs)

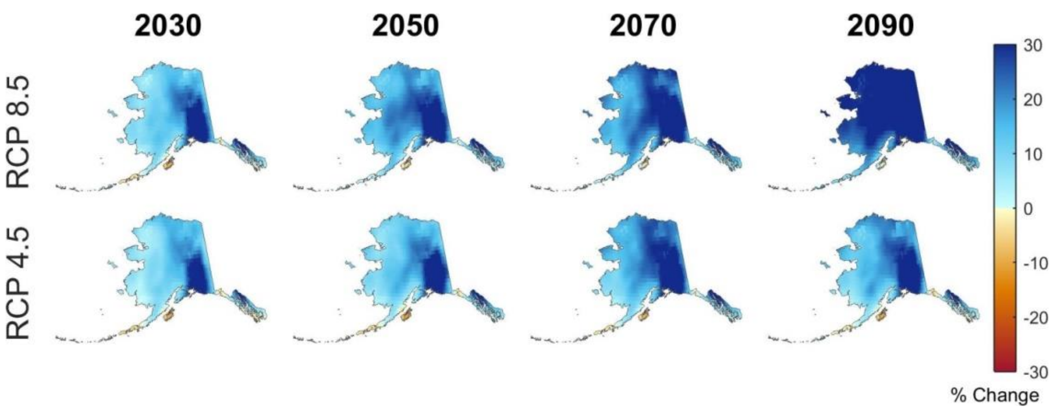


Figure 1.13. Percent Change from Reference Period in Maximum Daily Precipitation across the Contiguous U.S. (Average across the Five LOCA GCMs)

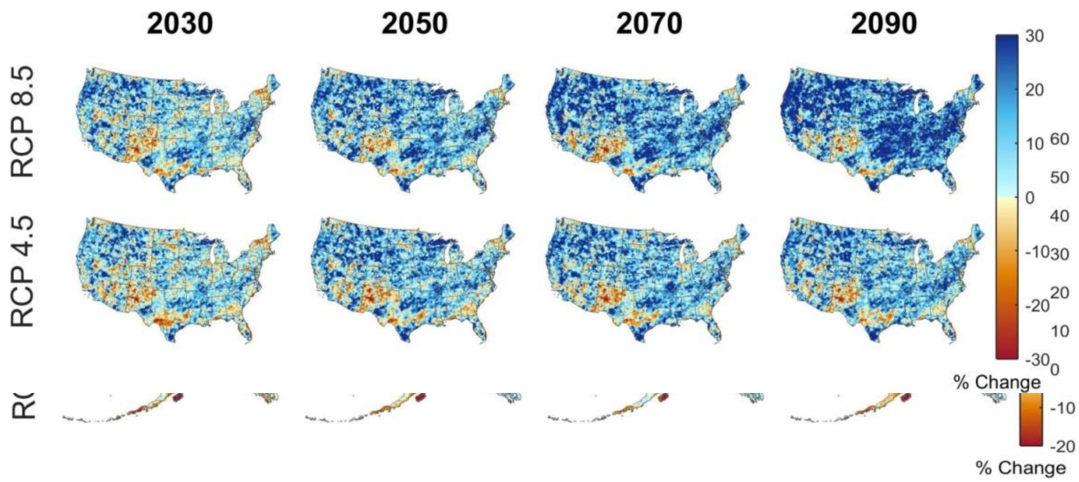
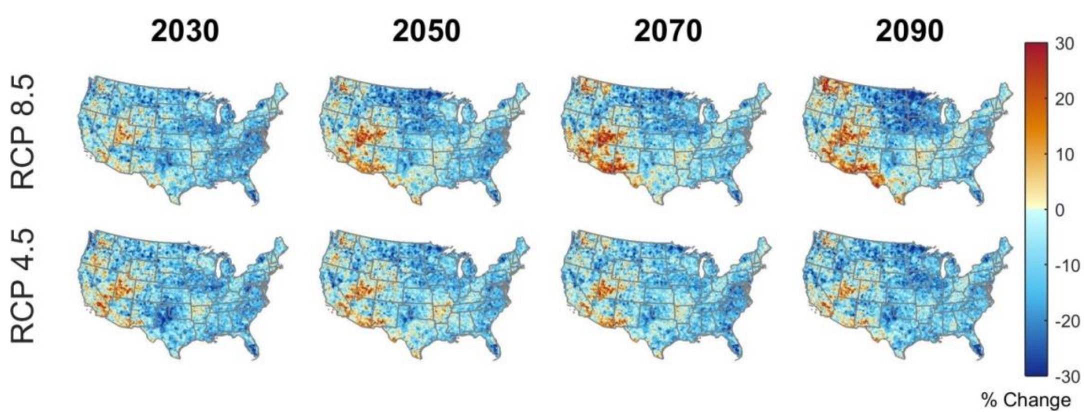


Figure 1.14. Percent Change from Reference Period in Maximum Monthly Precipitation across Alaska (Average across the Two SNAP GCMs)

Lastly, climate change may affect the frequency of drought across the country. As shown in Figure 1.15, areas of the Northwest and Southwest of the contiguous U.S. are projected to experience an increase in the number of consecutive dry days by the end of the century, particularly under RCP8.5. Many other parts of the country are projected to show decreases in the number of consecutive dry days. Section A.4 of the Appendix to this Technical Report presents the results for each GCM.

Figure 1.15. Percent Change from Reference Period in Consecutive Dry Days across the Contiguous U.S. (Average across the Five LOCA GCMs)



2. CIRA PROJECT BACKGROUND

2.1. ADVANCEMENTS IN THE CIRA FRAMEWORK

The results presented in this report build off the CIRA framework developed for the 2015 CIRA report *Climate Change in the United States: Benefits of Global Action*.[54] The CIRA modeling framework has been updated to be consistent with USGCRP-recommended modeling guidelines such that these results may serve as inputs to the forthcoming NCA4. Specifically, this Technical Report utilizes radiative forcing and climate scenarios consistent with those being used in NCA4. For more information on the modeling framework from the first phase of the CIRA modeling project, see pages 10-19 of the 2015 report.[55] For more information on the climate scenarios and projections used in this Technical Report, see the Modeling Framework section.

Table 2.1 below provides a brief summary of differences between the two modeling frameworks. As a result of using different scenario frameworks, and alternative or enhanced methodologies for some sectors, differences exist in the magnitude of results reported in this document and those found in the 2015 report.[56] Importantly, both frameworks enable the quantification of climate change impacts that may have positive or negative effects on human health, the environment, and the economy.

In addition to updating the modeling framework, this report also includes multiple new sectoral impacts not included in the 2015 report. These include: Aeroallergens; West Nile Virus; Harmful Algal Blooms; Domestic Migration; Rail; Alaska Infrastructure; Winter Recreation; and the consideration of international crop impacts affecting U.S. agricultural markets. Several sectoral models were expanded or enhanced from the 2015 report, including: Bridges; Urban Drainage; Water Quality; Inland Flooding; Shellfish; and the inclusion of hydropower availability in Electricity Demand and Supply. Two sectors present in the 2015 report use different methods or models in this report, including: Air Quality and Municipal and Industrial Water Supply (formerly referred to as Water Supply and Demand). Finally, there are two sectors from the 2015 report that are not included in this report: Forestry (Timber Yields and Market Effects) and Drought. In the case of forestry modeling, the underlying timber yield modeling was not completed in time for inclusion in this report. For drought, the effects of climate change on precipitation are captured in a number of other sectors which experience physical and economic impacts associated with changes in drought. These include infrastructure sectors (e.g., Bridges), water resource sectors, Agriculture, and Wildfires.

Several sectoral analyses in this Technical Report improve representation of adaptation and analysis of the costs, benefits, and effectiveness of adaptation options, including Extreme Temperature Mortality, Infrastructure (Roads, Bridges, Rail, and Coastal Property), and Winter Recreation. This not only allows for improved estimates of climate change impacts and economic costs, but contributes to the knowledge base to inform responses at national, regional, and local levels. Future CIRA work will likely expand the coverage of sectoral impacts, leverage improved economic methods for valuing impacts, explore the effectiveness of adaptation in more sectors, and expand the consideration of how impacts are distributed across different socioeconomic populations.

---

[54] EPA, 2015: Climate Change in the United States: Benefits of Global Action. United States Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-15-001.

[55] Ibid.

[56] In addition, damages were presented in $2014 in the 2015 report and are presented in $2015 in this Technical Report.

Table 2.1. Comparison of Modeling Frameworks

	2015 Report (CIRA1.0)	2017 Report (CIRA2.0)
Climate Forcing Scenarios	Emissions scenarios developed specifically for benefits analysis[57] using the Emissions Predictions and Policy Analysis (EPPA-5) model.	Representative Concentration Pathways (RCPs), consistent with scenario selection for NCA4.[58]
	Business as usual with a GHG radiative forcing of 8.6 W/m^2. Global GHG mitigation scenario at 3.2 W/m^2, limiting the increase in global mean temperature to 2°C by 2100.	Severe: RCP8.5 Moderate: RCP4.5
General Circulation Models	Integrated Global System Model-Community Atmospheric Model Framework (IGSM-CAM), and the IGSM pattern-scaling methodology.[59]	Coupled Model Intercomparison Project (CMIP5)
Bias-Correction and Downscaling	Bias-correction using delta method for temperature and ratio method for precipitation.	Externally-developed datasets: LOCA[60] for the contiguous U.S. and SNAP for Alaska.[61]
Eras	Era length varies by sectors. Reference period varies by sector. • 2025 • 2050 • 2075 • 2100	20-year eras. Reference period: (generally 1986-2005). • 2030 (2020-2039) • 2050 (2040-2059) • 2070 (2060-2079) • 2090 (2080-2099)
Sea Level Rise Scenarios	Business as usual scenario: 56 in. by 2100. Mitigation scenario: 37 in. by 2100.	Six 2100 sea levels (0.3, 0.5, 1.0, 1.5, 2.0, and 2.5 m) are given RCP-specific weights[62] consistent with the USGCRP CSSR.

[57] Paltsev, S., E. Monier, J. Scott, A. Sokolov, and J. Reilly, 2013: Integrated economic and climate projections for impact assessment. *Climatic Change*, doi:10.1007/s10584-013-0892-3.

[58] U.S. Global Change Research Program, 2015: U.S. Global Change Research Program General Decisions Regarding Climate-Related Scenarios for Framing the Fourth National Climate Assessment. USGCRP Scenarios and Interpretive Science Coordinating Group. Available online at https://scenarios.globalchange.gov/accouncement/1158

[59] Monier, E., X. Gao, J.R. Scott, A.P. Sokolov, and C.A. Schlosser, 2014: A framework for modeling uncertainty in regional climate change. *Climatic Change*, doi:10.1007/s10584-014-1112-5.

[60] U.S. Bureau of Reclamation, Climate Analytics Group, Climate Central, Lawrence Livermore National Laboratory, Santa Clara University, Scripps Institution of Oceanography, U.S. Army Corps of Engineers, and U.S. Geological Survey, 2016: Downscaled CMIP3 and CMIP5 Climate Projections: Release of Downscaled CMIP5 Climate Projections, Comparison with Preceding Information, and Summary of User Needs. Available online at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/downscaled_climate.pdf. Data available at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/

[61] University of Alaska Fairbanks, cited 2017: SNAP: Scenarios Network for Alaska and Arctic Planning. International Arctic Research Center. Available online at: https://www.snap.uaf.edu/

[62] Kopp, R.E., R.M. Horton, C.M. Little, J.X. Mitrovica, M. Oppenheimer, D.J. Rasmussen, B.H. Strauss and C. Tebaldi, 2014: Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future*, **2**, 383–406, doi:10.1002/2014EF000239.

	2015 Report (CIRA1.0)	2017 Report (CIRA2.0)
Population	County-scale projections from the ICLUS model, driven by a single national population projection from EPPA. U.S. population reaches 514 million by 2100.	County-scale projections from the ICLUSv2 model, driven by the UN Median variant scenario. U.S. population reaches 450 million by 2100.
Economic Growth	GDP projections under each emission scenario from the EPPA-5 model.[63]	A single GDP projection from the EPPA-6 model[64] consistent with the national population projection.
Dollar Year of Reported Damages	$2014	$2015

[63] Paltsev, S., E. Monier, J. Scott, A. Sokolov, and J. Reilly, 2013: Integrated economic and climate projections for impact assessment. *Climatic Change*, doi:10.1007/s10584-013-0892-3.

[64] Chen, Y.-H. H., S. Paltsev, J. Reilly, J. Morris, and M. Babiker, 2015: The MIT EPPA6 Model: Economic Growth, Energy Use, and Food Consumption. MIT Joint Program on the Science and Policy of Global Change, Report 278, Cambridge, MA. Available online at http://globalchange.mit.edu/research/publications/2892

2.2. METRICS AND SCOPE OF ANALYSES

As noted previously, only a portion of the impacts of climate change are estimated, and therefore this Technical Report captures just a fraction of the potential risks and damages (or benefits) that may be avoided or reduced through GHG mitigation. The extent to which the methodologies encapsulate the full range of impacts varies from sector to sector, and are also dependent on data availability and modeling limitations. Table 2.2 below briefly summarizes the scope of physical and economic analysis modeled in each sector. For more information on methods, see the individual sector sections and the underlying research papers cited.

Table 2.2. Scope of Physical and Economic Analysis by Sector

	Scope of Physical Analysis	Economic Valuation of the Impact
HEALTH		
Air Quality	Future ozone concentrations and resulting number of premature deaths	Value of a statistical life (VSL)
Aeroallergens	Change in oak pollen season length and concentrations, and resulting number of emergency department visits for asthma	Emergency department cost-per-visit
Extreme Temperature Mortality	Number of premature deaths attributable to extreme hot and cold temperatures in 49 cities	VSL
Labor	Lost labor supply hours due to changes in hot and cold temperature, including extreme temperatures	Lost Wages
West Nile Virus	Impact of temperature on number of West Nile Neuroinvasive Disease cases	VSL and hospitalization costs
Harmful Algal Blooms	Change in occurrence of cyanobacterial harmful algal blooms in 279 reservoirs	Lost consumer surplus from reservoir recreation
Domestic Migration	Percent change in population	N/A
INFRASTRUCTURE		
Roads	Vulnerability of paved, unpaved, and gravel roads to changes in temperature, precipitation, and freeze-thaw cycles	Reactive or proactive repair or reconstruction costs to maintain level of service
Bridges	Vulnerability of non-coastal bridges to changes in peak water flow	Costs of proactive maintenance and repairs to maintain level of service
Rail	Vulnerability of the Class 1 rail network (passenger and freight) to changes in temperature	Costs of delays (reduced speed and traffic) to railroad companies and to public, and proactive adaptation costs to install sensors
Alaska Infrastructure	Vulnerability of roads, buildings, airports, railroads, and pipelines to changes in permafrost thaw, freeze-thaw cycles, precipitation, and precipitation-induced flooding	Reactive and proactive adaptation expenditures to maintain level of service
Urban Drainage	Change in urban drainage volume from more intense rainfall and increased runoff in 100 cities	Proactive adaptation costs to implement stormwater best management practices
Coastal Property	Vulnerability of on-shore property to sea level rise and storm surge	Value of abandoned property and costs of protection

	Scope of Physical Analysis	Economic Valuation of the Impact
ELECTRICITY		
Electricity Demand and Supply	Changes in energy demand and supply and hydropower generation in response to changes in temperature and flow	Electric power system costs (capital, O&M, fuel costs)
WATER RESOURCES		
Inland Flooding	Changes in frequency of 100-year riverine flooding events	Damages to assets located in floodplains (e.g., buildings)
Water Quality	Changes in river, lake, and reservoir water quality based on modeling of temperature, dissolved oxygen, total nitrogen, total phosphorus	Willingness to pay to offset changes in water quality index
Municipal and Industrial Water Supply	Changes in water supply to meet municipal indoor, municipal outdoor, and industrial water demands	Consumer welfare
Winter Recreation	Impact of snowpack on recreation visits for downhill skiing and snowboarding, cross-country skiing, and snowmobiling at 247 locations	Lost recreation (lift ticket and entry prices)
AGRICULTURE		
Domestic Yield and Welfare Effects	Impacts of changing climate conditions on yields of major U.S. crops (e.g., corn, soybean, wheat, alfalfa hay, cotton), and the subsequent decisions landowners may make regarding crop mix, production practices, and land allocation	Producer and consumer welfare
U.S. and Global Agriculture Interactions	Impact of global agricultural changes on U.S. crop (corn, soybean, wheat) yields, production, consumption, and price	N/A
ECOSYSTEMS		
Coral Reefs	Percent change in shallow coral reef cover in Hawaii, South Florida, and Puerto Rico	Lost recreational value
Shellfish	Effects of ocean acidification on growth rates of oysters, scallops, geoducks, quahogs, and clams, with subsequent effects on shellfish supply	Consumer welfare
Freshwater Fish	Change in the spatial distribution of suitable habitat for coldwater, warmwater, and rough fish living in rivers and streams.	Lost recreational value
Wildfire	Change in terrestrial ecosystem vegetative cover and acres burned on non-agricultural, rural lands.	Response costs
Carbon Storage	Terrestrial carbon flux (storage and annual flows) in metric tons	N/A

2.3. SOURCES OF UNCERTAINTY

The modeling framework for analyses underlying this Technical Report enables the comparison of physical and economic impacts of climate change across a large number of U.S. sectors in a consistent fashion. As with any study, there are sources of uncertainty that are important to consider, several of which are described below. Future work to address these will further strengthen confidence in the estimates presented in this report. Limitations specific to the individual sectoral analyses are described in those sections of this report, as well as in the peer-reviewed literature underlying the analyses.

Emissions and Climate Scenarios

With the goal of presenting a consistent and straightforward set of climate change impact analyses across sectors, this Technical Report presents results using climate projections from five GCMs under RCP8.5 and RCP4.5. These two RCPs, along with the use of climate projections from the LOCA downscaled dataset, match those recommended for use in NCA4.[65] Due to the level of effort necessary to run each scenario through the large number of sectoral models of the project, the CIRA project uses only five of the more than twenty GCMs with daily climate data from the CMIP5 ensemble. While these five GCMs were chosen to capture a large range of the variability observed across the entire ensemble, this subset is not a perfect representation. Analyzing results under the full set of CMIP GCMs would better characterize the range and potential likelihood of future risks.

Even the full set of CMIP5 GCMs is not likely to span the entire range of potential physical responses of the climate system to changes in the concentration of atmospheric GHGs. Previous literature has demonstrated the importance of climate sensitivity assumptions in understanding a wide range of potential changes to the climate system,[66,67] as well as the effect of natural variability on timing and magnitude of impacts.[68,69] The first phase of CIRA modeling investigated the relative importance of four types of uncertainty inherent to projecting future climate: emissions scenarios, climate sensitivity, natural variability, and climate model. For temperature, projected changes were most influenced by decisions regarding whether to reduce GHG emissions and the value of climate sensitivity used (GHG emissions scenario being the dominant contributor). Conversely, these same four sources of uncertainty contribute in roughly equal measure to projected changes in precipitation over the U.S., with large spatial differences.[70]

Coverage of Sectors and Impacts

The analyses presented in this Technical Report cover a broad range of potential climate change damages or benefits in the U.S., but many important impacts are not included. Examples of these omitted impacts include other health effects (e.g., mortality due to extreme events other than heat waves; food safety and nutrition; mental health and behavioral outcomes), effects on ecosystems (e.g., changes in marine fisheries; impacts on specialty crops and livestock; species migration and

---

[65] U.S. Global Change Research Program, 2015: U.S. Global Change Research Program General Decisions Regarding Climate-Related Scenarios for Framing the Fourth National Climate Assessment. USGCRP Scenarios and Interpretive Science Coordinating Group. Available online at https://scenarios.globalchange.gov/accouncement/1158

[66] Paltsev, S., E. Monier, J. Scott, A. Sokolov, and J. Reilly, 2013: Integrated economic and climate projections for impact assessment. *Climatic Change*, doi:10.1007/s10584-013-0892-3.

[67] Monier, E., X. Gao, J.R. Scott, A.P. Sokolov, and C.A. Schlosser, 2014: A framework for modeling uncertainty in regional climate change. *Climatic Change*, doi:10.1007/s10584-014-1112-5.

[68] Monier, E., and X. Gao, 2014: Climate change impacts on extreme events in the United States: an uncertainty analysis. *Climatic Change*, doi:10.1007/s10584-013-1048-1.

[69] Mills, D., R. Jones, K. Carney, A. St Juliana, R. Ready, A. Crimmins, J. Martinich, K. Shouse, B. DeAngelo, and E. Monier, 2014: Quantifying and Monetizing Potential Climate Change Policy Impacts on Terrestrial Ecosystem Carbon Storage and Wildfires in the United States. *Climatic Change*, doi:10.1007/s10584-014-1118-z.

[70] EPA. 2015. Climate Change in the United States: Benefits of Global Action. United States Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-15-001.

distribution), and social impacts (e.g. national security; violence). Without information on these impacts, this report provides only partial insight into the potential risks of climate change. Benefits of climate change, for instance due to reductions in cold related deaths or from carbon fertilization, were considered and are reported in the sectors.

In addition, it is important to note that impacts are only partially valued economically in many sectors. For example, the Wildfire section presents estimated response costs, but not other damages (e.g., health effects from decreased air quality or water contamination, property damages, or loss of recreational space). Therefore, the damages described in this report are likely an undervaluation of the actual climate impacts that would occur under any given scenario. Furthermore, the methods used to calculate economic impacts differ between sectors. For example, the Air Quality sector estimates the economic value of premature death using a value of statistical life (VSL), a form of willingness-to-pay (WTP) for reductions in the risk of death, while the Water Quality sector estimates economic implications using WTP for improved water quality. Sectors like Aeroallergens and West Nile Virus use mean costs of hospital visits. Some sectors, such as Freshwater Fish and Shellfish sectors, use estimates of consumer surplus. Still other sectors measure adaptation or response costs. These varying methods of estimating impacts may not capture all costs.

Finally, this Technical Report does not present results on the possibility of large-scale, abrupt changes that have wide-ranging and possibly catastrophic consequences, such as the intensification of tropical storms, or the rapid melting of the Greenland or West Antarctic ice sheets.[71] In general, there are many uncertainties regarding the timing, likelihood, and magnitude of the impacts resulting from these abrupt changes, and data limitations have precluded their inclusion in the analyses presented in this report. Their inclusion would assist in better understanding the totality of risks posed by climate change.

Sectoral Impacts Modeling

With the exception of several sectors of this report (e.g., Electricity Demand and Supply; Water Quality), the impact estimates presented were developed using a single sectoral impact model. These models are complex analytical tools, and choices regarding the structure and parameter values of the model can create important assumptions that affect the estimation of impacts. Ongoing studies, such as the Inter-sectoral Impact Model Intercomparison Project (ISI-MIP), are investigating the influence of structural uncertainties across sectoral impact models.[72] The use of additional models for each sector of this Technical Report would help improve the understanding of potential impacts in the future.

The results presented in each sector were primarily developed independently of one another. As a result, the estimated impacts may omit important interactive effects. For example, the Wildfire projections presented in this report will likely generate meaningful increases in air pollution, a potentially important linkage not included in the Air Quality analysis. Similarly, there are numerous connections among the agriculture, water, and electricity sectors that affect impacts estimates.[73] Although some of these interactions are captured within integrated assessment models, it is difficult for these broader frameworks to capture all of the detail provided in the sectoral analyses. Although first

---

[71] For more information on these types of impacts, see: National Research Council, 2013: Abrupt Impacts of Climate Change: Anticipating Surprises. Washington, DC: The National Academies Press.

[72] Huber, V., H.J. Schellnhuber, N.W. Arnell, K. Frieler, A.D. Friend, D. Gerten, I. Haddeland, P. Kabat, H. Lotze-Campen, W. Lucht, M. Parry, F. Piontek, C. Rosenzweig, J. Schewe, and L. Warszawski, 2014: Climate impact research: beyond patchwork. *Earth System Dynamics*, 5, 399–408.

[73] For a discussion of interactions among the energy, water, and land use sectors, see: Hibbard, K., T. Wilson, K. Averyt, R. Harriss, R. Newmark, S. Rose, E. Shevliakova, and V. Tidwell, 2014: Ch. 10: Energy, Water, and Land Use. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program.

order connectivity was achieved in some cases (e.g., the water resource model informed irrigation water availability in the agriculture analysis and availability for hydropower and thermo-electric cooling in the Electricity Demand and Supply analysis), improved connectivity between sectoral models would aid in gaining a more complete understanding of climate change impacts across sectors in the U.S.

Variability in Societal Characteristics

Though climate change will affect all Americans, it will not affect all Americans equally. In addition to regional differences in impacts, socioeconomic factors (e.g., income, education) affect exposure, sensitivity, or adaptive capacity, and can make some communities more or less vulnerable to impacts.[74] In some cases, physiological differences place some individuals at greater risk, such as children, older adults, persons with disabilities, or persons with preexisting or chronic medical conditions. An individual's vulnerability to climate change impacts is also a function of their behavior, and is an emerging area of research. In general, the results in this report do not separately report impacts for vulnerable populations, nor analyze how individual behavior affects vulnerability. However, some sectors explore these issues, such as the social vulnerability section of the Coastal Property sector, and separation of impacts across different age groups in the Air Quality and Aeroallergen sectors.

Feedbacks

The modeling framework analyzes changes in socioeconomics and climatic drivers on impacts, with consistent inputs across multiple models. The socioeconomic scenarios that drive the modeling analyses do not incorporate potential feedbacks from climate change impacts to the socioeconomic system (e.g., changes in albedo from land use change or increased GHG emissions resulting from vegetative changes) nor from sectoral damages to the economy (e.g., significant expenditures on protective adaptation measures, such as seawalls, would likely reduce available financial capital to the economy for other productive uses).

Geographic Coverage

In general, this Technical Report does not examine impacts and damages occurring outside of U.S. borders. Aside from the inherent value of people and ecosystems around the world, these impacts could also affect the U.S. through, for example, changes in migration and concerns for national security.

In addition, the primary geographic focus of this report is on the contiguous U.S., with most of the sectoral analyses excluding Hawai'i, Alaska, and the U.S. territories.[75] This omission is particularly important given the unique climate change vulnerabilities of these high-latitude and/or island locales. Finally, several sectoral analyses assess impacts in a limited set of major U.S. cities (e.g., Extreme Temperature Mortality; Urban Drainage), and incorporation of additional locales would gain a more comprehensive understanding of likely impacts.

---

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

[75] Infrastructure and wildfire impacts were estimated in Alaska, and effects on coral reefs were estimated for Hawai'i and Puerto Rico.

2.4. REVIEW OF RELATED LITERATURE

The third National Climate Assessment notes that valuation of the economic consequences of climate change and estimation of how mitigation and adaptation can reduce risk have been lacking in recent assessments, and were identified as priorities for future research.[76,77] In recent years, research on climate change risks and economic impacts has advanced considerably both in the U.S. and globally, which has improved our understanding of the physical, environmental, social and economic impacts of climate change. In the U.S., several large-scale, coordinated analytical efforts have been initiated to evaluate the economic consequences of climate change to the U.S. Specifically, the CIRA project uses a multi-model framework to systematically assess risks, impacts, and economic damages of climate change on human health, key economic sectors, and ecosystems in the U.S.[78] Two phases of CIRA modeling have been completed to date: the first phase released in 2015,[79] and the second phase, which is presented in this Technical Report. Another study, the American Climate Prospectus (ACP), assesses the economic risks of climate change to U.S. households, businesses, and the economy.[80,81] At the state-level, the California Climate Change Assessments provide region-specific projections of physical and economic impacts across a number of sectors.[82] These studies, among others, show that significant risks and economic damages in the U.S. will occur in the 21st century under high emissions scenarios. Further, climate change mitigation, and adaptation in some sectors, would substantially reduce the most dangerous risks of climate change, thereby avoiding costly damages.

Both the CIRA and ACP analyses have developed internally consistent analytical frameworks (e.g., climate forcing, socioeconomic scenarios) to quantify climate change impacts and economic damages across a range of impact categories (including human health, agriculture, coastal areas, and electricity) at the national, regional and local scales. However, there are some key differences between the studies. Both phases of CIRA modeling emphasize bottom-up, process-based understanding of climate change impacts and rely on numerous sectoral simulation models to estimate the biophysical and economic impacts of climate change, including a range of non-market, ecosystem impacts (e.g., wildfire, coral reefs, and marine habitats). The ACP analysis focuses its quantitative analysis on a more limited number of sectoral impacts and economic risks (i.e., in agriculture, labor, health, crime, energy and coastal communities), and discusses important qualitative impacts and risks in other sectors (i.e., in water, forests, tourism, and security). The ACP relies on empirically-derived econometric models of climate impacts in four of the quantified sectors and on process-based models in two other sectors (energy and coastal communities). Additionally, the ACP integrates these direct probabilistic impacts into a macro-economic model to assess the indirect effects of climate impacts on the economy.

---

[76] Corell, R. W., D. Liverman, K. Dow, K. L. Ebi, K. Kunkel, L. O. Mearns, and J. Melillo, 2014: Ch. 29: Research Needs for Climate and Global Change Assessments. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 707-718. doi:10.7930/J03R0QR3.

[77] Liverman, D., 2015: U.S. national climate assessment gaps and research needs: overview, the economy and the international context. Appearing in *The U.S. National Climate Assessment*, Springer doi: 10.1007/978-3-319-41802-5_13.

[78] Waldhoff, S., Martinich, J., Sarofim, M., DeAngelo, B., McFarland, J., Jantarasami, L., Shouse, K., Crimmins, A., Ohrel, S. and Li, J., 2014: Overview of the special issue: a multi-model framework to achieve consistent evaluation of climate change impacts in the United States. *Climatic Change*, pp.1-20.

[79] EPA, 2015: Climate Change in the United States: Benefits of Global Action. United States Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-15-001.

[80] Houser, T., Kopp, R., Hsiang, S.M., Delgado, M., Jina, A., Larsen, K., Mastrandrea, M., Mohan, S., Muir-Wood, R., Rasmussen, D.J., Rising, J., and Wilson, P., 2015: *Economic Risks of Climate Change: An American Prospectus*. Columbia University Press.

[81] Gordon, K., 2014: Risky Business: The Economic Risks of Climate Change in the United States. A product of the Risky Business Project.

[82] State of California, cited 2017: California Climate Change Assessments. Available online at http://climatechange.ca.gov/climate_action_team/reports/climate_assessments.html

While the CIRA analyses presented in this Technical Report use the deterministic projections based on the IPCC Fifth Assessment Report (AR5) RCP and CMIP5 scenario framework, the ACP developed a new dataset exploring the probabilistic distributions of AR5 projections to estimate and communicate the risks of climate extremes. Both studies analyze and characterize many sources of uncertainty in the estimates of climate change impacts and damages.

Internationally, there are significant ongoing multi-sector, multi-model analytical efforts that use internally consistent scenarios to assess the impacts of climate change at sectoral, regional, and global levels.[83] These efforts have been developed with diverse purposes and exhibit different features (Appendix A.5 provides a summary of the recent multi-sector, multi-model studies reviewed and their key features). Of the studies reviewed, a majority of the projects evaluate climate change impacts and the implications of climate change mitigation under alternative climate forcing scenarios (e.g., ISI-MIP[84], BRACE[85], PESETA[86]); while a few focus on understanding climate change impacts under a business-as-usual (i.e., no climate change mitigation) scenario (e.g., CIRCLE[87]), or impacts under high warming scenarios (IMPRESSIONS[88] and HELIX[89]). A majority of the studies examine multiple categories of climate change impacts (e.g., agriculture, health, infrastructure, coastal areas, energy), while some focus on a specific sector, such as agriculture (AgMIP[90]), ecosystems,[91] and coastal areas (RISES-AM[92]). While most of the studies estimate climate change impacts in individual sectors, several studies have begun to investigate the effects of cross-sector interactions and the structural uncertainty across sectoral impact models (e.g., ISI-MIP, IMPRESSIONS). These studies vary in their outputs: some studies have a stronger focus on understanding the physical and biophysical impacts of climate change (e.g., BRACE) and a few studies focus on understanding the economic impacts of climate change in key economic sectors (e.g., CIRCLE, PESETA). Most studies include both biophysical and economic outcomes. Geographic coverage varies among these studies: some of the studies have a global focus (e.g., ISI-MIP), some focus on Europe (e.g., PESETA), but a number of studies provide both a global perspective and investigation in specific regions and/or countries (e.g., BRACE, IMPRESSIONS, HELIX). All of these studies have a strong emphasis on understanding and characterizing uncertainties, such as those arising from climate and socioeconomic scenarios and model structure. Some studies incorporate innovative approaches, such as agent-based modeling to simulate adaptive responses and analysis of institutional and behavioral constraints to adaptation (e.g., IMPRESSIONS). Several projects build in stakeholder engagement and

---

[83] See discussion in Huber, V., H.J. Schellnhuber, N.W. Arnell, K. Frieler, A.D. Friend, D. Gerten, I. Haddeland, P. Kabat, H. Lotze-Campen, W. Lucht, and M. Parry, 2014: Climate impact research: beyond patchwork. *Earth System Dynamics*, 5, 399.

[84] Warszawski, L., K. Frieler, V. Huber, F. Piontek, O. Serdeczny, and J. Schewe, 2014: The inter-sectoral impact model intercomparison project (ISI–MIP): project framework. *Proceedings of the National Academy of Sciences*, 111, 3228-3232.

[85] O'Neill, B., and A. Gettelman, Eds., 2016: The Benefits of Reduced Anthropogenic Climate changE (BRACE) Project. University Corporation for Atmospheric Research, National Center for Atmospheric Research. *Climatic Change* Special Issue. Available online at https://chsp.ucar.edu/brace-climatic-change-special-issue

[86] Ciscar, J.C., L. Feyen, A. Soria, C. Lavalle, F. Raes, M. Perry, F. Nemry, H. Demirel, M. Rozsai, A. Dosio, M. Donatelli, A. Srivastava, D. Fumagalli, S. Niemeyer, S. Shrestha, P. Ciaian, et al., 2014: *Climate Impacts in Europe*. The JRC PESETA II Project. JRC Scientific and Policy Reports, EUR 26586EN.

[87] OECD, 2015: The Economic Consequences of Climate Change. OECD Publishing, Paris. doi: 10.1787/9789264235410-en

[88] Capela Lourenço, T., M.J. Cruz, H. Carlsen, A. Dzebo, J.D. Tàbara, F. Cots, J. Haslett, and P. Harrison, 2015: Common Frame of Reference to support the understanding of adaptation decisionmaking under high-end scenarios. EU FP7 IMPRESSIONS Project Deliverable D1.1.

[89] HELIX, cited 2017: High-End cLimate Impacts and eXtremes (HELIX). Available online at http://helixclimate.eu/home

[90] Rosenzweig, C., J.W. Jones, J.L. Hatfield, A.C. Ruane, K.J. Boote, P. Thorburn, J.M. Antle, G.C. Nelson, C. Porter, S. Janssen, and S. Asseng, 2013: The agricultural model intercomparison and improvement project (AgMIP): protocols and pilot studies. *Agricultural and Forest Meteorology*, 170, 166-182.

[91] Scholze, M., Knorr, W., Arnell, N.W. and Prentice, I.C. 2006: A climate-change risk analysis for world ecosystems *PNAS*, 103 (35), 13116–13120

[92] RISES-AM-, cited 2017: RISES-AM- EU Research Project. Available online at http://www.risesam.eu/

decision support in the analytical frameworks to support adaptation and resilience decisions (RISES-AM, IMPRESSIONS, HELIX).

In parallel to the advancements in climate impact assessments that utilize integrated assessment models and sectoral or economic simulation models, there have been significant advancements in the use of improved empirical methods and data that enable climate impact assessments based on empirically-derived damage functions.[93,94,95] A recent review discussed these advancements and synthesized the state of knowledge on the social and economic impacts of climate change, including on human health (mortality, morbidity, early life development), labor productivity, agriculture, energy, infrastructure, trade, income, macroeconomy, social interactions, and demographic trend.[96] The synthesis suggests that both the current and projected future climate change has significant, negative impacts on human health, welfare, society and the global economic growth. Overall, as suggested by various reviews, representation of adaptation responses and pathways is limited in all the existing studies. Analysis of ecosystem and non-market impacts of climate change varies considerably among the studies and is missing in many studies.

To date, the CIRA and ACP analyses have produced the most detailed estimates of the economic impacts of climate change across a range of sectors at both national and subnational levels in the U.S. The global studies mentioned above mostly treat the U.S. as a region, or part of a larger region (e.g., North America). For the global studies that have subnational (e.g., grid-level) estimates in the U.S., assumptions for analyses are mostly based on global projections or storylines that do not align closely with nationally-derived socioeconomic scenarios and projections (e.g., for demographic change, land use, economic growth). Such storylines are potentially less useful to inform the NCA4, as it would require subnational estimates of climate change impacts for the major sectors that use those scenarios to be consistent with the rest of the assessment.

---

[93] Deschênes, O. and M. Greenstone, 2011: Climate change, mortality, and adaptation: evidence from annual fluctuations in weather in the US. *American Economic Journal: Applied Economics*, 3, 152-185.

[94] Lobell, D.B., W. Schlenker, and J. Costa-Roberts, 2011: Climate trends and global crop production since 1980. *Science*, 333, 616-620.

[95] Schlenker, W. and M.J. Roberts, 2009: Nonlinear temperature effects indicate severe damages to US crop yields under climate change. *Proceedings of the National Academy of sciences*, 106, 15594-15598.

[96] Carleton, T.A. and S.M. Hsiang, 2016: Social and economic impacts of climate. *Science*, 353, aad9837.

2.5. TERMS AND ACRONYMS COMMONLY USED IN THIS REPORT

Adaptation Costs: Economic damages incurred when implementing a wide range of adaptation options, whether a reactive response (i.e., implemented in response to climate change impacts that have already occurred) or proactive measure (i.e., implemented in anticipation of future climate change impacts).

Control Scenario: The control scenario, or the "no climate change scenario," refers to a modeled future scenario that does not include climate change, but typically includes future changes in population and/or economic growth. These control scenarios allow for the isolation of climate change impacts from other non-climate drivers of change; specific sectoral application is described in each Approach section.

Damage: Economic damages are the monetized value of impacts attributed to climate change. Metrics of damages differ by sector; these metrics are shown in Table 2.2 above and described in each sectoral Approach section.

GCM: Global Climate Models are mathematical models that simulate the physics, chemistry, and biology that influence the climate system. Related term: *General Circulation Model.*

5-GCM: In this report, the analyses generally use five global climate models: CanESM2, CCSM4, GISS-E2-R, HadGEM2-ES, and MIROC5 (see Selection of GCMs above). In many instances, estimates are presented as a "five-model average," which means the average of the results of these five GCMs.

Impact: Climate change impacts are the physical or economic effects (positive or negative) occurring in response to climate stressors.

RCP: Representative Concentration Pathways are GHG concentration trajectories from the Intergovernmental Panel on Climate Change's (IPCC's) Fifth Assessment Report (2014) that reflect possible increases in radiative forcing associated with emissions over time.

RCP8.5: The Representative Concentration Pathway with an approximate total radiative forcing (not emissions) in the year 2100, relative to 1750, of 8.5 W/m^2. RCP8.5 implies a future with continued high emissions growth under limited efforts to reduce GHGs. Thus, in this report, RCP8.5 represents the "higher" or "more severe" scenario. Under RCP8.5, global atmospheric CO_2 levels rise from current-day levels of approximately 400 up to 936 parts per million (ppm) by 2100.

RCP4.5: The Representative Concentration Pathway with an approximate total radiative forcing (not emissions) in the year 2100, relative to 1750, of 4.5 W/m^2. RCP4.5 implies a future with moderate emissions growth under substantial global efforts to reduce GHGs. Thus, in this report, RCP4.5 represents the "lower" or "less severe" scenario. Under the RCP4.5, atmospheric CO_2 levels at the end of the century remain below 550ppm.

Reference Period: The reference period or the historical reference period refers to the period of years upon which future impacts are compared. The years included in these periods are described in each sectoral Approach section.

Sector: This report is separated into impact sectors based primarily on the underlying model used in the analysis and the category of climate change impacts estimated within that larger topic area.

HEALTH

3. AIR QUALITY

3.1 KEY FINDINGS

- Climate change is expected to result in weather conditions that are increasingly conducive to high concentrations of ground-level ozone over many parts of the U.S.
- Unless offset by additional domestic reductions in ozone precursor emissions, climate-driven changes in ozone under RCP8.5 are projected to result in an additional 420-1,200 premature deaths per year in 2050 and 920-2,500 premature deaths per year in 2090. Under RCP4.5, an increase of 300-810 premature deaths is projected annually in 2050, rising to 630-1,700 additional premature deaths in 2090.
- Annual national costs of climate-driven, premature ozone-related deaths under RCP8.5 are projected to be $9.8 billion in 2050 and $26 billion in 2090. Under RCP4.5, annual costs of premature deaths are projected to be $6.9 billion in 2050 and $18 billion in 2090.
- Compared to RCP8.5, the level of summer season ozone projected under the RCP4.5 scenario demonstrates a substantially lower burden of air pollution on U.S. respiratory health by reducing ozone concentrations, thereby reducing the need for further emissions controls on domestic sources to address ozone air pollution.

3.2 INTRODUCTION

As of 2015, more than 120 million Americans live in counties where air pollution levels exceed the National Ambient Air Quality Standards (NAAQS). Ground-level ozone and fine particle pollution ($PM_{2.5}$) are the overwhelming contributors to these cases of poor air quality, and both pollutants have significant adverse effects on human health through respiratory and cardiovascular impacts. Actions to reduce the emissions that lead to high levels of ozone and fine particles have been highly successful over the past 15 years; since 2000, ozone levels have been reduced by 17% and fine particle concentrations have been reduced by 37% nationally.[97] However, climate change has the potential to slow the improvements to U.S. air quality by altering weather patterns and increasing the prevalence of conditions that lead to episodes of poor air quality.[98] Previous studies have suggested that the future

---

[97] EPA, 2016: National Air Quality –Status and Trends of Key Air Pollutants. United States Environmental Protection Agency, Office of Air Quality Planning and Standards. Available online at www.epa.gov/air-trends.

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

health impacts of climate change resulting from degraded air quality could be significant, with an economic burden ranging from hundreds of millions to hundreds of billions of dollars.[99,100]

3.3 APPROACH

This analysis projects impacts of climate change on future ground level ozone concentrations and resulting health consequences within the contiguous U.S. for three periods representing the reference (2000), mid-century (2050), and late-century (2090) conditions.[101] A series of global and regional models is used to assess future climate-driven changes in summer (May through September) ozone concentrations over the contiguous U.S. Here, the regional climate across the contiguous U.S. is represented by *dynamically-downscaled* data rather than *statistically-downscaled* data from LOCA. As a result of this, there will be differences in the absolute magnitudes of climate variables (e.g., temperature and precipitation) at local scales between the dynamically downscaled Weather Research and Forecasting (WRF) data and the LOCA dataset used elsewhere in this Technical Report and described in the Scenarios and Projections section. See Appendix A.6 for the WRF regional climate summaries. Air pollutant levels can be strongly influenced by meteorological conditions other than temperature and precipitation (e.g., mixing layer depths, wind speed and direction, among others). The dynamical downscaling is used to create the temporal evolution of those three-dimensional meteorological data that are required as inputs for the simulations of air quality. See Appendix A.6 for a discussion of climate impacts on $PM_{2.5}$.

Climate impacts are simulated with the CCSM4 GCM[102] under RCP8.5 and RCP4.5 and dynamically downscaled over North America using the WRF model[103,104] to provide climate-influenced meteorological inputs for 2050 and 2090 relative to 2000.[105] These meteorological data, along with emissions that are projected to represent mid-century conditions,[106] are used to drive the Community Multiscale Air Quality model (CMAQ)[107] over the contiguous U.S. using a 36-kilometer grid resolution. The 2000, 2050, and 2090 estimates are each represented by 11 years of simulations centered on those years to consider interannual variability in meteorology. The reference period simulation is driven by the

---

[99] Fann, N., C.G. Nolte, P. Dolwick, T.L. Spero, A. Curry Brown, S. Phillips, and S. Anenberg, 2015: The geographic distribution and economic value of climate change-related ozone health impacts in the United States in 2030. *Journal of the Air & Waste Management Association*, **65**, 570-580. http://dx.doi.org/10.1080/10962247.2014.996270.

[100] Garcia-Menendez, F., R.K. Saari, E. Monier, and N.E. Selin, 2015: U.S. air quality and health benefits from avoided climate change under greenhouse gas mitigation. *Environmental Science and Technology*, **49**, 7580-7588, doi:10.1021/acs.est.5b01324

[101] The estimates for 2050 and 2090 represent the average for the periods 2045-2055 and 2085-2095, respectively. The reference period for the analysis is 1995-2005.

[102] Gent, P.R., G. Danabasoglu, L.J. Donner, M.M. Holland, E.C. Hunke, S.R. Jayne, D.M. Lawrence, R.B. Neale, P.J. Rasch, M. Vertenstein, P.H. Worley, Z.-L. Yang, and M. Zhang, 2011: The Community Climate System Model Version 4. *J. Climate*, **24**, 4973-4991, doi:10.1175/2011JCLI4083.1

[103] Skamarock, W.C., and J.B. Klemp, 2008: A time-split nonhydrostatic atmospheric model for weather research and forecasting applications. *J. Comput. Phys*., **227**, 3465–3485.

[104] Following the methods of: Spero, T.L., C.G. Nolte, J.H. Bowden, M.S. Mallard, and J.A. Herwehe, 2016: The impact of incongruous lake temperatures on regional climate extremes downscaled from the CMIP5 archive using the WRF model. *J. Climate*, **29**, 839–853.

[105] Due to the computational demands in dynamically downscaling GCMs, only one of the five GCMs being used throughout this Technical Report is applied in this air quality analysis. As a result, this approach does not capture uncertainty across climate models, which may be important for characterizing air quality impacts. As described in the Modeling Framework section of this Technical Report, CCSM4 lies close to the ensemble mean in terms of variability in national and regional projections of annual average and seasonal temperature and precipitation change.

[106] EPA, 2016: Emissions Inventory for Air Quality Modeling Technical Support Document: Heavy-Duty Vehicle Greenhouse Gas Phase 2 Final Rule, EPA-420-R-16-008, 210 pp.

[107] Byun, D., and K. L. Schere, 2006: Review of the governing equations, computational algorithms, and other components of the Models-3 Community Multiscale Air Quality (CMAQ) modeling system. *Appl. Mech. Rev*., **59**, 51–77.

CCSM4 representation of meteorological conditions for that period rather than using observed meteorological conditions. The CMAQ model is used to simulate the transformation of air pollutant emissions to ozone in the reference period and each of the multi-year scenarios of climate change-driven changes in meteorology. While natural emissions from vegetation respond to changes in meteorology, domestic non-GHG emissions are held constant through the future period so that the effects of climate change can be isolated from changes in emissions policies.[108]

The potential impacts of the climate-driven changes in air pollutant concentrations for specific health endpoints are estimated using the Benefits Mapping and Analysis Program – Community Edition (BenMAP-CE).[109] Estimates of the number of individuals exposed to future levels of ozone concentrations are projected using population counts from the Integrated Climate and Land Use Scenarios version 2 (ICLUSv2).[110] BenMAP-CE quantifies ozone-attributable deaths and illnesses using the same suite of concentration-response functions documented in Fann et al. (2015).[111] The economic value of these premature deaths is estimated with a value of statistical life (VSL) adjusted to future years based on a projection of economic growth.[112] The results presented in this section represent the additional deaths due to climate change compared to the observed mortality in the reference period. Additional information on the approach is provided in Fann et al. (2015).[113]

3.4 RESULTS

Ozone, which is regulated by NAAQS, is known to adversely affect human health through respiratory and cardiovascular pathways, resulting in additional reported acute respiratory symptoms, missed school and work days, hospital admissions, and premature deaths. The analysis is focused on the summer months when ozone concentrations tend to be higher in response to higher temperatures. The changes presented here are for each future period relative to the reference period. The simulations represent a single member of a large ensemble of potential future climate outcomes, and this analysis should be viewed in that context.

---

[108] Domestic non-GHG emissions in the future periods were based on EPA projections for the mid-century, as described in technical support documents for the 2040 Heavy Duty Greenhouse Gas Phase 2 Rule, and did not change across climate scenarios or time periods so that the effects of climate change could be isolated. These technical support documents are available from www.regulations.gov: EPA-HQ-OAR-2014-0827-2301 and EPA-HQ-OAR-2014-0827-2303.

[109] EPA, 2014: Environmental Benefits Mapping and Analysis Program -Community Edition (BenMAP-CE). United States Environmental Protection Agency, Office of Air Quality Planning and Standards, Health and Environmental Impacts Division. Available at www.epa.gov/benmap

[110] EPA, 2017: Updates to the Demographic and Spatial Allocation Models to Produce Integrated Climate and Land Use Scenarios (ICLUS) (Version 2). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-16/366F. Available online at https://cfpub.epa.gov/ncea/iclus/recordisplay.cfm?deid=322479

[111] Fann, N., C.G. Nolte, P. Dolwick, T.L. Spero, A. Curry Brown, S. Phillips, and S. Anenberg, 2015: The geographic distribution and economic value of climate change-related ozone health impacts in the United States in 2030. *Journal of the Air & Waste Management Association*, **65**, 570-580. http://dx.doi.org/10.1080/10962247.2014.996270.

[112] At the time of this analysis, the EPA's Guidelines for Preparing Economic Analyses recommends a VSL of $7.9 million ($2008) based on 1990 incomes. To create a VSL using $2015 and based on 2015 incomes, the standard value was adjusted for inflation and for income growth adjustment based on the approach described in EPA's BenMAP-CE model and its documentation. The resulting value, $10.0 million for 2015 ($2015), was adjusted to future years by assuming an elasticity of VSL to GDP per capita of 0.4. Projections of U.S. GDP and population described in the Modeling Framework section of this Technical Report were employed. Using this approach, the VSL is estimated at $12.4 million in 2050 and $15.2 million in 2090. Sources: 1) EPA, 2014: Guidelines for Preparing Economic Analyses. National Center for Environmental Economics. Available online at http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0568-52.pdf/$file/EE-0568-52.pdf ; and 2) EPA, cited 2017: Benefits Mapping and Analysis Program (BenMAP): Manual and Appendices for BenMAP-CE. Available online at https://www.epa.gov/benmap/manual-and-appendices-benmap-ce.

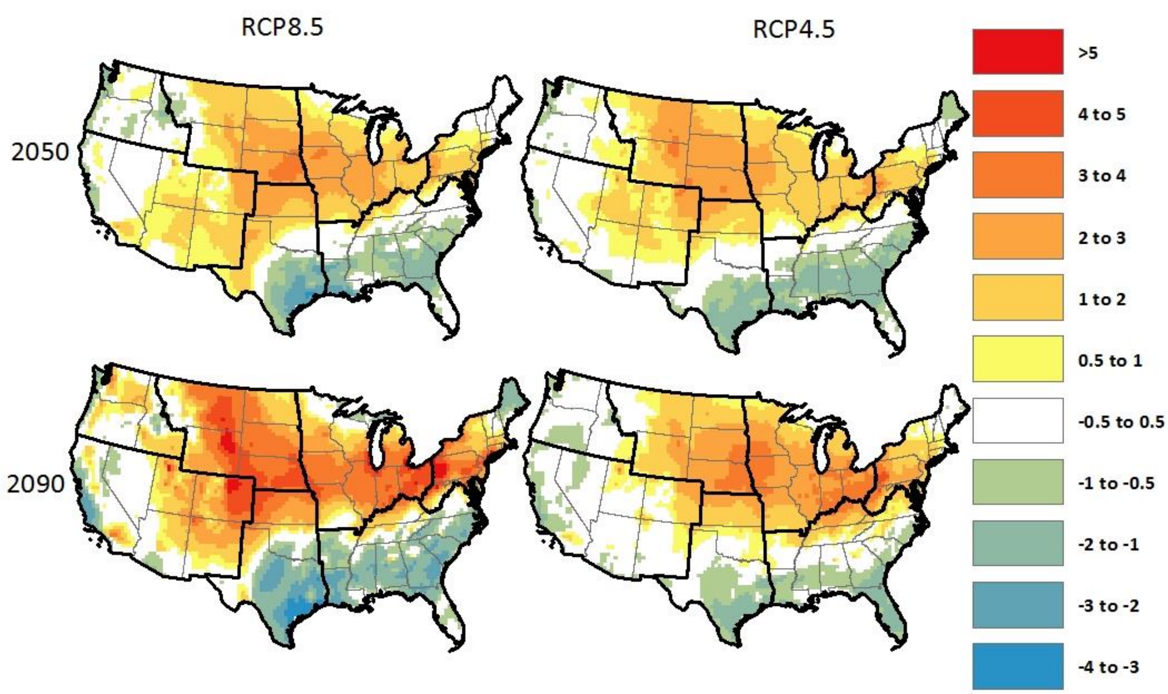
[113] Fann, N., C.G. Nolte, P. Dolwick, T.L. Spero, A. Curry Brown, S. Phillips, and S. Anenberg, 2015: The geographic distribution and economic value of climate change-related ozone health impacts in the United States in 2030. *Journal of the Air & Waste Management Association*, **65**, 570-580. http://dx.doi.org/10.1080/10962247.2014.996270.

Under both RCPs, daily maximum summer temperatures are projected to increase across the contiguous U.S., with summer temperatures generally intensifying through the end of the century (see Figure A.6.1 in Appendix A.6). In 2090, daily maximum summer temperatures are projected to rise by 3-7°C under RCP8.5. Although warmer than the reference period conditions, the summer daily maximum temperatures in 2090 under RCP4.5 are lower than those projected in 2050 under RCP8.5. Annual precipitation is projected to increase in the Northwest, Southeast, and Northeast, but decrease in the Southwest and Southern Plains (see Figure A.6.2).

Figure 3.1 shows the projected change in summer-average maximum daily 8-hour ozone concentrations over the U.S. in 2050 and 2090 relative to the reference period (2000). The results are consistent with other published studies in that they show that a warming climate is generally expected to lead to increased ozone concentrations in parts of the U.S. Seasonal-average ozone increases of up to 5 parts per billion (ppb) are simulated at 2090 under RCP8.5 over parts of the U.S. This effect is often referred to as the "climate penalty,"[114] where attaining national air quality standards will become more difficult because climate change will counteract improvements that may be expected from emissions reductions.[115] In parts of the Southeast and Southern Plains, climate-driven meteorological changes result in conditions slightly less conducive to ozone formation, potentially due to an increase in precipitation during summer months (not shown in Figure A.6.2) and wind trajectories that transport cleaner marine air into these regions.

Figure 3.1. Change in Summer-Average Maximum Daily Ozone

Maps show the change in summer-average maximum daily 8-hour ozone concentrations (ppb) in 2050 (2045-2055) and 2090 (2085-2095) compared to 2000 (1995-2005).



[114] Wu, S., L. J. Mickley, E. M. Leibensperger, D. J. Jacob, D. Rind, and D. G. Streets, 2008: Effects of 2000-2050 global change on ozone air quality in the United States. *Journal of Geophysical Research*, **113**, D06302. doi:10.1029/2007JD008917.

[115] Climate-driven changes in meteorological patterns will also impact $PM_{2.5}$ concentrations throughout the U.S. However, unlike ozone, there is no current consensus as to whether these changes will result in increasing or decreasing $PM_{2.5}$ levels. The $PM_{2.5}$ results from this modeling are provided in Appendix A.6.

At the national scale, these projected climate-attributable increases in summer ozone have a quantifiable adverse effect on human health as shown in Figure 3.2 and summarized by region in Table 3.1. The analysis estimates that an additional 790 premature ozone-related deaths occur annually (between May and September) in 2050 under RCP8.5 relative to the reference period. As climate warming persists through 2090, this value increases to 1,700 additional premature deaths each year. Compared to RCP8.5, RCP4.5 reduces mortality impacts by avoiding 240 deaths by 2050 and 500 deaths by 2090. Projected increases in premature deaths are largest in the Midwest and Northeast, while decreases in ozone-related deaths are projected in the Southeast and Southern Plains under some scenario and time period combinations. Table 3.2 provides the monetized values associated with the estimated changes in premature mortality. RCP4.5 is also projected to significantly reduce the number of incidents of ozone-related, acute respiratory symptoms leading to hospital visits and school absences. See Appendix A.6 for more details on ozone morbidity effects.

Figure 3.2. Change in Ozone-Related Premature Deaths

Maps show county-level estimates for the average change in ozone-related premature deaths over the summer months in 2050 (2045-2055) and 2090 (2085-2095) compared to 2000 (1995-2005).

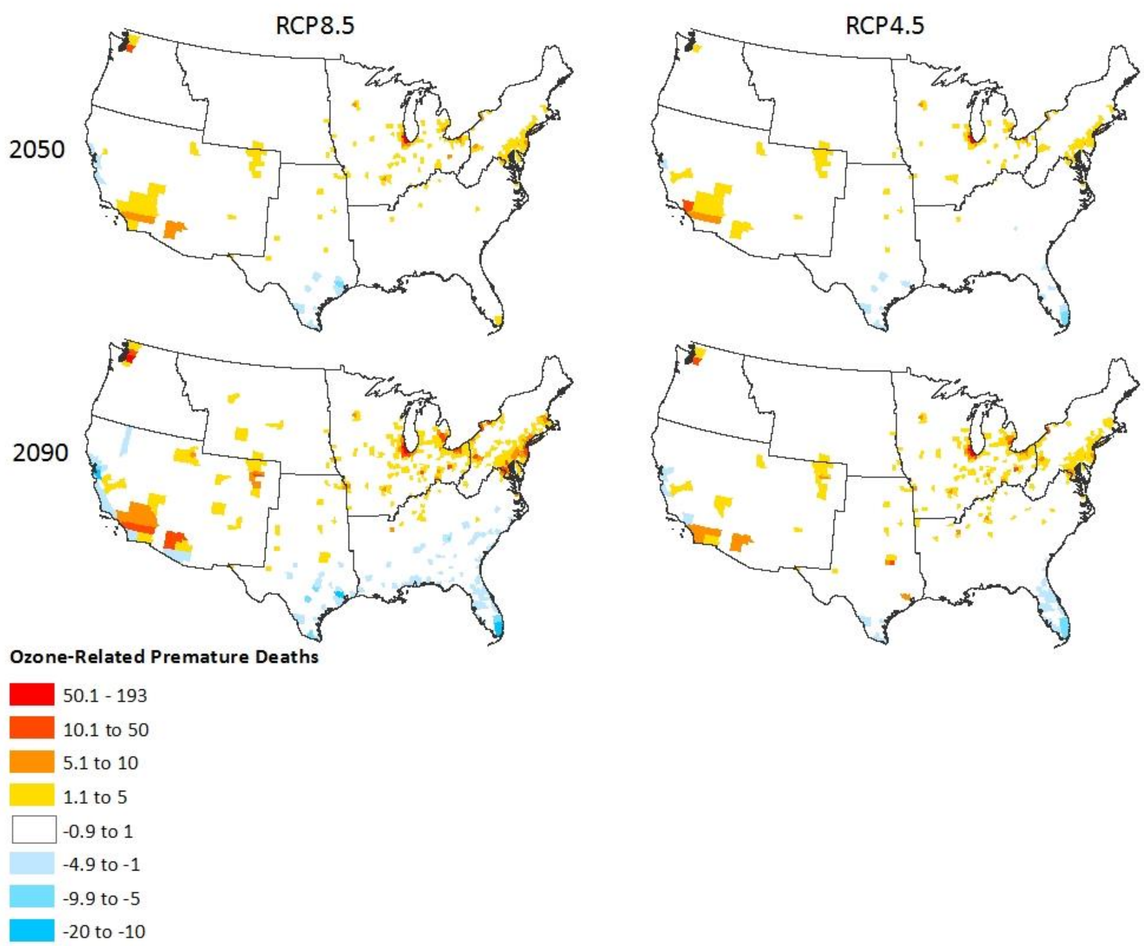


Table 3.1. Excess (or Avoided) Ozone-Related Premature Deaths
The table presents estimates for 2050 (2045-2055) and 2090 (2085-2095) under RCP8.5 and RCP4.5 compared to 2000 (1995-2005). The 95th percentile confidence intervals are provided in parentheses[116]. Values may not sum due to rounding.

Region	2050		2090	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Northeast	230 (120 to 340)	200 (110 to 300)	670 (360 to 980)	310 (160 to 450)
Southeast	69 (37 to 100)	-40 (-59 to -21)	-72 (-100 to -38)	88 (47 to 130)
Midwest	380 (200 to 550)	300 (160 to 440)	910 (490 to 1,300)	580 (310 to 840)
Northern Plains	23 (12 to 33)	20 (11 to 30)	42 (22 to 61)	29 (16 to 43)
Southern Plains	3.2 (1.7 to 4.7)	-4.2 (-6.2 to -2.3)	-37 (-54 to -20)	89 (48 to 130)
Southwest	62 (33 to 91)	71 (38 to 100)	110 (59 to 160)	57 (30 to 83)
Northwest	20 (10 to 29)	5.2 (2.8 to 7.6)	93 (50 to 140)	29 (16 to 43)
National Total	**790 (420 to 1,200)**	**550 (300 to 810)**	**1,700 (920 to 2,500)**	**1,200 (630 to 1,700)**

[116] The confidence intervals are calculated using a Monte Carlo technique, in which random draws are taken from a distribution of standard errors reported in epidemiological and economic value studies. This distribution reflects sampling error alone, and does not account for uncertainty introduced in other “upstream” elements of the analysis—including the projection of emissions, meteorology, air quality modeling, etc.

Table 3.2. Cost of Excess (or Avoided) Ozone-Related Premature Deaths
The table presents estimates for 2050 (2045-2055) and 2090 (2085-2095) under RCP8.5 and RCP4.5 compared to 2000 (1995-2005). Units are millions of $2015. The 95th percentile confidence intervals are provided in parentheses. Values may not sum due to rounding.

Region	2050		2090	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Northeast	$2,900 ($260 to $8,200)	$2,500 ($230 to $7,200)	$10,000 ($910 to $29,000)	$4,700 ($420 to $13,000)
Southeast	$850 ($77 to $2,400)	-$500 (-$1,400 to -$45)	-$1,100 (-$3,100 to -$98)	$1,300 ($120 to $3,800)
Midwest	$4,700 ($420 to $13,000)	$3,700 ($330 to $11,000)	$14,000 ($1,200 to $39,000)	$8,800 ($790 to $25,000)
Northern Plains	$280 ($25 to $810)	$250 ($23 to $720)	$630 ($57 to $1,800)	$440 ($40 to $1,300)
Southern Plains	$40 ($3.6 to $110)	-$53 (-$150 to -$4.7)	-$560 (-$1,600 to -$50)	$1,400 ($120 to $3,800)
Southwest	$770 ($69 to $2,200)	$880 ($79 to $2,500)	$1,700 ($150 to $4,800)	$860 ($77 to $2,500)
Northwest	$240 ($22 to $690)	$65 ($5.8 to $180)	$1,400 ($130 to $4,000)	$450 ($40 to $1,300)
National Total	**$9,800 ($880 to $28,000)**	**$6,900 (-$900 to $21,000)**	**$26,000 (-$2,200 to $78,000)**	**$18,000 ($1,600 to $51,000)**

3.5 DISCUSSION

The findings shown here indicate that increasing temperatures will non-uniformly alter summer concentrations of ozone across the contiguous U.S. in 2050 and 2090 relative to 2000. Although ozone is strongly influenced by temperature, other meteorological factors (such as wind speed, cloud cover, wind trajectories, and precipitation amounts) will also affect those ozone concentrations. Adverse health outcomes projected from increased ozone are aligned with population centers, such that densely populated areas that experience increased ozone will see a greater impact on health. The largest increases in ozone are projected to occur from the Northern Plains through the eastern Great Lakes, which are generally the regions with the largest temperature increases (see Figure A.6.1). The simulations held pollutant emissions at 2040 levels in both the reference period and the future periods, so any ozone increases are driven by changes in meteorology or in biogenic emissions. Additionally, average relative humidity values during the summer are projected to be lower in this region in the future due to climate change, which is also conducive to higher ozone concentrations. Other meteorological parameters that could potentially impact ozone (e.g., depth of the mixed layer, wind speed and direction, precipitation frequency) appear to have smaller impacts in this region than the higher temperatures and drier conditions projected.

Projections under RCP4.5 demonstrate a substantially decreased burden of air pollution on U.S. respiratory health by reducing ozone concentrations relative to RCP8.5. In other words, RCP8.5 will lead to meteorological conditions that are generally more favorable for ozone production than RCP4.5. Future ozone levels will depend not only on the meteorological conditions in which ozone is formed, but also on future trends in ozone precursor emissions. Thus, the need for further emissions controls on domestic sources to meet certain air quality goals will likely be greater under RCP8.5. RCP4.5 could substantially decrease the future impacts of air pollution on U.S. respiratory health by reducing ozone concentrations relative to unconstrained climate change, thereby reducing the need for additional emissions controls on domestic sources of ozone air pollution. These findings are consistent with others described in the assessment literature,[117] and the results of a previous CIRA analysis using different methods.[118] This analysis does not quantify the additional benefits to air quality and health that would stem from simultaneous reductions in traditional air pollutants along with GHG emissions.

Wildfires are strong local sources of air pollutants, including compounds that form PM and ozone, and their occurrence is often linked to a confluence of extreme meteorological conditions (e.g., drought, strong winds, lightning) combined with a natural fuel load in forested areas. Wildfires are localized, rare events that can have severe impacts on air quality and human health. However, the natural initiation of wildfires, the extreme meteorological conditions that increase susceptibility to wildfires, and the trajectories of the plumes from wildfire smoke are all difficult to project with confidence (even with observation-driven meteorological models), particularly in areas of rapidly changing terrain elevation. Furthermore, there are important but highly uncertain human and economic components to whether a wildfire occurs, how people respond, and what impacts are associated (e.g., wildfires resulting from arson or negligence, accessibility of wildfire locations, availability of resources and trained response personnel, evacuation efforts, size of the population directly impacted by or downwind of the wildfire, and personal behaviors to reduce exposure to wildfire smoke). Future research is needed to link the methods applied in this section to wildfire modeling so that these effects can be investigated.

Health outcomes from climate-driven impacts on $PM_{2.5}$, even excluding expected increases in wildfire emissions, may also be signficant but remain uncertain. The changes in $PM_{2.5}$ are driven by complex meteorological processes related to the distributions of cloud cover, radiation, and precipitation at any given location. However, there is considerable uncertainty in the geographic distribution of these changes to $PM_{2.5}$ and the overall trend, not just in this modeling analysis but in the literature overall.[119] The interactions of some sources of $PM_{2.5}$ with sunlight, clouds, and solar radiation are also uncertain.[120] See Appendix A.6 for further discussion.

---

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

[118] Garcia-Menendez, F., R.K. Saari, E. Monier, and N.E. Selin, 2015: U.S. air quality and health benefits from avoided climate change under greenhouse gas mitigation. *Environmental Science and Technology*, **49**, 7580-7588, doi:10.1021/acs.est.5b01324.

[119] Fiore, A. M., V. Naik, and E. M. Leibensperger, 2015: Air quality and climate connections. *Journal of the Air & Waste Management Association*, **65**, 645–685. doi:10.1080/10962247.2015.1040526.

[120] Bond, T.C., S.J. Doherty, D.W. Fahey, P.M. Forster, T. Bernsten, B.J. DeAngelo, M.G. Flanner, S.Ghan, B. Karcher, D. Koch, S. Kinne, Y. Kondo, P.K. Quinn, M.C. Sarofim, M.G. Schultz, M. Shulz, C. Venkataraman, H. Zhang, S. Zhang, N. Bellouin, S.K. Guttikunda, P.K. Hopke, M.Z. Jacobson, J.W. Kaiser, Z. Klimont, U. Lohmann, J.P. Swartz, D. Shindell, T. Storelvmo, S.G. Warren, and C.S. Zender, 2013: Bounding the role of black carbon in the climate system: a scientific assessment. *Journal of Geophysical Research – Atmospheres*, **118**, 5380–5552.

4. AEROALLERGENS

4.1 KEY FINDINGS

- Aeroallergens currently pose a substantial U.S. public health burden, including emergency department visits for the most severe reactions; climate change is projected to increase U.S. allergic disease incidence from oak pollen. People living in the Northeast and children less than 18 years old are at higher risk.
- Though all three regions analyzed (Northeast, Southeast, and Midwest) show projected increases in pollen season length under all time periods and scenarios, changes are particularly large under RCP8.5 in 2090, when season length is increased by 3.8 days in the Midwest, 3.5 days in the Northeast, and 1.7 days in the Southeast.
- By 2090, total oak pollen-related asthma emergency department (ED) visits in the Northeast, Southeast, and Midwest are projected to increase by 3.9% and 9.6% compared to the reference period under RCP4.5 and RCP8.5, respectively. Increases in ED visits in 2090 under RCP8.5 are particularly high in the Midwest (13%) and Northeast (12%).
- Across the three regions analyzed, costs from oak pollen-related asthma ED visits from climate change increase in all scenarios, time periods, and regions, particularly in the Northeast and Midwest. The increase in annual costs of ED visits in all three regions in 2090 is $1.2 million under RCP8.5 and $0.52 million under RCP4.5. Inclusion of additional pollen types would likely increase these damages.

4.2 INTRODUCTION

Rising CO_2 concentrations and associated climate change is expected to lengthen and intensify pollen season in parts of the U.S.,[121,122] potentially leading to additional cases of allergic rhinitis (commonly known as "hay fever") and allergic asthma episodes.[123,124] For example, the duration of pollen release for common ragweed, the aeroallergen that most commonly affects persons in the United States, has been increasing as a function of latitude in recent decades in the Midwest region.[125] Among individuals with allergic asthma, exposure to allergens can result in exacerbation of symptoms, including asthma episodes, sinusitis, or anaphylaxis.[126] Asthma is widespread in the U.S., affecting approximately 7% of

[121] Zhang, Y., L. Bielory, T. Cai, Z. Mi, and P. Georgopoulos, 2015: Predicting onset and duration of airborne allergenic pollen season in the United States. *Atmospheric Environment*, **103**, 297-306.
[122] Fann, N., T. Brennan, P. Dolwick, J.L. Gamble, V. Ilacqua, L. Kolb, C.G. Nolte, T.L. Spero and L. Ziska, 2016: Ch. 3: Air Quality Impacts. In: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 69-98, doi: 10.7930/J0GQ6VP6.
[123] Reid, C.E., and J.L. Gamble, 2009: Aeroallergens, allergic disease, and climate change: Impacts and adaptation. *EcoHealth*, **6**, 458-470.
[124] Sheffield, P.E., K.R. Weinberger, and P.L. Kinney, 2011: Climate change, aeroallergens and pediatric allergic disease. *Mount Sinai Journal of Medicine*, **78**, 78-84.
[125] Fann, N., T. Brennan, P. Dolwick, J.L. Gamble, V. Ilacqua, L. Kolb, C.G. Nolte, T.L. Spero and L. Ziska, 2016: Ch. 3: Air Quality Impacts. In: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 69-98, doi: 10.7930/J0GQ6VP6.
[126] Nielsen, G.D., J.S. Hansen, R.M. Lund, M. Bergqvist, S.T. Larsen, S.K. Clausen, P. Thygensen, and O.M. Poulsen, 2002: IgE-mediated asthma and rhinitis I: A role of allergen exposure? *Pharmacology & Toxicology*, **90**, 231-242.

adults and 9% of children,[127] and resulting in $56 billion in medical expenditures, missed work and school days, and early deaths in 2007.[128]

Rising CO_2 concentrations and climate-induced changes in temperature and precipitation may impact pollen season timing and length, the amount of pollen produced throughout the season, the allergen content of pollen grains, and the spatial distribution of species producing allergenic pollen.[129] For tree pollen specifically, warmer temperatures both year-round and in the months preceding the pollen season have been linked to increased season intensity and length.[130]

4.3 APPROACH

This analysis examines the health consequences of present-day and climate-induced changes in pollen exposure in the Northeast, Southeast, and Midwest regions of the contiguous U.S., focusing on oak pollen- and asthma-related ED visits. Oak pollen season length and seasonal average pollen concentrations are collected from observations for the reference period (1994-2010) at 59 National Allergy Bureau monitoring stations and simulated for future years (2030, 2050, 2070, and 2090) using published relationships between temperature, precipitation, and oak pollen season length. These relationships are applied to climate projections under RCP8.5 and RCP4.5 using the five GCMs. Epidemiologically-derived health impact functions are combined with demographic projections to estimate oak pollen-associated asthma ED visits for all days in the recent past and simulated future oak pollen season using the Environmental Benefits Mapping and Analysis Program (BenMAP-CE). A monetary value of pollen-related ED visits is determined by applying the mean of two cost-per-visit estimates.[131,132] Adjusted for inflation, the mean per-visit cost in 2015 dollars is $490/visit. Importantly, this analysis only considers climate impacts on oak pollen in three regions of the contiguous U.S., and therefore does not estimate the total potential national health effects of climate-driven changes to aeroallergens. For more information regarding the approach used in this section to estimate climate change impacts on aeroallergens, please refer to Anenberg et al. (2017).[133]

4.4 RESULTS

As shown in Figure 4.1, oak pollen season is projected to lengthen in the Northeast, Southeast, and Midwest under both RCPs and in both time periods (except under the GISS-E2-R model in the Southeast). Impacts are projected to be greater under RCP8.5 than RCP4.5, particularly in 2090. The projected increase in season length is highest in the Midwest (2.1 days in 2050 and 3.8 days in 2090 under RCP8.5 for the five-GCM average), followed closely by the Northeast (1.9 days in 2050 and 3.5

---

[127] USGCRP, 2016: The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment. U.S. Global Change Research Program. Available online at http://www.globalchange.gov/health-assessment

[128] CDC, 2011: Vital Signs, May 2011. United States Department of Health and Human Services, Centers for Disease Control and Prevention. Available online at http://www.cdc.gov/vitalsigns/asthma/

[129] Fann, N., T. Brennan, P. Dolwick, J.L. Gamble, V. Ilacqua, L. Kolb, C.G. Nolte, T.L. Spero and L. Ziska, 2016: Ch. 3: Air Quality Impacts. In: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 69–98, doi: 10.7930/J0GQ6VP6.

[130] Ariano, R., G.W. Canonica, and G. Passalacqua, 2010: Possible role of climate changes in variations in pollen seasons and allergic sensitizations during 27 years. *Annals of Allergy, Asthma & Immunology*, **104**, 215-222.

[131] Smith, D.H., D.C. Malone, K.A. Lawson, L.J. Okamoto, C. Battista, and W.B. Saunders, 1997: A national estimate of the economic costs of asthma. *Am J Resp Crit Care Med*, **156**, 787-793.

[132] Stanford, R., T. McLaughlin and L.J. Okamoto, 1999: The cost of asthma in the emergency department and hospital. *Am J Resp Crit Care Med*, **160**, 211-215.

[133] Anenberg, S. C., K. R. Weinberger, H. Roman, J. E. Neumann, A. Crimmins, N. Fann, J. Martinich, and P. L. Kinney (2017), Impacts of oak pollen on allergic asthma in the United States and potential influence of future climate change, *GeoHealth*, **1**, doi:10.1002/2017GH000055.

days in 2090 under RCP8.5 for the five-GCM average).[134] Two models (HadGEM2-ES and MIROC5) projected increases in season length of more than 5 days in the Midwest by 2090 under RCP8.5. In the Southeast, the projected change in season length is smaller (0.96 days in 2050 and 1.7 days in 2090 under RCP8.5 for the five-GCM average).

Figure 4.1. Change in Oak Pollen Season Length

Graph shows the projected change in oak pollen season length (days) in 2050 and 2090 relative to the 1994-2010 reference period for the Northeast, Southeast, and Midwest regions for each GCM. The results represent the average of the results for all monitoring locations in each region (15 locations in the Northeast, ten in the Southeast, and seven in the Midwest). The season length in the reference period is 26 days in the Northeast, 29 days in the Southeast, and 26 days in the Midwest, based on the average season length across each region's monitoring locations.

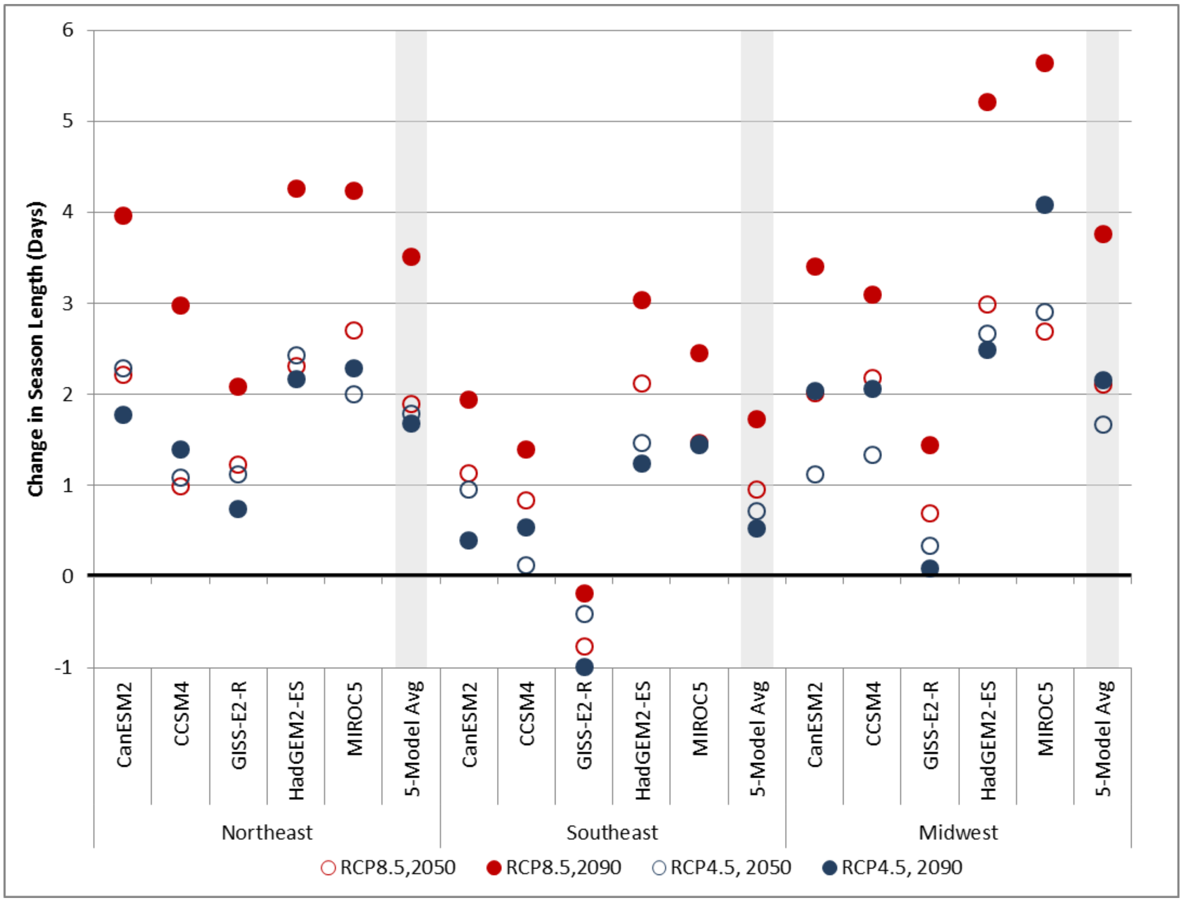


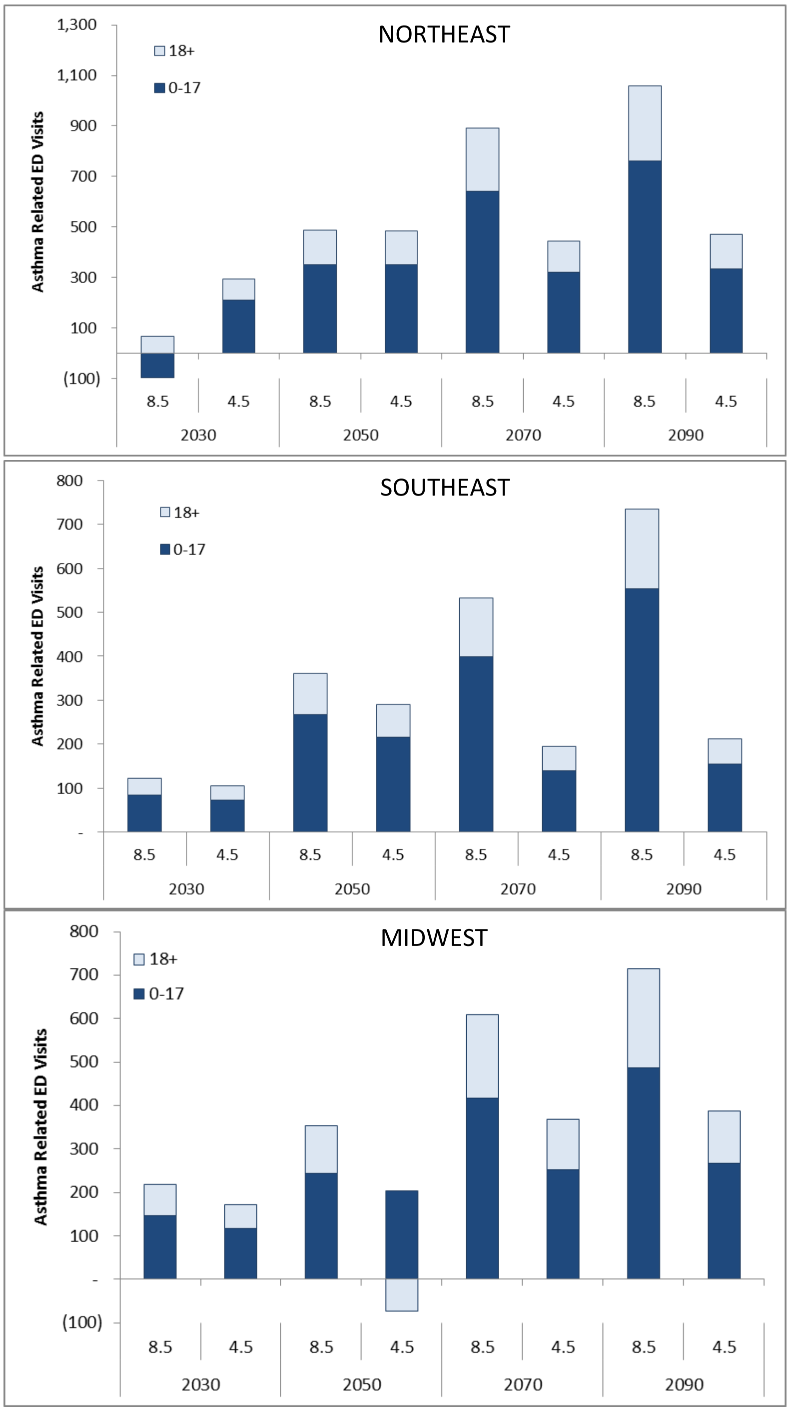
Figure 4.2 presents the projected change in asthma-related ED visits relative to the reference period (1994-2010) for the three regions analyzed. Results are calculated separately for ages 0-17 and 18+. By 2090, the Northeast is projected to experience an increase in asthma-related ED visits of approximately 760 and 330 for the 0-17 age group and 300 and 140 for the 18+ age group under RCP8.5 and RCP4.5, respectively (five-GCM average). The projected changes in the Southeast by 2090 are lower, at 550 and 160 visits for the 0-17 age group and 180 and 60 visits for the 18+ age group under RCP8.5 and RCP4.5,

[134] The baseline oak pollen season lengths (based on the average season length across the monitoring stations in each region) are 26 days in the Northeast, 29 days in the Southeast, and 26 days in the Midwest.

respectively (five-GCM average). In the Midwest, the 2090 projected changes are 490 and 270 visits for the 0-17 age group and 230 and 120 visits for the 18+ age group under RCP8.5 and RCP4.5, respectively (five-GCM average).

Figure 4.2. Change in Asthma-Related Emergency Department Visits

The graphs show change from the reference period (1994-2010) by age groups for the three regions studied under RCP8.5 and RCP4.5. Results represent averages of the five GCMs.



Costs from oak pollen-related asthma ED visits are generally projected to increase due to climate change across the three regions, particularly in the later part of the century. The projected annual costs in 2090 are highest in the Northeast under both RCPs (Table 4.1).

Table 4.1. Change in Annual Costs of Emergency Department Visits

Values reported in thousands of $2015, and represent averages of the five GCMs. The 90% confidence interval results (5th and 95th percentiles) are presented in parentheses following the mean estimate.

	2030		2050		2070		2090	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Northeast	-$15 (-$90 to $74)	$140 ($15 to $290)	$240 ($19 to $480)	$240 ($16 to $470)	$440 ($57 to $870)	$220 ($32 to $430)	$520 ($60 to $1,000)	$230 ($25 to $470)
Southeast	$60 ($17 to $110)	$52 ($15 to $98)	$180 ($31 to $350)	$140 ($30 to $270)	$260 ($31 to $520)	$96 ($37 to $190)	$360 ($43 to $720)	$100 ($31 to $200)
Midwest	$110 (-$3.4 to $24)	$84 (-$1.2 to $190)	$170 (-$2.5 to $380)	$64 ($0 to $120)	$300 (-$5.7 to $670)	$180 (-$5.4 to $400)	$350 ($3.3 to $810)	$190 ($5.7 to $440)
3 Region Total	$150 (-$76 to $420)	$280 ($29 to $580)	$590 ($48 to $1,200)	$440 ($46 to $870)	$1,000 ($82 to $2,100)	$490 ($64 to $1,000)	$1,200 ($110 to $2,600)	$520 ($62 to $1,100)

4.5 DISCUSSION

This analysis isolates the impact of climate change on oak pollen season length in the Northeast, Midwest, and Southeast regions of the U.S. By 2090, climate change driven changes in oak pollen season length are projected to increase asthma ED visits by 3.9% (1,100) and 9.6% (2,500) compared to the reference period for RCP4.5 and RCP8.5, respectively, with the largest changes in the Midwest (13%), followed by the Northeast (12%) and Southeast (6.5%). The study finds that moderate versus severe climate change could avoid more than half (1,400) of the additional oak pollen-related asthma ED visits projected in 2090. Although these results were limited to one pollen type (oak) and one health outcome (asthma ED visits), they suggest that aeroallergens pose a substantial burden on U.S. public health and that future climate change is likely to increase allergic disease incidence in the U.S.

Compared with nationwide impacts of ambient air pollution, estimated oak pollen asthma ED visits in the Northeast, Southeast, and Midwest are approximately 10% of estimated asthma ED visits associated with fine particulate matter ($PM_{2.5}$) among children age <18 years (110,000) and approximately 90% of those associated with ozone among all ages in 2005 (19,000).[135] Since this analysis included only one pollen type, these comparisons suggest that the burden of aeroallergens on asthma ED visits in the U.S. could be of a similar magnitude to that of ambient air pollution. However, oak pollen exposure-response relationships may already capture some portion of health effects from other pollen types since some are temporally correlated.[136] This analysis focused on regions containing the highest prevalence of oak trees

[135] Fann, N., A.D. Lamson, S.C. Anenberg, K. Wesson, D. Risley, and B.J. Hubbell, 2011: Estimating the national public health burden associated with exposure to ambient PM2.5 and ozone. *Risk Analysis*, **32**, 81-95.

[136] Ito, K., K.R. Weinberger, G.S. Robinson, P.E. Sheffield, R. Lall, R. Mathes , Z. Ross, P.L. Kinney, and R.D. Matte, 2015: The associations between daily spring pollen counts, over-the-counter allergy medication sales, and asthma emergency department visits syndrome in New York City, 2002-2012. *Environ Health*, **14**, 71.

and approximately 50% of the population in the U.S., but additional health impacts from oak pollen exposure would be expected elsewhere. Climate change consequences could be underestimated because some of the largest increases in oak pollen season length occur in the West. This analysis also excludes climate impacts on seasonal average pollen concentrations, changes in pollen allergenicity, and the geographic range of oak trees. Finally, the health-response functions used in this analysis are not adjusted for future physiological changes in immunity or changes in behavior (e.g., increases in self-protection), both of which possess large uncertainties when projecting into the future.

5. EXTREME TEMPERATURE MORTALITY

5.1 KEY FINDINGS

- Changes in extreme temperatures are projected to result in a net average increase of approximately 9,300 premature deaths per year under RCP8.5 by 2090 in the 49 modeled cities. Under RCP4.5, more than 5,000 deaths are avoided each year by 2090.
- The projected reduction in deaths from extremely cold days is far less than the projected increase in deaths from extremely hot days in all climate models, scenarios, and time frames.
- Annual damages associated with additional extreme temperature related deaths are estimated at $140 billion under RCP8.5 and $60 billion under RCP4.5 by the end of the century.
- Mortality from extremely hot days decreased more than 50% under both RCP8.5 and RCP4.5 in 2050 and 2090 when the human health response to extreme temperatures was evaluated using Dallas' threshold for extreme heat (in all cities with thresholds initially cooler than Dallas), as a sensitivity analysis to consider the effect of adaptation.

5.2 INTRODUCTION

Climate change will alter the weather conditions to which we are accustomed. Extreme temperatures are projected to rise in many areas across the U.S., bringing more frequent and intense heat waves and increasing the number of heat-related illnesses and deaths.[137,138] Exposure to extreme heat can compromise the body's ability to regulate its temperature, resulting in heat exhaustion and/or heat stroke, and can also exacerbate existing medical problems, such as heart and lung diseases.[139] By one measure, heat waves are already the largest cause of fatalities from extreme weather in the U.S.[140] For instance, during a 1995 heat wave in Chicago, an estimated 700 individuals died as a result of the extreme heat.[141] Increases in both average and extreme temperatures are also projected to result in fewer extremely cold days, and this is expected to reduce deaths associated with extreme cold.

5.3 APPROACH

This analysis estimates the number of deaths over the course of the 21st century attributable to extreme temperatures in 49 cities in the contiguous U.S., which account for approximately one third of the national population. City-specific relationships between daily deaths (from all causes) and extreme

---

[137] USGCRP, 2016: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. Crimmins, A., J. Balbus, J.L. Gamble, C.B. Beard, J.E. Bell, D. Dodgen, R.J. Eisen, N. Fann, M.D. Hawkins, S.C. Herring, L. Jantarasami, D.M. Mills, S. Saha, M.C. Sarofim, J. Trtanj, and L. Ziska, Eds. U.S. Global Change Research Program, Washington, DC, 312 pp., doi: 10.7930/J0R49NQX.

[138] Luber, G., K. Knowlton, J. Balbus, H. Frumkin, M. Hayden, J. Hess, M. McGeehin, N. Sheats, L. Backer, C.B. Beard, K.L. Ebi, E. Maibach, R. S. Ostfeld, C. Wiedinmyer, E. Zielinski-Gutiérrez, and L. Ziska, 2014: Ch. 9: Human Health. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G.W. Yohe, Eds., U.S. Global Change Research Program, 220-256. doi:10.7930/J0PN93H5.

[139] Sarofim, M.C., S. Saha, M.D. Hawkins, D.M. Mills, J. Hess, R. Horton, P. Kinney, J. Schwartz, and A. St. Juliana, 2016: Ch. 2: Temperature-Related Death and Illness. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 43–68, doi: 10.7930/J0MG7MDX.

[140] Bell, J.E., S.C. Herring, L. Jantarasami, C. Adrianopoli, K. Benedict, K. Conlon, V. Escobar, J. Hess, J. Luvall, C.P. Garcia-Pando, D. Quattrochi, J. Runkle, and C.J. Schreck, III, 2016: Ch. 4: Impacts of Extreme Events on Human Health. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 99–128, doi: 10.7930/J0BZ63ZV.

[141] EPA, 2016. Climate Change Indicators in the United States, 2016. Fourth edition. EPA 430-R-16-004. Available online at https://www.epa.gov/climate-indicators

temperatures were estimated based on historical observations, and are combined with the projections of extremely hot and cold days (average of three years centered on 2050 and 2090) using city-specific extreme temperature thresholds to project future deaths from extreme heat and cold under RCP8.5 and RCP4.5 in five GCMs. Extremely hot days are defined as those with a daily minimum temperature warmer than 99 percent of the days in the reference period (1989-2000) and that are at least 20°C (68°F). Extremely cold days are defined as those with a daily maximum temperature colder than 99 percent of the days in the reference period (1989-2000) and do not exceed 10°C (50°F). As a result, the study explicitly addresses the question of the net mortality impact of changes in extreme temperature days in the future due to climate change.

The potential impact of future population change is accounted for using the ICLUSv2 population projections described in Modeling Framework section of this Technical Report. To monetize the effects of changing mortality, the analysis uses a baseline VSL adjusted to future years based on a projected change in economic growth.[142] The results presented in this section have been updated since Mills et al. (2014) to include additional cities and more recent mortality rate data.[143] This analysis does not estimate impacts across ages or socioeconomic status. As these demographics change, they could impact the results. Finally, this analysis does not estimate extreme temperature effects on morbidity, which could result in a higher number of cases compared to mortality.[144] For more information on the approach and results for the extreme temperature mortality sector, please refer to Mills et al. (2014).[145]

5.4 RESULTS

Under RCP8.5, the average number of extremely hot days in the U.S. is projected to nearly double from 2050 to 2100. The projected increase in deaths due to more frequent extremely hot days is much larger than the projected decrease in deaths due to fewer extremely cold days (Table 5.1), a finding that is consistent with the conclusions of the assessment literature.[146] Under RCP8.5, the net increase in projected deaths from more extremely hot days and fewer extremely cold days in 49 cities is

---

[142] At the time of this analysis, the EPA's *Guidelines for Preparing Economic Analyses* recommends a VSL of $7.9 million (2008$), based on 1990 incomes. To create a VSL using $2015 and based on 2015 incomes, the standard value was adjusted for inflation and for income growth adjustment based on the approach described in EPA's BenMAP-CE model and its documentation. The resulting value, $10.0 million for 2015 ($2015), was adjusted to future years by assuming an elasticity of VSL to GDP per capita of 0.4. Projections of U.S. GDP and population described the Modeling Framework section of this Technical Report were employed. Using this approach, the VSL in 2050 is estimated at $12.4 million and $15.2 million in 2090. Sources: 1) EPA, 2014: Guidelines for Preparing Economic Analyses. National Center for Environmental Economics. Available online at http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0568-52.pdf/$file/EE-0568-52.pdf; and 2) EPA, cited 2017: Benefits Mapping and Analysis Program (BenMAP): Manual and Appendices for BenMAP-CE. Available online at https://www.epa.gov/benmap/manual-and-appendices-benmap-ce

[143] The approach described in Mills et al. (2014) was updated in several ways. First, the analysis was expanded from 33 cities to encompass a total of 49 out of 50 of the cities (excluding Honolulu) analyzed by Medina-Ramon and Schwartz (2007). Medina-Ramon and Schwartz did not calculate heat mortality response functions for cities where the minimum temperature for the 99 percentile hottest day was equal to or below 20°C (8 cities), or cold mortality response functions where the maximum temperature for the 1 percentile coldest day was greater than or equal to 10°C (7 cities). In a warming climate, cities that were too warm to meet the criteria for the cold threshold will continue to be too warm, making a cold mortality response function insignificant. Most of the cities that were too cool to meet the criteria for the hot threshold are expected to warm enough that their 99 percentile hottest days will exceed 20°C in the future. Therefore, inclusion of cities without a heat mortality response function will lead to an underestimate of the change in future mortality in those cities, and therefore an underestimate of avoided deaths. However, inclusion of a wider range of cities gives a more complete picture of impacts in the U.S. Additionally this study was updated to limit the analysis to the actual counties corresponding to the cities specified in Medina-Ramon and Schwartz (2007), rather than the MSAs used in Mills et al. (2014). This reduces the total population considered within the original 33 cities. Furthermore, BenMAP data for the all-age mortality rates in the cities is used, resulting in some small differences in calculations.

[144] Eisenman, D., Wilhalme, H., Tseng, C., English, P., Chester, M., Fraser, A., Pincetl, S, 2016. Heat death associations with the built environment, social vulnerability and their interactions with rising temperature. *Health Place*, doi: 10.1016/j.healthplace.2016.08.007.

[145] Mills, D., J. Schwartz, M. Lee, M. Sarofim, R. Jones, M. Lawson, M. Duckworth, and L. Deck, 2014: Climate Change Impacts on Extreme Temperature Mortality in Select Metropolitan Areas in the United States. *Climatic Change*, doi: 10.1007/s10584-014-1154-8.

[146] Sarofim, M.C., S. Saha, M.D. Hawkins, D.M. Mills, J. Hess, R. Horton, P. Kinney, J. Schwartz, and A. St. Juliana, 2016: Ch. 2: Temperature-Related Death and Illness. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 43–68, doi: 10.7930/J0MG7MDX.

approximately 3,400 deaths per year in 2050, and 9,300 deaths per year in 2090. In comparison, RCP4.5 avoids nearly 800 deaths each year by 2050, and more than 5,400 deaths each year by 2090, a mortality reduction of 24% and 58% respectively.

Table 5.1. Changes in Annual Mortality

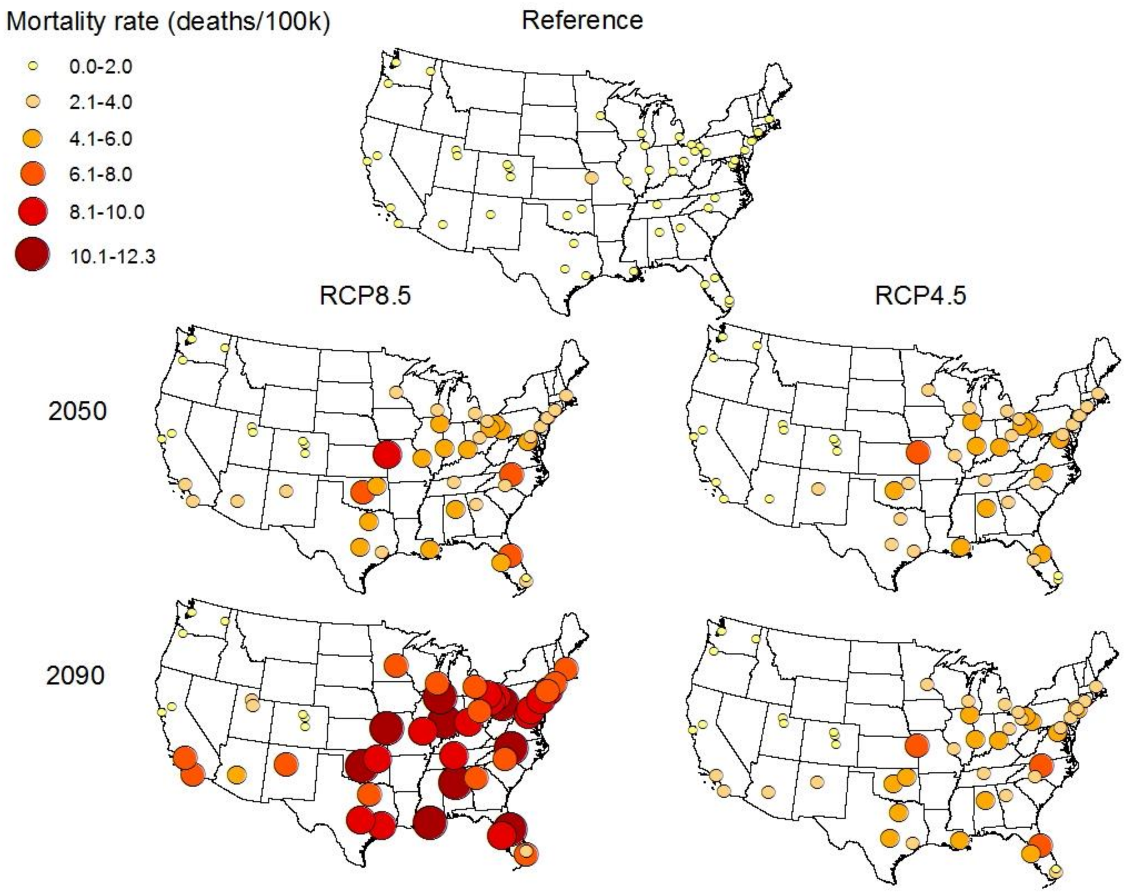
The results represent the change in annual mortality from the 1989-2000 reference period due to extreme heat, extreme cold, and combined stressors. Values represent results for the 49 cities, and assume increased population growth. Estimates may not sum due to rounding.

	2050		2090	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Heat				
CanESM2	4,200	2,800	12,000	3,700
CCSM4	2,300	1,700	7,200	2,500
GISS-E2-R	2,500	2,300	5,500	2,700
HadGEM2-ES	5,900	3,900	13,000	7,400
MIROC5	2,500	2,300	8,900	3,400
5-Model Average	**3,500**	**2,600**	**9,300**	**3,900**
Cold				
CanESM2	-49	-41	-51	-36
CCSM4	-34	-47	-48	-35
GISS-E2-R	-10	-16	-52	-6
HadGEM2-ES	-32	-49	-58	-37
MIROC5	-40	-10	-55	-51
5-Model Average	**-33**	**-33**	**-53**	**-33**
Total (Change in Combined Heat and Cold Deaths)				
CanESM2	4,100	2,700	12,000	3,700
CCSM4	2,300	1,700	7,100	2,400
GISS-E2-R	2,500	2,300	5,400	2,700
HadGEM2-ES	5,900	3,900	13,000	7,400
MIROC5	2,400	2,300	8,900	3,300
5-Model Average	**3,400**	**2,600**	**9,300**	**3,900**

Mortality rates from extreme hot and cold temperatures by city are greatest under RCP8.5 in 2090 (Figure 5.1). In this time period and climate scenario, nearly all cities experience net mortality rates greater than eight deaths per 100,000 residents from extreme hot and cold, with the exception of the Northwest. However, several cities, notably Kansas City, have high mortality rates under RCP4.5 and in 2050.

Figure 5.1. Projected Extreme Temperature Mortality in Select Cities

Estimated net mortality rate from extremely hot and cold days (average of five GCMs; number of deaths per 100,000 residents). Cities without circles should not be interpreted as having no extreme temperature impact.



Impacts vary regionally; however, it is important to note that the number of cities and the number of people included within each region of this study are not homogenous. In the reference period, most of the cities that had the highest increase in mortality from exceeding heat thresholds were located in the Northeast and the Midwest – therefore, for a similar amount of warming, these cities will see a greater increase in mortality than some of the more southern cities (see Figure 5.1). The finding that some hot cities in the Southwest and southern Florida have lower increases in mortality during extreme heat events is consistent with a number of studies[147][148] and is thought to be a result of adaptation measures (physiological, behavioral, and infrastructure based).[149] In the reference period, cities had insufficient exceedances of extreme heat thresholds in the Northwest or parts of the Southwest region (Colorado and northern California), and therefore this analysis projects no increase in mortality in those cities. The

[147] Kalkstein, L. S., S. Greene, D. M. Mills, and J. Samenow, 2011: An evaluation of the progress in reducing heat-related human mortality in major U.S. cities. Natural Hazards, 56, 113-129. doi:10.1007/s11069-010-9552-3

[148] Anderson, G. B., and M. L. Bell, 2011: Heat waves in the United States: Mortality risk during heat waves and effect modification by heat wave characteristics in 43 U.S. communities. Environmental Health Perspectives, 119, 210-218. doi:10.1289/ehp.1002313

[149] Sarofim, M.C., S. Saha, M.D. Hawkins, D.M. Mills, J. Hess, R. Horton, P. Kinney, J. Schwartz, and A. St. Juliana, 2016: Ch. 2: Temperature-Related Death and Illness. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 43–68, doi: 10.7930/J0MG7MDX

empirical dataset did not include cities located in the Northern Plains, therefore no results are reported for that region. Annual damages from increases in extreme heat related deaths are $140 billion under RCP8.5 and $60 billion under RCP4.5 by the end of the century.

As a sensitivity study, this analysis was also conducted using assumptions that approximated higher physiological adaptation and increased availability of air conditioning. The "with adaptation" values (Table 5.2) evaluate the potential impacts of temperature adaptation by setting the threshold temperature for extreme heat days equal to the values for Dallas, Texas, the second warmest city in the analysis (unless the city had a higher threshold). Assuming all cities have the adaptive capacity of residents of Dallas results in substantially lower increases in premature deaths, more than halving mortality under all years and climate scenarios.

Table 5.2. Change in Annual Premature Mortality from Extreme Heat and Resulting Damages

Changes in annual mortality by region are five-GCM means of premature deaths from the 1989-2000 *reference period, due to extreme heat only (not including change in cold-related mortality),. Totals based on the 49 modeled cities are also shown for combined heat and cold (noted as '*with cold' below) and for the heat-only mortality results of the adaptation sensitivity study (noted as '*with adaptation' below). No cities in the Northern Plains region were modeled. Values may not sum due to rounding.*

	2050			
	RCP8.5		RCP4.5	
	Premature Deaths (Annual)	Valuation (millions of $2015)	Premature Deaths (Annual)	Valuation (millions of $2015)
Northeast	660	$8,200	660	$8,200
Southeast	610	$7,600	470	$5,800
Midwest	800	$10,000	700	$8,700
Southern Plains	550	$6,900	360	$4,400
Southwest	850	$11,000	400	$5,000
Northwest	0	$0	0	$0
Total	**3,500**	**$43,000**	**2,600**	**$32,000**
**With Cold*	*3,400*	*$42,000*	*2,600*	*$32,000*
**With Adaptation*	*1,000*	*$13,000*	*650*	*$8,100*
	2090			
	RCP8.5		**RCP4.5**	
	Premature Deaths (Annual)	**Valuation (millions of $2015)**	**Premature Deaths (Annual)**	**Valuation (millions of $2015)**
Northeast	2,300	$35,000	970	$15,000
Southeast	1,600	$25,000	670	$10,000
Midwest	2,000	$31,000	840	$13,000
Southern Plains	1,300	$19,000	620	$9,400
Southwest	2,000	$31,000	830	$13,000
Northwest	0	$0	0	$0
Total	**9,300**	**$140,000**	**3,900**	**$60,000**
**With Cold*	*9,300*	*$140,000*	*3,900*	*$60,000*
**With Adaptation*	*4,300*	*$65,000*	*1,300*	*$19,000*

5.5 DISCUSSION

The result that climate change will lead to an annual increase of thousands of deaths in the U.S. is consistent in direction and magnitude with the majority of studies in this field.[150] The main estimates presented in this section account for the difference in sensitivity due to geography (e.g., a 100-degree day in Texas generally leads to fewer health impacts than a 100-degree day in Vermont), but do not account for changes in sensitivity over time as humans adapt to a changing climate, whether due to increased availability of air conditioning or how the human body can become accustomed to high temperatures over time. The sensitivity analysis considered a future in which the human health response to extreme temperatures in all 49 cities in the future was equal to that of Dallas today, and in this case the results showed that mortality dropped more than 50% compared to the main estimates. This provides one estimate of the number of lives adaptation might save, but even in this scenario, deaths increased significantly compared to present-day conditions.

Beyond this one sensitivity analysis, the overall study only covers 49 cities, or approximately 1/3 of the U.S. population, and so these values are likely underestimates. Furthermore, this study does not consider the interactive effects of extreme heat and air quality, which could have compounding effects. It is also important to recognize that some populations are at greater risk to extreme heat conditions, particularly older adults, children, people working outdoors, the socially isolated and economically disadvantaged, those with chronic illnesses, and some communities of color.[151]

The study also only considers deaths related to extreme temperatures, though extreme heat will very likely lead to an increase in morbidity as well. Loss of internal temperature control can result in a cascade of illnesses, including heat cramps, heat exhaustion, heatstroke, and hyperthermia in the presence of extreme heat, and hypothermia and frostbite in the presence of extreme cold. Temperature extremes can also worsen chronic conditions such as cardiovascular disease, respiratory disease, cerebrovascular disease, and diabetes-related conditions. Prolonged exposure to high temperatures is associated with increased hospital admissions for cardiovascular, kidney, and respiratory disorders. Exposures to high minimum temperatures may also reduce the ability of the human body to recover from high daily maximum temperatures.[152] None of these health impacts, nor any associated mental health impacts, are included in this analysis.

---

[150] Ibid.
[151] Ibid.
[152] Ibid.

6. LABOR

6.1 KEY FINDINGS

- Under RCP8.5, labor hours in the U.S. are projected to decrease due to increases in extreme temperatures, especially for outdoor industries whose workers are exposed to the elements. Considering changes in both extreme heat and cold, approximately 1.9 billion labor hours are projected to be lost in 2090, costing an estimated $160 billion in lost wages.
- RCP4.5 avoids the loss of more than 900 million labor hours and nearly $75 billion in wages in 2090 compared to RCP8.5.

6.2 INTRODUCTION

Climate change affects labor in a number of ways, but projections of hotter summer temperatures raise a particular concern. Extreme summer temperatures will be more frequent and intense in the future.[153] Exposure to higher average temperatures and temperature extremes affect workers' health, safety, and productivity.[154] When exposed to high temperatures, workers are at risk for heat-related illnesses (e.g. heat stroke and heat exhaustion) and fatigue[155] and therefore may take more frequent breaks, or may have to stop work entirely, resulting in lower overall labor capacity. This is especially true for high-risk industries where workers are doing physical labor and have a direct exposure to outdoor temperatures (e.g., agriculture, construction, utilities, and manufacturing).[156]

6.3 APPROACH

This analysis focuses on the impact of changes in extreme temperatures on labor supply[157] across the contiguous U.S. Specifically, the analysis estimates the number of labor hours lost due to changes in extreme temperatures using dose-response functions for the relationship between temperature and labor from Graff Zivin and Neidell (2014).[158] Mean maximum temperatures from the five GCMs are projected for four future periods (five-year averages centered on 2030, 2050, 2070, and 2090) at the county level for RCP8.5 and RCP4.5. The analysis estimates the total labor hours lost in all categories of the labor force and also for workers in high-risk industries (most likely to be strongly exposed to extreme temperature), taking into account county-level population projections from the ICLUSv2

---

[153] Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M. Wehner, J. Willis, D. Anderson, S. Doney, R. Feely, P. Hennon, V. Kharin, T. Knutson, F. Landerer, T. Lenton, J. Kennedy, and R. Somerville, 2014: Ch. 2: Our Changing Climate. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 19-67. doi:10.7930/J0KW5CXT.

[154] USGCRP, 2016: The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment. Crimmins, A., J. Balbus, J.L. Gamble, C.B. Beard, J.E. Bell, D. Dodgen, R.J. Eisen, N. Fann, M.D. Hawkins, S.C. Herring, L. Jantarasami, D.M. Mills, S. Saha, M.C. Sarofim, J. Trtanj, and L. Ziska, Eds. U.S. Global Change Research Program, Washington, DC, 312 pp. doi: 10.7930/J0R49NQX.

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

[156] Graff Zivin, J. and M. Neidell, 2014: Temperature and the allocation of time: implications for climate change. *Journal of Labor Economics*, **32,** 1-26, doi:10.1086/671766.

[157] This analysis uses the term labor supply to refer to hours worked, but cannot determine whether that choice is driven by employees or employers.

[158] Graff Zivin, J. and M. Neidell, 2014: Temperature and the allocation of time: implications for climate change. *Journal of Labor Economics*, **32,** 1-26, doi:10.1086/671766.

model.[159] The fraction of workers in high-risk industries is calculated using Bureau of Labor Statistics data from 2003-2007 and is assumed to remain fixed over time for each county.[160] The dose-response functions are estimates of short-run responses to changes in weather, and as such do not account for longer-term possibilities, such as acclimation of workers, relocation of industries, technological advancements to reduce exposure, or broader changes in the labor force.[161] The analysis estimates the cost of the projected losses in labor hours based on the Bureau of Labor Statistics' estimated average wage in 2005, adjusted to future years based on the projected change in GDP per capita.[162,163] For more information on the approach for the labor sector, please refer to Graff Zivin and Neidell (2014)[164] and EPA (2015).[165]

6.4 RESULTS

Without global GHG mitigation, an increase in extreme heat is projected to have a large negative impact on U.S. labor hours, especially for outdoor labor industries. Under RCP8.5, almost 1.9 billion labor hours across the national workforce are projected to be lost annually by 2090 due to unsuitable working conditions (individual GCM results range from 1.0 to 2.7 billion hours lost). Losses are particularly large in the Southeast (0.57 billion labor hours annually) and Midwest (0.40 billion labor hours annually). Loss of labor hours across the U.S. is projected to be very costly, totaling over $160 billion in lost wages per year by 2090 (range from $87- $220 billion). More than a third of this national loss is projected to occur in the Southeast ($47 billion annually).

As shown in Figure 6.1, the majority of the country is projected to experience decreases in labor hours due to extreme temperature effects. In 2090, losses of high-risk labor hours up to 6.5% are estimated for counties in the Southwest, Texas, and Florida under RCP8.5. Only a limited number of counties are projected to experience increases in labor hours, shown by the green-shaded areas Figure 6.1, which occur in areas that do not frequently experience extreme heat but whose extremely cold temperatures will be warmed in the future. See Section A.7 of the Appendix for GCM-specific maps of percent change in labor hours.

---

[159] EPA, 2017: Updates to the Demographic and Spatial Allocation Models to Produce Integrated Climate and Land Use Scenarios (Iclus) (Version 2). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-16/366F. Available online at https://cfpub.epa.gov/ncea/iclus/recordisplay.cfm?deid=322479

[160] Bureau of Labor Statistics, cited 2017: Quarterly Census of Employment and Wages. [Available online at http://www.bls.gov/cew/]. High-risk workers were defined as those employed in agriculture, forestry, and fishing; hunting, mining, and construction; and manufacturing, transportation, and utilities industries. It is important to note the national distribution of workers remains fixed relative to the average distribution from 2003-2007, and that air conditioning and other time-allocation behaviors remain fixed.

[161] The underlying method described in Graff Zivin and Neidell (2014) found no temporal displacement of labor across days in the sample dataset, indicating decreased working hours caused by high temperatures do not cause workers to supply additional labor at other times (i.e., to make up for lost work).

[162] Bureau of Labor Statistics, cited 2017: Quarterly Census of Employment and Wages. [Available online at http://www.bls.gov/cew/]. Average wage ($23.02 per hour in a 35-hour work week) calculated using high-risk labor categories only, as most extreme temperature impacts on labor hours occur in these industries.

[163] Cost of projected losses in labor hours were estimated by adjusting the Bureau of Labor Statistics' estimated average wage in 2005 of $23.02 to $27.47 and calculating to 2100 using an index reflecting projected changes in GDP per capita given real $2015 GDP and population.

[164] Graff Zivin, J. and M. Neidell, 2014: Temperature and the allocation of time: implications for climate change. *Journal of Labor Economics*, **32,** 1-26, doi:10.1086/671766.

[165] EPA, 2015: Technical Appendix for Report: Climate Change in the United States: Benefits of Global Action. Section G: Technical Details Related to Labor Analysis. U.S. Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-15-001. Available online at https://www.epa.gov/cira/downloads-cira-report

Figure 6.1. Percent Change in Hours Worked

Estimates represent change in hours worked from the 2003-2007 reference period at the county level for high-risk industries only, and are normalized by the high-risk working population in each county. Values represent five-year averaged results across the five GCMs in 2050 and 2090 under RCP4.5 and RCP8.5.

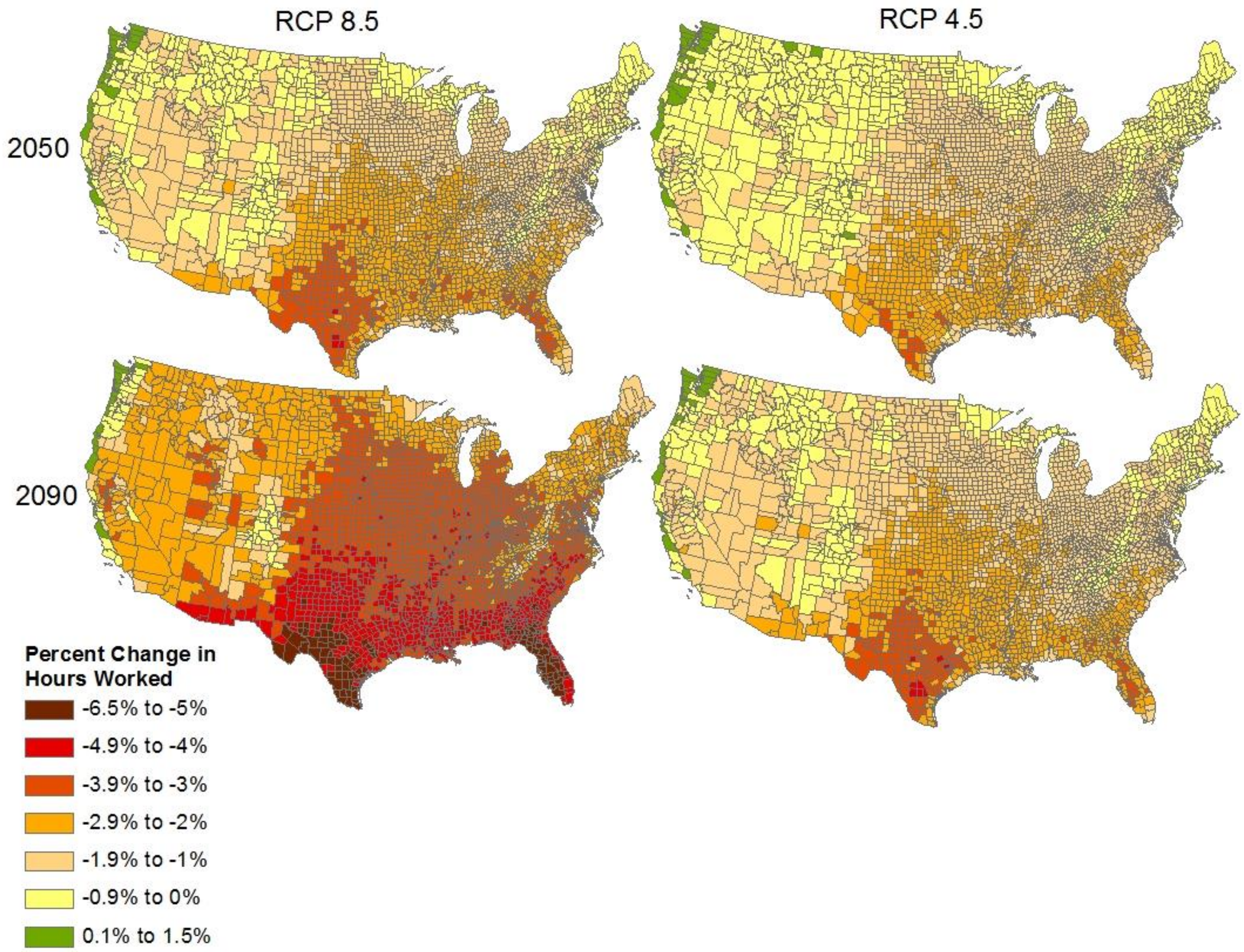


Table 6.1. Change in Annual Hours Worked and Wages Lost for High Risk Industries

Estimates are five-year averaged changes from the 2003-2007 reference period in 2050 and 2090 under RCP8.5 and RCP4.5. Values may not sum due to rounding.

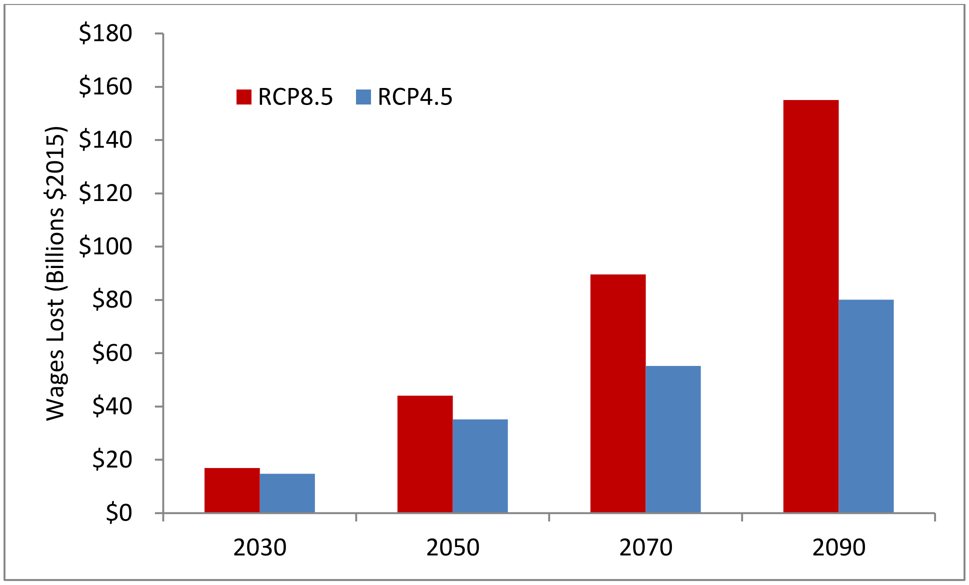
	2050		2090	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Change in Hours (millions) Compared to 2005				
CanESM2	-920	-640	-2100	-840
CCSM4	-810	-590	-1700	-920
GISS_E2_R	-500	-380	-1000	-620
HadGEM2_ES	-1400	-1100	-2700	-1500
MIROC5	-760	-780	-1800	-960
5-Model Average	**-880**	**-700**	**-1900**	**-970**
Change in Wages (millions of $2015) Compared to 2005				
CanESM2	-$46,000	-$32,000	-$180,000	-$70,000
CCSM4	-$41,000	-$30,000	-$140,000	-$76,000
GISS_E2_R	-$25,000	-$19,000	-$87,000	-$52,000
HadGEM2_ES	-$70,000	-$56,000	-$220,000	-$120,000
MIROC5	-$38,000	-$39,000	-$150,000	-$79,000
5-Model Average	**-$44,000**	**-$35,000**	**-$160,000**	**-$80,000**

At the national level, impacts to hours worked (Figure 6.1) and to labor costs (Figure 6.2) are substantially smaller under RCP4.5 than RCP8.5, particularly in 2090. The difference between RCP8.5 and RCP4.5 is approximately 180 million labor hours per year across the workforce by 2050, representing a savings of nearly $9.0 billion in annual wages (Table 6.1). In 2090, RCP4.5 would prevent the loss of more than 910 million labor hours annually and nearly $75 billion in wages compared to RCP8.5[166]. The avoided loss of labor hours under RCP4.5 compared to RCP8.5 is more than five times higher in 2090 than in 2050.

[166] Differences are based on the actual values and not the rounded numbers reported in Table 6.1.

Figure 6.2. Wages Lost for All Labor Categories

Estimates represent the change in wages compared to the reference period (2003-2007) for the contiguous U.S. in 2030, 2050, 2070, and 2090 under RCP4.5 and RCP8.5



6.5 DISCUSSION

Rising temperatures and changes in extreme heat events are projected to lead to significant losses in hours worked in high-risk industries resulting in significant losses in wages across the contiguous U.S., particularly by the end of the century. The results presented show a significant difference between RCP8.5 and RCP4.5 impacts on both changes in hours worked and wages for high-risk industries by the end of the century. The Southeast and the Midwest are particularly vulnerable to future labor productivity losses. A similar study of climate change impacts on labor also found that increasingly extreme heat across the nation—especially in the Southwest, Southeast, and Upper Midwest—threatens productivity and human health.[167]

This analysis only partially captures the effects that changes in humidity could have on worker's health and productivity. Studies have found that the Southeast is particularly vulnerable to high wet-bulb temperatures.[168,169] For example, one study found that labor productivity by the end of the century is projected to decrease up to 3.1% in the Southeast, the area with the highest wet-bulb temperatures, for high-risk job sectors like construction, mining, utilities, transportation, agriculture, and manufacturing.[170] In addition to changes in temperature and humidity, climate change also affects the

---

[167] Gordon, K., 2014: Risky Business: The Economic Risks of Climate Change in the United States: a Climate Risk Assessment for the United States. M. Lewis and J. Rogers, Eds. Available online at http://riskybusiness.org/site/assets/uploads/2015/09/RiskyBusiness_Report_WEB_09_08_14.pdf

[168] Dunne, J. P., R.J. Stouffer, and J.G. John, 2013: Reductions in labour capacity from heat stress under climate warming. *Nature Climate Change*, **3,** 563–566, doi:10.1038/nclimate1827.

[169] Rhodium Group, 2014: American Climate Prospectus: Economic Risks in the United States. Input to the Risky Business Project. Available online at http://climateprospectus.org/assets/publications/AmericanClimateProspectus_v1.2.pdf

[170] Gordon, K., 2014: Risky Business: The Economic Risks of Climate Change in the United States: a Climate Risk Assessment for the United States. M. Lewis and J. Rogers, Eds. Available online at http://riskybusiness.org/site/assets/uploads/2015/09/RiskyBusiness_Report_WEB_09_08_14.pdf

health of outdoor workers by worsening air quality and increasing pollen exposure, increasing the frequency or severity of other forms of extreme weather, and altering exposure to vector-borne diseases.[171] Some of these impacts are quantified in this Technical Report (see the Air Quality, Aeroallergen, and West Nile Virus sections), but others are not assessed, including the potential compounding effects from multiple climate-induced stressors.

As noted in the Approach section, this study does not consider the influence of potential adaptation measures either by workers (e.g. physiological acclimation), employers (e.g. policies or infrastructure to reduce exposure), or industries (e.g. technological advancements). Adaptation measures would likely improve the health and safety of workers, but resulting impacts on worker productivity remain uncertain.

---

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

7. WEST NILE VIRUS

7.1 KEY FINDINGS

- Increases in annual average temperature are expected to continue to increase incidence of West Nile virus in multiple regions of the U.S.
- Annual national cases of West Nile neuroinvasive disease (WNND) are projected to more than double by 2050, increasing by 1,300 and 1,000 cases above the reference period (970 cases in 1995) under RCP8.5 and RCP4.5, respectively. In 2090, an additional 3,300 and 1,700 annual cases compared to the reference period are projected under RCP8.5 and RCP4.5, respectively.
- The associated monetized impact of these additional climate-attributable cases is estimated at $1.1 billion and $0.87 billion in 2050 under RCP8.5 and RCP4.5, respectively, and $3.3 billion and $1.8 billion in 2090 under RCP8.5 and RCP4.5, respectively.

7.2 INTRODUCTION

West Nile virus (WNV) is the most widely distributed arthropod-borne virus in the world, and the leading cause of arthropod-borne viral disease in the U.S.[172,173] It was first detected in the Western Hemisphere in 1999 and rapidly spread across much of the Americas by 2005.[174,175] The virus is now endemic throughout most of the contiguous U.S., and is transmitted between birds and several species of mosquitoes, which can cause infection in humans.[176] Climate change has the potential to alter the geographic distributions of WNV and its vectors.[177] Above-normal temperatures have been among the most consistent predictors of outbreaks, due in part to the acceleration of viral incubation in mosquitoes and increased mosquito reproduction rates at higher temperatures.

WNV is classified as a nationally notifiable health outcome; accordingly, state health agencies are responsible for reporting West Nile virus cases to the Centers for Disease Control and Prevention (CDC).[178] WNV cases can be distinguished by severity of the patient's symptoms; milder cases may produce symptoms (e.g., fever, headache, rash, vomiting) that are indistinguishable from other illnesses.[179] As a result, there are questions about the accuracy of reported case counts for these milder expressions of WNV because of potential under-reporting and incorrect attribution. In contrast, West Nile neuroinvasive disease (WNND) cases, which occur for less than 1% of people infected with the disease, can affect the patient's brain or cause neurologic dysfunction and these cases typically result in

---

[172] Kramer, L.D., L.M. Styer, and G.D. Ebel, 2008: A Global Perspective on the Epidemiology of West Nile Virus. *Annu Rev Entomol*, **53**, 61-81.

[173] Lindsey, N.P., J.A. Lehman, E. Staples, and M. Fischer, 2015: West Nile Virus and Other Nationally Notifiable Arboviral Diseases – United States, 2014. *Morbidity and Mortality Weekly Report*, **64**, 929-934.

[174] Gubler, D.J., 2007: The Continuing Spread of West Nile Virus in the Western Hemisphere. *Clin Infect Dis*, **45**, 1039-1046.

[175] Hayes, E.B. and D.J. Gubler, 2006: West Nile Virus: Epidemiology and Clinical Features of an Emerging Epidemic in the United States. *Annu Rev Med*, **57**, 181-194.

[176] Reisen, W.K., 2013: Ecology of West Nile Virus in North America. *Viruses*, **5**, 2079-2105.

[177] Beard, C.B., R.J. Eisen, C.M. Barker, J.F. Garofalo, M. Hahn, M. Hayden, A.J. Monaghan, N.H. Ogden, and P.J. Schramm, 2016: Chapter 5: Vector-Borne Diseases. In: The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment, U.S. Global Change Research Program, Washington, DC, 129-156. http://dx.doi.org/10.7930/J0765C7V

[178] CDC, 2015: West Nile Virus: Surveillance Resources. Centers for Disease Control and Prevention. Available online at https://www.cdc.gov/westnile/resourcepages/survresources.html

[179] CDC, 2016: National Notifiable Diseases Surveillance System (NNDSS): Arboviral Diseases, Neuroinvasive and Non-Neuroinvasive 2015 Case Definition. Centers for Disease Control and Prevention. Available online at https://wwwn.cdc.gov/nndss/conditions/arboviral-diseases-neuroinvasive-and-non-neuroinvasive/case-definition/2015/

a patient's hospitalization. Because it is unlikely that these WNND patients could or would avoid hospitalization given the severity of their syndromes, there is more certainty with these reported WNND cases.[180]

7.3 APPROACH

This analysis explores the relationship between temperature and WNND in the contiguous U.S. using WNND cases, population, and temperature data from 2004-2012 to develop county-specific health impact functions. Specifically, the study estimates regional associations between temperatures and the probability of above-average WNND incidence. Based on these health impact functions, county-level expected WNND incidence rates are then estimated for a 1995 reference period (1986-2005) and two future years (2050: 2040-2059 and 2090: 2080-2099) using temperature data from the five GCMs under two RCPs. These results are combined with projections of county-level populations to calculate the potential number of cases for 2050 and 2090. All-age, county-level population projections are from the ICLUSv2[181] for 2010, 2050, and 2090. The 2010 population estimates were used with the reference period for 1986-2005 to provide a more recent representation of the population.

Cases were allocated to fatal and nonfatal outcomes based on a 6.5% mortality rate reported in the national summary of 2014 WNND cases.[182] For nonfatal outcomes, a cost of $41,391 ($2015) was used, which reflects incurred hospital charges for patients with associated meningitis, encephalitis, and acute flaccid paralysis syndrome. Hospitalization costs do not account for lost productivity during hospitalization, related outpatient costs, or associated pain and suffering. Fatal WNND case costs are estimated using a baseline VSL adjusted to future years based on changes in economic growth.[183] For more information on the approach to estimating climate change impacts on WNV cases, please refer to Belova et al. (2017).[184]

7.4 RESULTS

Approximately half of all U.S. counties reported a WNND case from 2004 to 2012. Because high temperatures are associated with a higher probability of above-average WNND incidence, this study projects the number of years within the future 20-year time periods that are substantially warmer than temperatures between 2004 and 2012, and therefore more likely to result in WNND outbreaks. In 2050 (under both RCPs) and under RCP4.5 in 2090, few counties are projected to have more than four years (out of the possible 20 year eras) during which projected temperatures are substantially warmer than

---

[180] Hahn, M.B., A.J. Monaghan, M.H. Hayden, R.J. Eisen, M.J. Delorey, N.P. Lindsey, R.S. Nasci, and M. Fischer, 2015: Meteorological Conditions Associated with Increased Incidence of West Nile Virus Disease in the United States, 2004-2012. *Am J Trop Med Hyg*, doi:10.4269/ajtmh.14-0737.

[181] EPA, 2017: Updates to the Demographic and Spatial Allocation Models to Produce Integrated Climate and Land Use Scenarios (ICLUS) (Version 2). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-16/366F. Available online at https://cfpub.epa.gov/ncea/iclus/recordisplay.cfm?deid=322479

[182] Lindsey, N.P., J.A. Lehman, E. Staples, and M. Fischer, 2015: West Nile Virus and Other Nationally Notifiable Arboviral Diseases – United States, 2014. *Morbidity and Mortality Weekly Report*, **64**, 929-934.

[183] At the time of this analysis, the EPA's *Guidelines for Preparing Economic Analyses* recommends a VSL of $7.9 million (2008$), based on 1990 incomes. To create a VSL using $2015 and based on 2015 incomes, the standard value was adjusted for inflation and for income growth adjustment based on the approach described in EPA's BenMAP-CE model and its documentation. The resulting value, $10.0 million for 2015 ($2015), was adjusted to future years by assuming an elasticity of VSL to GDP per capita of 0.4. Projections of U.S. GDP and population described in the Modeling Framework section of this Technical Report were employed. Using this approach, the VSL in 2050 is estimated at $12.4 million and $15.2 million in 2090. Sources: 1) EPA, 2014: Guidelines for Preparing Economic Analyses. National Center for Environmental Economics. Available online at http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0568-52.pdf/$file/EE-0568-52.pdf; and 2) EPA, cited 2017: Benefits Mapping and Analysis Program (BenMAP): Manual and Appendices for BenMAP-CE. Available online at https://www.epa.gov/benmap/manual-and-appendices-benmap-ce

[184] 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.

the 2004 to 2012 observed annual mean (based on the five GCM average). However, many counties are projected to have multiple future years (e.g. more than 10 years out of the possible 20 year eras) with annual mean temperatures that are substantially different compared to the observed 2004-2012 period under RCP8.5 in 2090.

Estimates of the expected change in the annual number of WNND cases in 2090 under RCP8.5 compared to the reference period (970 cases nationally for the 1986-2005 period) differ considerably from the 2050 and RCP4.5 estimates, as seen in Figure 7.1 and Table 7.1. While all regions show increases in the future expected annual number of cases, the results for the Southeast are the most striking: the number of total cases grows from approximately 100 in the reference period to more than 1,200 in 2090 under RCP8.5. Variability in GCM results are shown in Figure 7.2, using the Southeast as an example.

Figure 7.1. Projected Regional WNND Cases

Maps show annual cases by region in the 1995 reference period (1986-2005), 2050 (2040-2059), and 2090 (2080-2099) under RCP8.5 and RCP4.5. Populations are consistent with the representative year, and results are averaged over the GCMs and modeled climate periods.

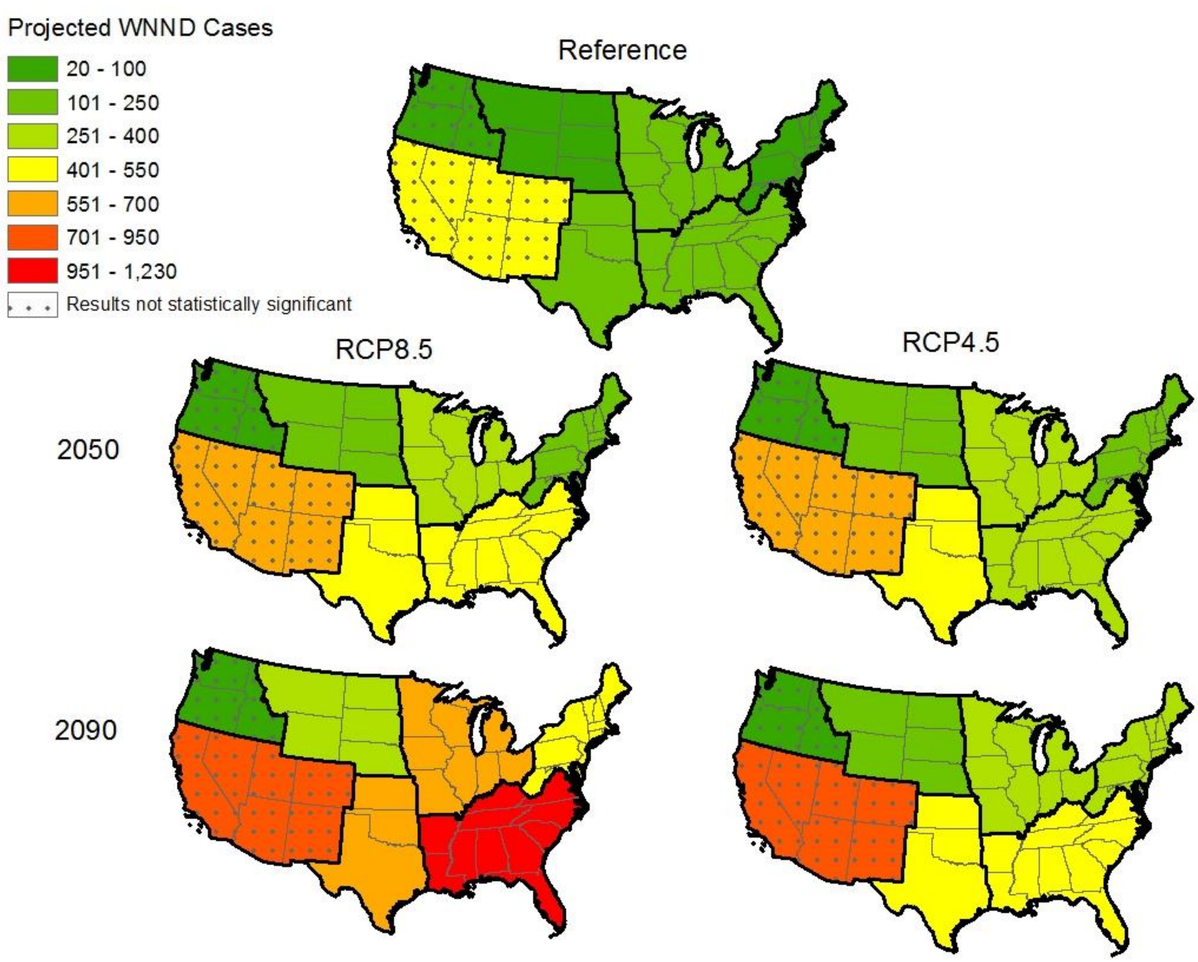


Table 7.1. Projected Increases in WNND Cases

Future cases by region are estimated under a dynamic population (populations are modeled for 2050 (2040-2059) and 2090 (2080-2099)) and holding population constant at 2010 levels to demonstrate the portion of additional cases attributable to climate change. Cases are reported as increases from the 1995 reference period (1986-2005). Values may not sum due to rounding.

	Dynamic Population				2010 Population			
	2050		2090		2050		2090	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Northeast	170	130	490	210	140	99	420	160
Southeast	370	270	1100	440	300	210	960	330
Midwest	170	130	450	210	110	81	350	130
Northern Plains	100	79	330	150	71	51	250	85
Southern Plains	220	200	450	330	70	51	160	71
Southwest	240	230	420	380	28	21	56	29
Northwest	6.5	6.4	11	11	0.44	0.35	0.84	0.47
Total	**1,300**	**1,000**	**3,300**	**1,700**	**720**	**510**	**2200**	**800**

There are often considerable differences across the estimates of the expected annual number of WNND cases for the U.S. in a specific a reporting period. These differences are largely a reflection of year-to-year variability in the projected annual average temperatures across the calendar years selected to represent the reporting period, as well as model and scenario uncertainty. In the example of the Southeast shown in Figure 7.2, across RCPs and reporting years (i.e., comparing results within the panels), the largest modeled mean value is approximately –three-to-four times the smallest value, highlighting this inter-model uncertainty. There is also increased year-to-year variability under RCP8.5 compared to the RCP4.5 scenario.

The costs of temperature-related increases in WNND cases (Table 7.2) in 2050 are approximately $1.1 billion and $0.87 billion for RCP8.5 and RCP4.5, respectively. Damages increase in 2090 to $3.3 billion and $1.8 billion under RCP8.5 and RCP4.5, respectively. Removing cases from regions where the temperature- incidence functions were not statistically significant in the underlying literature[185] reduces these values to $0.87 billion and $0.68 billion in 2050, and to $2.9 billion and $1.4 billion in 2090, under RCP8.5 and RCP4.5, respectively.

[185] Hahn, M.B., A.J. Monaghan, M.H. Hayden, R.J. Eisen, M.J. Delorey, N.P. Lindsey, R.S. Nasci, and M. Fischer, 2015: Meteorological Conditions Associated with Increased Incidence of West Nile Virus Disease in the United States, 2004-2012. *Am J Trop Med Hyg*, doi:10.4269/ajtmh.14-0737.

Figure 7.2. Projected Change in WNND Cases in the Southeast Region
The graphs present the mean estimated WNND cases in 2050 (2040-2059) and 2090 (2080-2099) by GCM and RCP in addition to the cases in the 1986-2005 reference period under a dynamic population (populations are modeled for 2050 and 2090). For the five GCMs, 2.5% and 97.5% confidence intervals are also provided. Data on the confidence intervals for the five-GCM average are not available.

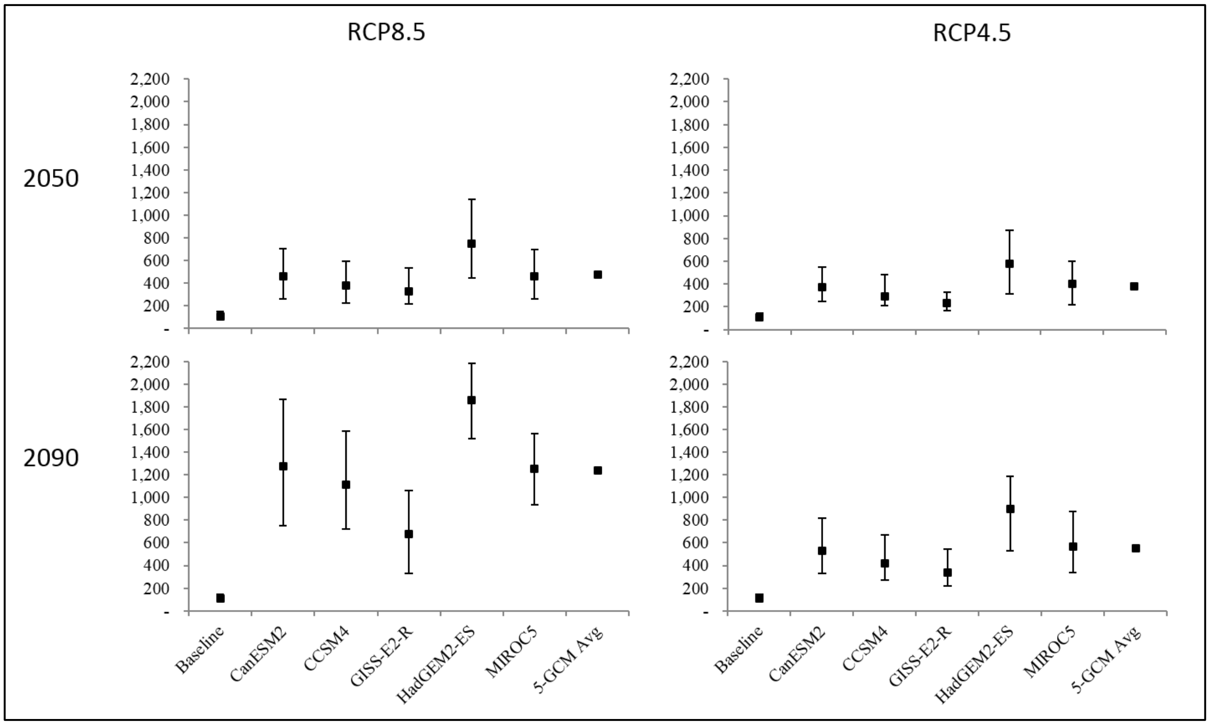


Table 7.2. Costs of Projected Additional Annual WNND Cases
The table presents the number of additional case counts relative to the 970 cases in the reference period (1986-2005). Case counts reflect impacts of changes in temp. and population projected for 2050 and 2090. Results shown in the 'Total Subset' row exclude results for three regions (Southwest, West, and Northwest) where odds ratio results were statistically insignificant according to Hahn et al. (2015). Values represent results for the five-GCM average. Values may not sum due to rounding.

	2050		2090	
	Annual Additional WNND Cases	Estimated Value (millions of $2015)	Annual Additional WNND Cases	Estimated Value (millions of $2015)
RCP8.5				
Fatal	82	$1,000	210	$3,200
Nonfatal	1,200	$49	3,100	$130
Total	**1,300**	**$1,100**	**3,300**	**$3,300**
Total Subset	*1,000*	*$870*	*2,900*	*$2,900*
RCP4.5				
Fatal	67	$830	110	$1,700
Nonfatal	970	$40	1,600	$67
Total	**1,000**	**$870**	**1,700**	**$1,800**
Total Subset	*800*	*$680*	*1,300*	*$1,400*

7.5 DISCUSSION

The results presented in this section indicate that climate change will increase the risk of WNND infection rates across the contiguous U.S. Placing these results in a broader context is challenging because to date, most of the work projecting the impact of climate change on vectorborne disease has focused on evaluating potential changes in season lengths and range expansion rather than developing incidence projections.

This study only accounts for projected changes in temperature, one of a number of factors that can influence WNND disease occurrence and case totals. Future research could be improved by accounting for changes in precipitation (an important factor for mosquito breeding) and changes in land use characteristics that may affect bird, mosquito, and human distributions. Furthermore, it is difficult to predict how human behavior may respond to a changing climate. This analysis assumes that the effects of interventions (e.g., mosquito control and public outreach regarding personal protection from mosquito biting) are captured by the original temperature-incidence relationships and that the nature of those relationships will not change over time.

The results presented in this analysis, which only account for neuroinvasive WNV cases, are likely conservative, as projections do not capture the potential for increases in WNV cases in the roughly half of U.S. counties where no WNV cases were reported from 2004 to 2012. In addition, the approach for monetizing hospitalization costs does not account for lost productivity during hospitalization, related outpatient costs, or associated pain and suffering. Still, the projected increases in WNND cases are noteworthy considering the absolute number of cases involved, the severity of associated health impacts, and the magnitude of these increases relative to the projected reference.

8. HARMFUL ALGAL BLOOMS

8.1 KEY FINDINGS

- Warming temperatures and changes in precipitation, which will drive alterations in river flow and nutrient availability, are projected to increase the occurrence of harmful algal blooms in many watersheds of the contiguous U.S.
- In 2090, a warming climate under RCP8.5 results in an additional full month with harmful algal concentrations above a recommended public health threshold, while RCP4.5 results in an additional half month. The resulting losses to reservoir recreation in the contiguous U.S. are estimated to be on the order of hundreds of millions of dollars per year by 2090.

8.2 INTRODUCTION

Harmful algal blooms (HABs) can affect human health and welfare by degrading the quality of drinking water supplies and forcing activity restrictions at recreational waterbodies. Today, lakes and reservoirs that serve as sources of drinking water for between 30 and 48 million Americans are susceptible to periodic contamination by algal or cyanobacterial toxins (also called cyanotoxins). For example, in August 2014 nearly 500,000 residents of Toledo, Ohio lost access to their drinking water after tests from a cyanobacterial harmful algal bloom (CyanoHAB) in Lake Erie revealed the presence of cyanotoxins near the water plant's intake.[186] Certain drinking water treatment processes can address algal toxins; however, removal efficiency can be as low as 60 percent.[187] Recreational exposure to cyanotoxins in lakes and other freshwater bodies can also adversely affect human health. In 2009 and 2010, cyanotoxins were responsible for nearly half of all disease outbreaks linked to recreational freshwater exposure.[188]

More freshwater CyanoHABs and increased human exposure risk are expected in the future as climate change contributes to more suitable environmental conditions for bloom formation.[189] Such conditions are primarily due to warming surface water temperatures, but are also affected by changing precipitation patterns. More frequent extreme precipitation events can increase freshwater runoff carrying excess nitrogen, phosphorus, other nutrients, and sediments into water bodies. In addition, intense precipitation followed by periods of drought increases residence time in reservoirs and supports bloom formation.

---

[186] Toledo, City of, 2014: Microcystin Event Preliminary Summary. 73 pp. City of Toledo Department of Public Utilities. [Available online at: http://toledo.oh.gov/media/132055/Microcystin-Test-Results.pdf]

[187] EPA, 2015: Recommendations for Public Water Systems to Manage Cyanotoxins in Drinking Water. United States Environmental Protection Agency, Office of Water. EPA 815-R-15-010. Available online at: http://www2.epa.gov/sites/production/files/2015-06/documents/cyanotoxin-management-drinking-water.pdf

[188] Hilborn, E.D., V.A. Roberts, L. Backer, E. DeConno, J.S. Egan, J.B. Hyde, D.C. Nicholas, E.J. Wiegert, L.M. Billing, M. DiOrio, M.C. Mohr, F.J. Hardy, T.J. Wade, J.S. Yoder, and M.C. Hlavsa, 2014: Algal bloom–associated disease outbreaks among users of freshwater lakes — United States, 2009–2010. MMWR. *Morbidity and Mortality Weekly Report*, **63**, 11-15. Available online at http://www.cdc.gov/mmwr/preview/mmwrhtml/mm6301a3.htm

[189] Trtanj, J., L. Jantarasami, J. Brunkard, T. Collier, J. Jacobs, E. Lipp, S. McLellan, S. Moore, H. Paerl, J. Ravenscroft, M. Sengco, and J. Thurston, 2016: Ch. 6: Climate Impacts on Water-Related Illness. The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment. U.S. Global Change Research Program, Washington, DC, 157–188. http://dx.doi.org/10.7930/J03F4MH

8.3 APPROACH

Building on the water resource framework described in the Water Quality section of this report,[190] this analysis uses a series of linked models to evaluate the biophysical impacts of climate change on CyanoHAB occurrence in the contiguous U.S. The linked model chain starts with climate projections from five GCMs under RCP8.5 and RCP4.5 that are input into a rainfall-runoff model (CLIRUN-II), which simulates monthly runoff in each of the 2,119 eight-digit hydrologic unit codes (HUCs) of the contiguous U.S. A water demand model then projects water requirements of the municipal and industrial (M&I) and agriculture sectors under a scenario assuming population growth consistent with the other sectors of this Technical Report. With these runoff and demand projections, a water resources systems model produces a time series of reservoir storage, release, and allocation to the various demands in the system (e.g., M&I, agriculture, environmental flows, transboundary flows, hydropower).

A modified version of the QUALIDAD water quality model[191] incorporates this information on managed flows and reservoir parameters while simulating a number of water quality metrics in waterbodies, including cyanobacteria concentrations. To address uncertainty in the relationship between cyanobacteria growth and water temperature, the analysis uses two algal growth scenarios: a) a "low-growth" scenario that plateaus as temperatures reach 26°C, and b) a "high-growth" scenario that assumes a linear growth rate with changes in temperature.

Finally, the analysis evaluates cyanobacteria concentrations for their potential recreational impacts in terms of potential days of restricted recreational activity at specific sites. The approach quantifies lost recreation at 279 reservoirs to estimate the partial economic effects associated with changes in algal bloom risk. To isolate the effects of climate change from the effects of population growth, the projected changes are all expressed relative to the a control scenario, which uses historical climate from 1986-2005, in addition to population growth effects. For more information on the approach to estimating climate change impacts on harmful algal blooms, please refer to Chapra et al. (2017).[192]

8.4 RESULTS

Climate change is projected to increase the risk of CyanoHAB occurrence in the future. Figure 8.1 shows the changes in cyanobacteria concentrations for the surface layer of all waterbodies at the four-digit HUC level. Across most watersheds of the country, concentrations increase over time and are higher under RCP8.5 compared to RCP4.5. The projected change in cyanobacteria concentrations is generally larger under the high-growth scenario compared to the low-growth scenario. The largest increases are projected for the Midwest, Northern Plains, and Southern Plains.

Under the low-growth scenario, areas of large decreases in annual average cell counts are observed in parts of the West, especially under RCP8.5. This counterintuitive finding occurs when the growth of cyanobacteria plateaus under the low-growth scenario (at water temperatures exceeding 30°C) while the respiration rate continues to increase with temperature, eventually causing decreases in cyanobacteria concentrations.[193] This effect is not observed in the high-growth scenario because growth

[190] As described in: Boehlert, B., K.M. Strzepek, S.C. Chapra, C. Fant, Y. Gebretsadik, M. Lickley, R. Swanson, A. McCluskey, J.E. Neumann, and J. Martinich, 2015: Climate change impacts and greenhouse gas mitigation effects on U.S. water quality. *Journal of Advances in Modeling Earth Systems*, **7**, 1326-1338, doi:10.1002/2014MS000400.

[191] Chapra, S.C., 2014: QUALIDAD: A parsimonious modeling framework for simulating river basin water quality, Version 1.1, Documentation and users manual, Civil and Environmental Engineering Dept., Tufts University, Medford, MA.

[192] Chapra, S.C., B. Boehlert, C. Fant, J. Henderson, D. Mills, D.M.L. Mas, L. Rennels, L. Jantarasami, J. Martinich, K.M. Strzepek, V.J. Jr. Bierman, and H.W. Paerl, 2017: Climate change impacts on harmful algal blooms in U.S. freshwaters: a screening-level assessment. *Environmental Science and Technology*, doi: 10.1021/acs.est.7b01498.

[193] This phenomenon of decreasing cyanobacteria concentrations at higher temperatures occurs when light and nutrient limitations restrict growth to about 15% of maximum.

does not plateau at these higher temperatures, but rather continues to increase along with respiration as temperature increases.

Figure 8.1. Projected Change in Cyanobacteria Concentrations

Changes in average annual waterbody surface cyanobacteria (thousands of cells per ml) for the low-growth and high-growth scenarios in 2050 (2040-2059) and 2090 (2080-2099) relative to the control scenario. Values for each RCP represent the average results for the five GCMs, and are aggregated to the four-digit HUC level, weighted by waterbody surface area.

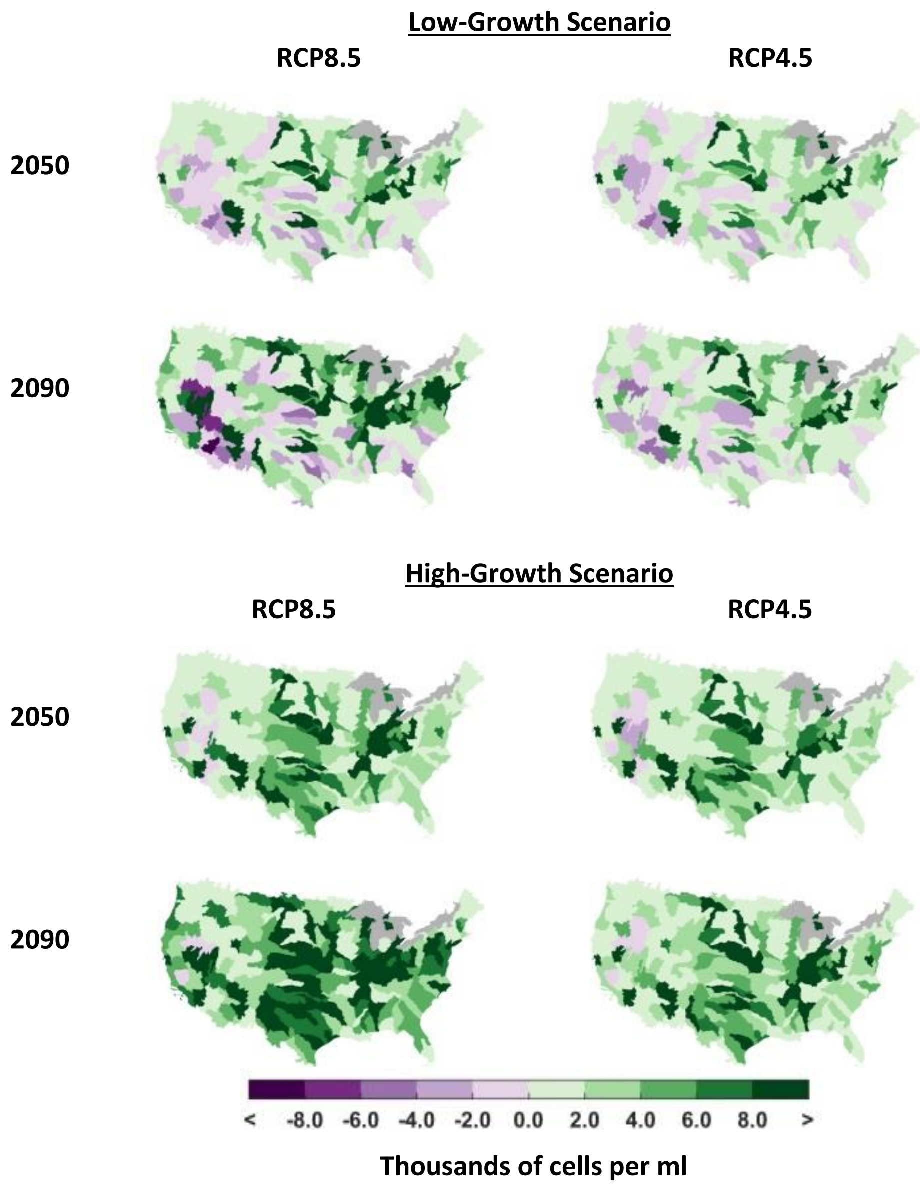


Figure 8.2 shows the population-weighted aggregated cyanobacteria concentration across the year for the results from the 2090 era. In the Control scenario, the aggregate concentrations are slightly lower than 20,000 cells/ml at the peak in August and September. In a changing climate, these peaks rise above 38,000 cells/ml on the low-end and above 70,000 on the high-end. Projected changes in cyanobacteria concentrations vary between the two growth scenarios, especially during the late summer, and for scenarios with higher projected temperature changes. In the low-growth scenario, the aggregate

concentrations show less of a spread across the climate scenarios than in the high-growth scenario, where increasing temperatures above 30°C continue to increase the growth rate. Under both growth scenarios, projected concentrations are largest under the hottest GCMs (CanESM2 and HadGEM2-ES), and the lowest under the GISS-E2-R GCM that projects a smaller amount of average warming.

Figure 8.2. Seasonal Profile of Aggregate Cyanobacteria Concentration

Population-weighted aggregate cyanobacteria concentration (in thousands of cells per ml) in 2090.

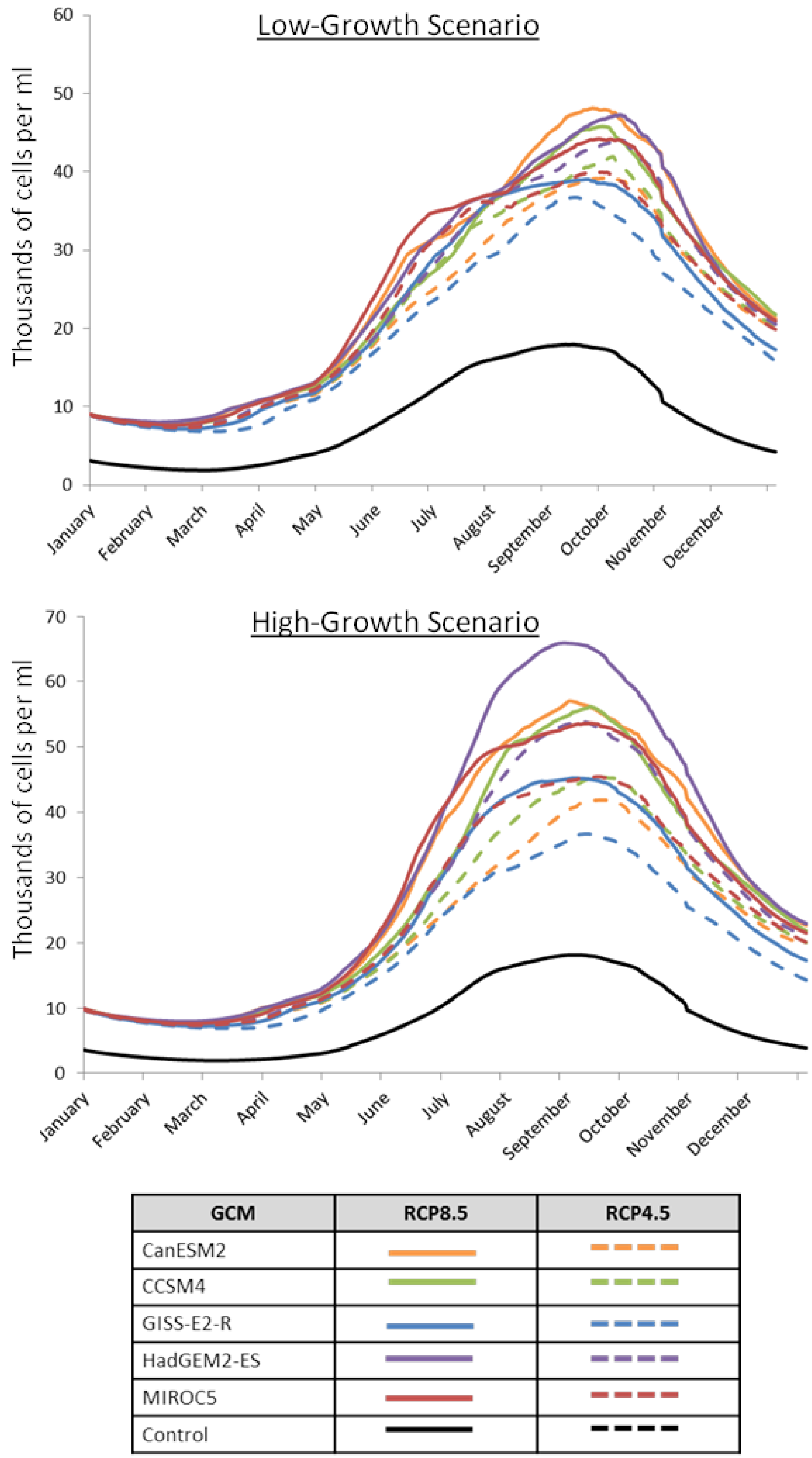


Table 8.1 shows the change in the mean number of days per year above two levels, 20,000 cells/ml and 100,000 cells/ml, recommended by the World Health Organization as important for managing human health risk.[194] The 20,000 cells/ml level is associated with moderate risk of short-term adverse health effects. The 100,000 cells/ml level represents a very high risk of short or long-term adverse health effects. The lowest increase in number of days is produced from the GISS-E2-R GCM, and the highest is produced by the HadGEM2-ES GCM due, primarily, to the respective projected changes in air temperature (which affects water temperature). For the 20,000 cells/ml threshold, the mean number of additional risk days ranges from about 4 to 44 in 2090 across all five GCMs, both climate forcing scenarios, and both growth scenarios. In 2090, a warming climate under RCP8.5 results in an additional full month with counts above 20,000 cells/ml, while RCP4.5 results in an additional half month.

Table 8.1. Projected Change in Bloom Occurrence

Change in the mean number of days above the 20,000 cells/ml and 100,000 cells/ml thresholds per year per waterbody, aggregated by population, relative to the control scenario. Results are shown for the low- and high-growth scenarios for each RCP/GCM combination. Darker green colors represent greater change in days per year with bloom occurrence.

		20,000 cells/ml				100,000 cells/ml			
		Low		High		Low		High	
		2050	2090	2050	2090	2050	2090	2050	2090
RCP8.5	CanESM2	11	23	15	34	7	14	10	20
	CCSM4	9	20	14	30	8	10	11	17
	GISS-E2-R	6	11	9	19	5	6	9	11
	HadGEM2-ES	14	23	25	44	8	13	15	24
	MIROC5	10	22	14	32	7	12	11	19
	5-Model Average	**10**	**20**	**16**	**32**	**7**	**11**	**11**	**18**
RCP4.5	CanESM2	9	9	12	13	6	6	9	9
	CCSM4	8	11	12	17	7	8	11	12
	GISS-E2-R	4	4	7	8	4	3	7	5
	HadGEM2-ES	12	17	19	27	8	9	13	15
	MIROC5	10	12	14	19	8	9	12	14
	5-Model Average	**9**	**11**	**13**	**17**	**7**	**7**	**10**	**11**

Changes in the risk of HAB occurrence will have wide-ranging economic impacts. This analysis estimates the effects on recreation at 279 freshwater reservoirs across the contiguous U.S. As shown in Table 8.2, climate change under both RCPs is estimated to result in economic losses to recreation in nearly all regions of the country, with estimated damages being greater under the high-growth scenario. Projected losses are generally larger under RCP8.5 compared to RCP4.5 in both 2050 and 2090, with the Northeast, Southeast, and Southern Plains experiencing the largest adverse effects. Importantly, these economic damage estimates represent only part of the total potential impact to human health and the environment. In addition, this analysis does not evaluate the economic effects of climate change on

[194] World Health Organization, 1999: Toxic Cyanobacteria in Water: A guide to their public health consequences, monitoring and management. London: E & FN Spon. Available online at http://www.who.int/water_sanitation_health/resourcesquality/toxcyanobacteria.pdf?ua=1

HABs in marine or estuarine waters or other freshwater bodies outside of the 279 reservoirs modeled. Economic damages associated with cyanotoxin exposure in humans, increased water treatment, ecological effects, and other impacts associated with HABs are not included in this analysis.

Table 8.2. Economic Impacts on Reservoir Recreation from HABs

Results represent the average of the five GCMs, and are shown in millions of undiscounted $2015. Positive dollar values indicate losses in recreation value due to HABs. Negative values indicate that for a given period there were less projected days of recreation loss under the climate change projection than under the control scenario that includes population growth (but no climate change).

Region	2050		2090	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Low Growth				
Northeast	$11	$6.8	$28	$16
Southeast	$48	$36	$82	$57
Midwest	$3.1	$1.7	$18	$3.5
Northern Plains	-$3.4	-$3.1	-$3.7	-$4
Southern Plains	$10	$10	$21	$16
Southwest	$7.1	$5	$5.1	$6.8
Northwest	$0.17	$0.21	$1.6	$0.12
Total	**$77**	**$57**	**$150**	**$95**
High Growth				
Northeast	$5.5	$4.9	$27	$13
Southeast	$47	$41	$110	$70
Midwest	$5.3	$3.6	$35	$5.4
Northern Plains	$1.7	$1.2	$4.3	$2.9
Southern Plains	$14	$16	$56	$25
Southwest	$8.1	$4.8	$8.2	$8.9
Northwest	$0.19	$0.22	$5.4	$0.18
Total	**$82**	**$71**	**$250**	**$130**

8.5 DISCUSSION

This analysis demonstrates that climate change is likely to increase the risk of HAB occurrence across many parts of the contiguous U.S. These results are consistent with the findings of the assessment literature, which describe that CyanoHABs are strongly influenced by rising temperatures and altered precipitation patterns, and that the seasonal and geographic range of suitable habitat for cyanobacterial species is projected to expand.[195]

It is important to keep in mind several caveats when interpreting the results presented above. All waterbodies are modeled as well mixed systems, although these are split into two vertical layers during

[195] Trtanj, J., L. Jantarasami, J. Brunkard, T. Collier, J. Jacobs, E. Lipp, S. McLellan, S. Moore, H. Paerl, J. Ravenscroft, M. Sengco, and J. Thurston, 2016: Ch. 6: Climate Impacts on Water-Related Illness. The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment. U.S. Global Change Research Program, Washington, DC, 157–188. http://dx.doi.org/10.7930/J03F4MH4

stratification. Given that cyanobacteria may concentrate vertically over specific depth ranges or horizontally due to lateral winds, potentially compounding concentrations by orders of magnitude,[196] the estimates presented here will be less than the potential maxima. This approach is not able to model cyanobacteria toxicity, which varies by many factors and would be a more direct indicator of human health risk. Since cyanobacteria range in shape and size, there is also uncertainty in the calculations to convert from biomass to cell count. In addition, the effects of very high water temperatures (>30°C) on the growth and respiration rate of cyanobacteria are not well understood. Although the results reported here use low and high growth rate scenarios and assumptions, these may not fully capture the range of potential outcomes. Finally, this analysis only partially quantifies the economic impacts of changes in HAB risk. Valuation of the broader effects of HABs on human health and ecosystems, as well as those that may occur outside of the reservoir-focus of this analysis, would increase the damages associated with these impacts.

[196] World Health Organization, 1999: Toxic Cyanobacteria in Water: A guide to their public health consequences, monitoring and management. London: E & FN Spon. Available online at http://www.who.int/water_sanitation_health/resourcesquality/toxcyanobacteria.pdf?ua=1

9. DOMESTIC MIGRATION

9.1 KEY FINDINGS

- Warmer weather and altered precipitation patterns due to climate change are projected to influence human migration patterns. Compared to population projections assuming no climate change, changes in regional climate are projected to increase populations along the coasts and in the Midwest, and decrease populations in the Great Plains and the Gulf states of the Southeast.
- Differences in migration patterns between RCPs and climate model projections are modest. However, the overall direction and magnitude of change at regional levels are consistent across all scenarios analyzed.
- While not a dominant driver, climate is one of many factors that influence human migration in the U.S. Some of these non-climate related factors are incorporated into the migration model, while others are too complex and variable to predict.

9.2 INTRODUCTION

Domestic migration in the U.S. most often occurs when people are young adults, as they finish college, make initial career decisions, serve in the military, and form families.[197] Many factors can influence migration, including economic opportunities or recessions, availability and affordability of housing, and climate conditions. For example, people often prefer to move to places with warmer winters or cooler, less-humid summers. Recent research has found a substantial increase in U.S. households' valuation of moderate or "nice" weather's contribution to quality of life, and migration to areas with such climates is likely to continue.[198,199] Anticipating areas in the U.S. that may have population growth or decline in the near future based on changes in climate variables can help communities plan for rising demands on housing, transportation, energy infrastructure, and the many other needs of a growing population.

9.3 APPROACH

This analysis examines the effects of climate change on migration within the U.S. (at a county-scale) using the ICLUSv2 (Integrated Climate and Land Use Scenarios, version 2) model.[200] The ICLUSv2 model uses 2010 U.S. Census county-level population data and shared socioeconomic pathways[201] to project population change using assumptions about fertility, mortality, and immigration through the end of the century. ICLUSv2 includes a climate amenity value by using historic climate data and Internal Revenue Service migration data covering the 1980-1999 period. Future projections of climate change are used to update these amenity values at each time step of the migration model, enabling ICLUSv2 to reflect the current and future amenity value of climate.

---

[197] Cromartie, J., and P. Nelson, 2009: Baby Boom Migration and Its Impact on Rural America, ERR-79, U.S. Dept. of Agri., Econ. Res. Serv.

[198] Rappaport, J., 2007: Moving to nice weather. Regional Science and Urban Economics, 37, 375-398, doi: 10.1016/j.regsciurbeco.2006.11.004.

[199] Rappaport, J., 2008: Consumption amenities and city population density. *Regional Science and Urban Economics*, **38**, 533-552, doi: 10.1016/j.regsciurbeco.2008.02.001.

[200] EPA, 2017: Updates to the Demographic and Spatial Allocation Models to Produce Integrated Climate and Land Use Scenarios (Iclus) (Version 2). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-16/366F. Available online at https://cfpub.epa.gov/ncea/iclus/recordisplay.cfm?deid=322479

[201] O'Neill, B. C., E. Kriegler, K. Riahi, K. L. Ebi, S. Hallegatte, T. R. Carter, R. Mathur, and D. P. v. Vuuren, 2014: A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic Change*, **122**, 387-400, doi:10.1007/s10584-013-0905-2.

For this analysis, climate factors from the five GCMs are incorporated into the model for both RCP8.5 and RCP4.5. ICLUSv2 uses a spatial interaction model to simulate the migration of people within the U.S. (net migration into and out of a county, but not into or out of the country), and this model incorporates measures of climate as predictive variables. Specifically, the model uses mean summer (July) apparent temperature (10-year running average), mean summer (June, July, August) precipitation (10-year running average), mean winter (January) apparent temperature (10-year running average), and mean winter (December, January, February) precipitation (10-year running average). Other factors included in the model include population density, population growth rate, and developable land area. To determine the role of climate change in future migration, the results presented in this section compare differences in migration between a "no-climate change" reference projection[202] and the migration model that includes climate factors. Unlike other sectoral analyses in this Technical Report, this study does not monetize the economic effects of the projected changes in climate-driven migration. Additional information about ICLUSv2 can be found in EPA (2017).[203]

9.4 RESULTS

The results presented in this section focus on the effects of climate change on domestic migration, and do not represent broader migration trends at the international level due to non-climate factors. While changes in climate have a relatively small influence on migration in the short term, the cumulative effect of this influence has a meaningful impact over time (Figures 9.1 and 9.2). However, results show only small differences between RCP8.5 and RCP4.5 over the course of the century (Figure 9.1), and differences across the GCMs are modest[204] (see Figure A8-2 in the Appendix for GCM-specific maps). Clusters of county-scale, climate-driven emigration (negative percent changes) are more obvious in the Southern Plains, for example, on the western edges of Texas, Kansas, and Nebraska; and throughout Montana and the Southeast. Positive percent changes are clear throughout the Midwest and Northeast. Some western states like Colorado, Oregon, and Washington are projected to have overall positive percentage change trends, though select counties have negative areas. On average, the total population of Midwest, Southwest, Northeast, and Northwest was higher relative to the no-climate change model, while a decline in population is projected in the Northern Plains, Southeast, and Southern Plains by 2090 relative to the no-climate change reference (Figure 9.2).

Across all scenarios analyzed, the largest percent change for any NCA region was in the Northeast (Figures 9.1 and 9.2). By 2090 and under RCP8.5, results under the HadGEM2-ES model show the greatest increase compared to the no-climate change scenario, approximately 7%, equaling a population gain of approximately 6 million individuals. The largest population decrease compared to the no-climate change scenario was an 8.7% loss of people projected in the Southern Plains, equivalent to 5 million individuals by 2090 under RCP8.5 of the HadGEM2-ES GCM. However, it is important to note that both of these climate change-driven changes are occurring on top of underlying increases in population growth in both regions, as other non-climate factors are dominant drivers of regional population change.

---

[202] This is the population projection used throughout the CIRA2.0 modeling framework to estimate county-level population changes. In this projection, county-scale changes in population are driven by underlying shifts in demographic trends (birth rates, mortality, migration) and preferences for urban, suburban, and rural surrounding. Please see the ICLUS 2017 documentation report for additional information regarding the structure and assumptions of the ICLUSv2 model.

[203] EPA, 2017: Updates to the Demographic and Spatial Allocation Models to Produce Integrated Climate and Land Use Scenarios (Iclus) (Version 2). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-16/366F. Available online at https://cfpub.epa.gov/ncea/iclus/recordisplay.cfm?deid=322479

[204] Nationally, the choice of climate model has only minimal influence over population changes. The largest difference is in the Northern Plains, which ranges from a -4.8% change (HadGEM2-ES, RCP4.5) to a -8.0% (GISS-E2-R, RCP8.5) by 2090 (Figure 9.2). See the Appendix A.8 for additional results.

Figure 9.1. Climate Change-Induced Domestic Migration

Relative net differences in county-level population projections by RCP and year. Values represent the average percentage change across the five GCMs compared to a "no climate change" control scenario.

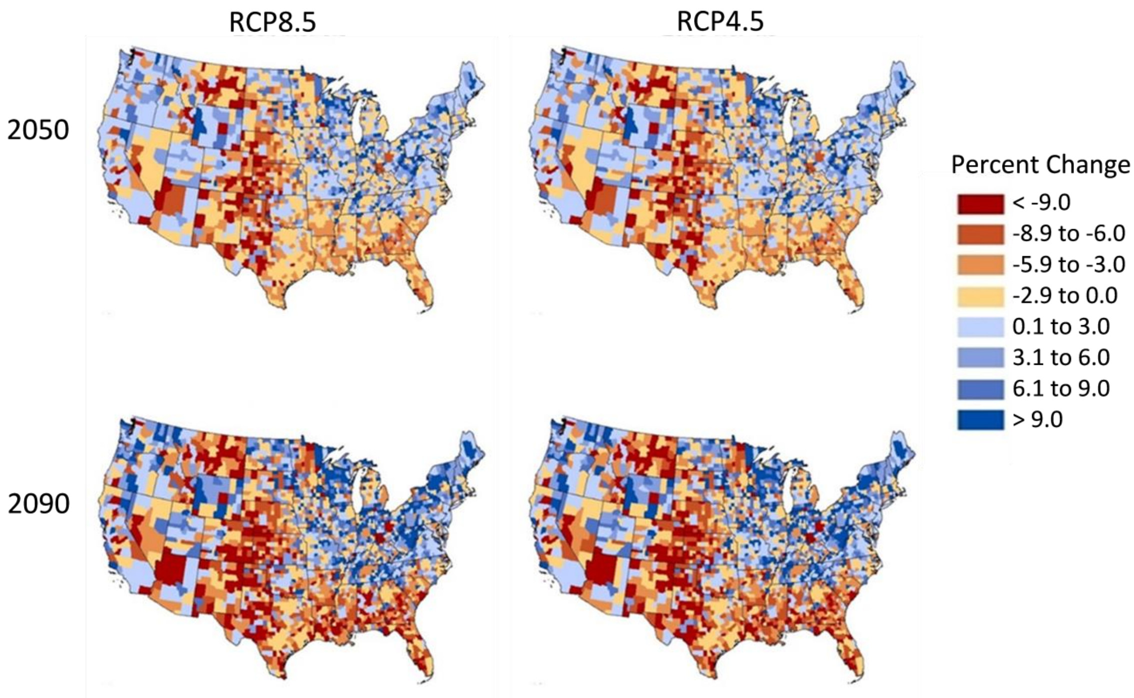
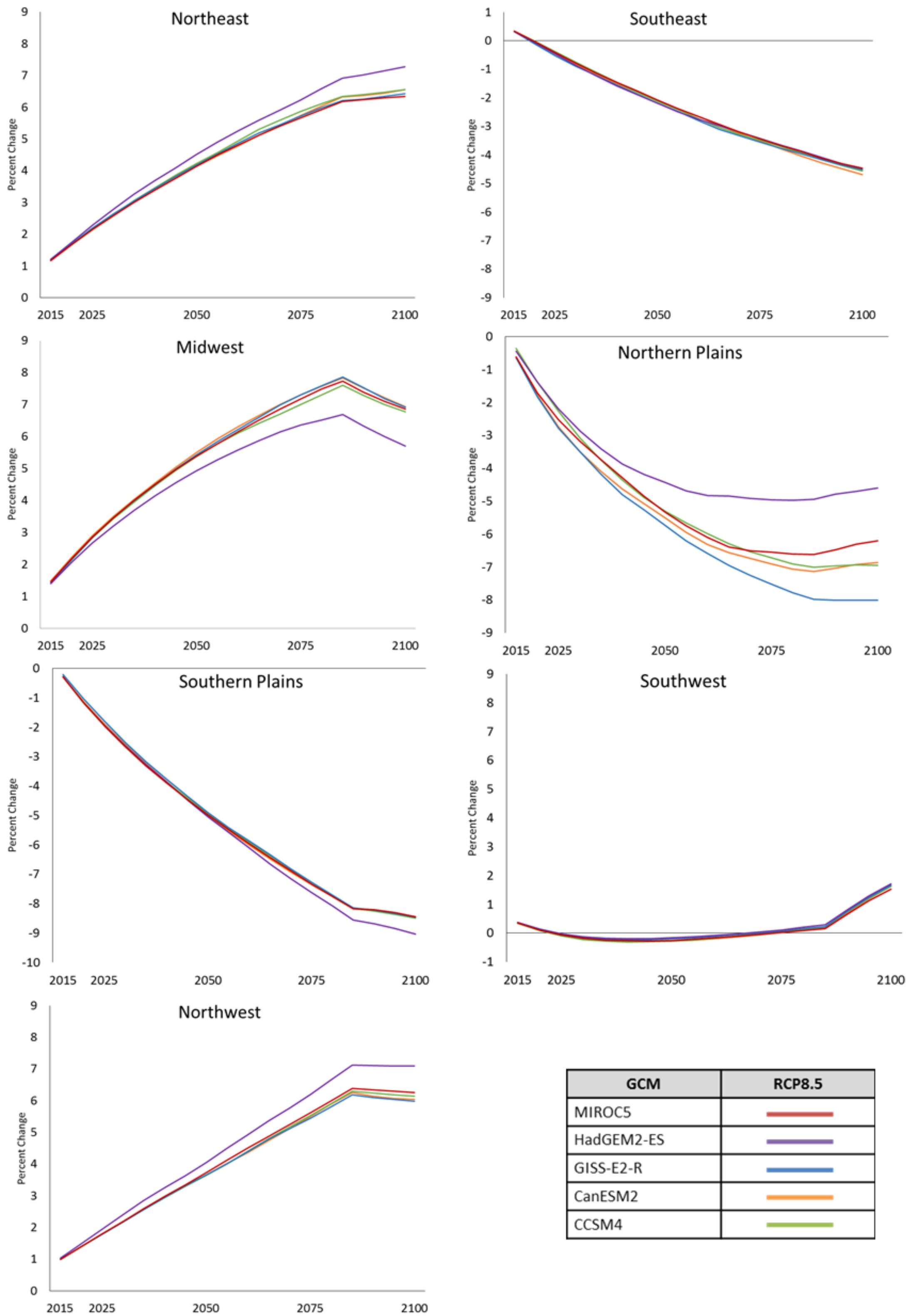


Figure 9.2. Regional Climate Change-Induced Migration

Relative net differences in projected regional population by forcing scenario and climate model. Values are expressed as the percentage change from a "no climate change" control scenario.



9.5 DISCUSSION

The findings described above suggest that climate change will influence human migration within the U.S. in the coming decades. This finding is consistent with results from other studies that have documented a link between climate and domestic migration.[205,206] However, the actual distribution is contingent upon many variables, and the ICLUSv2 model used in this analysis represents one configuration of how those variables may affect future migration. For example, land area and population density are included in the ICLUSv2 model, and have a greater influence on migration than climate change. In addition, this analysis assumes a single scenario regarding overall birth, death, and migration rates, which can be challenging to project over long time scales. Other factors not explicitly included in the model, like economic opportunity, can also influence migration patterns. Finally, this analysis also assumes that every individual will have the same response to climate change, when in reality people have unique responses to temperature and precipitation patterns based on preferences over time.

Climate change will also have other impacts beyond changing precipitation and temperature patterns which may influence population distribution. Shifting areas of vectors that can carry diseases, land loss due to sea level rise, or declining air quality[207] could increase or decrease the likelihood that people move, as well as their destination. Finally, migration is likely to change the geography of demands on housing, transportation, energy infrastructure, and the many other needs of a growing population. Using a migration model that evaluates the effect of climate change on these parameters would provide a more robust characterization of these affects.

---

[205] Sinha, P., and M.L. Cropper, 2013: The value of climate amenities: evidence from US migration decisions. Resources for the Future, Discussion paper: RFF DP 13-01.

[206] Cragg, M., and M. Kahn, 1997: New estimates of climate demand: evidence from location choice. *Journal of Urban Economics*, **42**, 261-284.

[207] USGCRP, 2016: The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment. Crimmins, A., J. Balbus, J.L. Gamble, C.B. Beard, J.E. Bell, D. Dodgen, R.J. Eisen, N. Fann, M.D. Hawkins, S.C. Herring, L. Jantarasami, D.M. Mills, S. Saha, M.C. Sarofim, J. Trtanj, and L. Ziska, Eds. U.S. Global Change Research Program, Washington, DC, 312 pp. http://dx.doi.org/10.7930/J0R49NQX

INFRASTRUCTURE

10. ROADS

10.1 KEY FINDINGS

- Climate change-driven changes in temperature and precipitation are projected to result in significant impacts to U.S. roads. Discounted, reactive adaptation costs (rehabilitation measures) are estimated at $230 billion through 2100 under RCP8.5 and $150 billion under RCP4.5, on average.
- The highest per-lane-mile reactive adaptation costs are associated with impacts on paved roads due to changes in temperature and precipitation. Changes in the freeze-thaw cycle are projected to lead to a cost savings relative to the reference period.
- Across all road types and climate stressors, proactive adaptation to protect roads against climate change-related impacts is projected to decrease costs over the century by 98% under RCP8.5 and 83% under RCP4.5.

10.2 BACKGROUND

The U.S. road network is one of the nation's most important capital assets. Roads are susceptible to damage from various climate stressors, including temperature, precipitation, and flooding. Increased temperatures can cause accelerated aging of binder material and rutting of asphalt; precipitation can cause cracking and erosion; and flooding can lead to washouts and overtopping of roads. As these climate change stressors continue to change, damages to roads and costs of maintenance and repair will vary across the U.S.[208] For example, roads may experience more frequent buckling due to increased temperatures, more frequent washouts of unpaved surfaces from increased flooding, and changes in freeze-thaw cycles that cause cracking.[209]

10.3 APPROACH

The analysis estimates the costs of reactive adaptation measures resulting from climate change impacts to roads in the contiguous U.S. and evaluates the ability of proactive adaptation measures (i.e., modification of roads prior to the occurrence of climate change-related damages) to improve resiliency and reduce costs. To develop these estimates, the analysis relies on the Infrastructure Planning Support System (IPSS), a software tool that integrates stressor-response algorithms, engineering data on the U.S.

---

[208] Schwartz, H. G., M. Meyer, C. J. Burbank, M. Kuby, C. Oster, J. Posey, E. J. Russo, and A. Rypinski, 2014: Ch. 5: Transportation. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 130-149. doi:10.7930/J06Q1V53.

[209] Transportation Research Board, 2008: Potential Impacts of Climate Change on U.S. Transportation. Special Report 290, Committee on Climate Change and U.S. Transportation, National Research Council of the National Academies.

road network, and the climate projections described in the Modeling Framework section of this Technical Report.[210,211] The IPSS tool estimates the potential impacts related to three climate stressors (temperature, precipitation,[212] and timing of freeze-thaw cycles[213]) for three road types (paved, unpaved, and gravel), as summarized in Table 10.1, and quantifies the costs of reactive adaptation in the form of maintenance activities required to ensure current levels of service.[214] These costs represent the incremental change in expenditures associated with projected climate change relative to the reference period (1950-2013) as modeled by the five GCMs under RCP8.5 and RCP4.5. In addition, many parts of the U.S. road network are under-maintained today, which can increase their vulnerability to climate change. This analysis focuses on the additional impacts due to climate change independent of this underlying vulnerability.

The IPSS tool also quantifies the costs of proactive adaptation measures to protect and rehabilitate roads against impacts caused by climate stressors, where applicable. The differences between the costs of proactive adaptation measures and the costs of reactive adaptation measures to address climate change-related impacts represent the effects of proactive adaptation for the roads sector.[215] For more information on the approach, please refer to Chinowsky and Arndt (2012), Espinet et al. (2016), and Neumann et al. (2014).[216,217,218]

---

[210] Schweikert, A., P. Chinowsky, X. Espinet, and M. Tarbert, 2014: Climate change and infrastructure impacts: comparing the impact on roads in ten countries through 2100. *Procedia Engineering*, **78**, 306-316.

[211] Chinowsky, P., A. Schweikert, G. Hughes, C.S. Hayles, N. Strzepek, K. Strzepek, and M. Westphal, 2015: The impact of climate change on road and building infrastructure: a four-country study. *International Journal of Disaster Resilience in the Built Environment*, **6**, 382-396.

[212] The hydrologic movement of water across a road surface, also known as overtopping due to a flooded waterway, is not directly modeled in this analysis.

[213] Freeze-thaw related impacts affect the sub-surface components of roads while temperature-related damage is limited to the surface.

[214] To maintain service, the level of maintenance applied can vary over time, and can therefore be larger or smaller than the historic level from the reference period.

[215] The analysis assumes that for a given climate stressor, proactive adaptation prevents the need for future climate-induced maintenance.

[216] Chinowsky, P. and C. Arndt, 2012: Climate Change and Roads: A Dynamic Stressor–Response Model. *Review of Development Economics*, **16**, 448-462.

[217] Espinet, X., A. Schweikert, N. van den Heever, and P. Chinowsky, 2016: Planning resilient roads for the future environment and climate change: quantifying the vulnerability of the primary transport infrastructure system in Mexico. *Transport Policy*, **50**, 78-86.

[218] Neumann, J.E., J. Price, P. Chinowsky, L. Wright, L. Ludwig, R. Streeter, R. Jones, J.B. Smith, W. Perkins, L. Jantarasami, and J. Martinich, 2014: Climate change risks to US infrastructure: impacts on roads, bridges, coastal development, and urban drainage. *Climatic Change,* **131**, 97-109.

Table 10.1. Summary of Modeled Damages and Proactive Adaptation Measures for U.S. Roads

Climate Stressor	Road Type	Impacts	Response Measures
Temperature	Paved	Surface degradation and increased roughness due to thermal cracking and rutting.	Change asphalt mix to include binder with appropriate temperature performance.
	Unpaved	Not Modeled*	N/A
	Gravel	Not Modeled*	N/A
Precipitation	Paved	Erosion of base and sub-base due to infiltration as well as increased cracking.	Modify binder/sealant application and increase depth of base layer.
	Unpaved	Erosion of surface and development of rutting.	Upgrade to gravel or paved road.^
	Gravel	Erosion of base due to subsidence resulting in uneven surface.	Increase thickness of gravel and sub-base to improve strength and allow for better drainage.
Freeze-Thaw	Paved	Degradation of base layer due to soil heaving, and increased surface damage due to settling and movement.	Modify design to increase surface density and reduce infiltration.
	Unpaved	Not Modeled*	N/A
	Gravel	Not Modeled*	N/A

*The effects of the temperature and freeze-thaw climate stressors on gravel and unpaved roads are likely inconsequential and are therefore not modeled.

^While the accepted method for adapting unpaved roads is to upgrade to a paved surface, newer and potentially less-costly approaches exists that are not widely established, and therefore not included in the modeling.

10.4 RESULTS

Through the end of the century, climate change is projected to result in $230 billion and $150 billion in reactive adaptation costs to U.S. roads under RCP8.5 and RCP4.5, respectively (2015-2099, $2015, discounted at 3%, five-GCM average). Across the five climate models, cumulative costs range from $59 to $530 billion under RCP8.5 and from $75 to $350 billion under RCP4.5. The largest impacts are estimated under the HadGEM2-ES model, which are the hottest climate projections analyzed, while the smallest impacts are seen under the coolest model, GISS-E2-R. As shown in Table 10.2, reactive adaptation costs are dominated by paved roads and are higher under RCP8.5 than under RCP4.5 in all but one of the five models (GISS-E2-R). On a per-lane-mile basis, projected costs are highest for paved roads ($37,000 under RCP8.5 and $24,000 under RCP4.5), followed by gravel roads ($4,500 under RCP8.5 and $3,800 under RCP4.5) and unpaved roads ($2,200 under RCP8.5 and $1,800 under RCP4.5).

Table 10.2. Cumulative Change in Reactive Adaptation Costs

The table presents the estimated change in reactive adaptation costs for the period 2015-2099 relative to the reference period (1950-2013) (billions $2015, discounted at 3%, five-GCM average).

GCM	Road Type	RCP8.5	RCP4.5
CanESM2	Paved	$160	$67
	Gravel	$7.7	$5.0
	Unpaved	$3.7	$2.4
	TOTAL	**$170**	**$75**
CCSM4	Paved	$240	$150
	Gravel	$2.9	$1.7
	Unpaved	$1.4	$0.9
	TOTAL	**$250**	**$150**
GISS-E2-R	Paved	$50	$74
	Gravel	$6.4	$8.0
	Unpaved	$3.1	$3.9
	TOTAL	**$59**	**$86**
HadGEM2-ES	Paved	$510	$340
	Gravel	$9.4	$9.1
	Unpaved	$4.5	$4.4
	TOTAL	**$530**	**$350**
MIROC5	Paved	$120	$74
	Gravel	$3.5	$1.1
	Unpaved	$1.7	$0.6
	TOTAL	**$130**	**$75**
5-GCM Average	**Paved**	**$220**	**$140**
	Gravel	**$6.0**	**$5.0**
	Unpaved	**$2.9**	**$2.4**
	TOTAL	**$230**	**$150**

Figure 10.1 presents the estimated annual per-lane-mile reactive adaptation costs in 2050 and 2090 at the regional level, broken down by climate stressor and RCP. Temperature-related impacts dominate in all regions, particularly in the Northeast, Southeast, and Midwest, and are consistently higher under RCP8.5 compared to RCP4.5. Impacts related to precipitation are smaller, but generally increase from 2050 to 2090. Partially offsetting these impacts, the freeze-thaw stressor is projected to result in negative costs (savings) compared to the reference period in all regions and under all scenarios. This is

due to the projected shift in freeze zone status for a large portion of the country, from moderate-freeze to no-freeze zones. The shift in these areas significantly reduces the maintenance costs for freeze-thaw costs relative to the reference period. As shown in Figure 10.1, these savings are projected to be particularly high in the Northeast. Although not shown in the figure, the largest total reactive adaptation costs are projected to occur in the Southeast and Midwest, which is partially due to the comparatively higher number of lane miles in these regions and also to greater climate stress.

Figure 10.1. Change in Annual Per-Lane-Mile Reactive Adaptation Costs

The graphs show changes in reactive adaptation costs in 2050 (2040-2059) and 2090 (2080-2099) relative to the reference period (1950-2013). Results represent the five-GCM average and are presented in thousands of $2015, undiscounted.

Potential for Adaptation to Reduce Impacts

Table 10.3 presents the cumulative change in costs for 2015-2099 relative to reference period (1950-2013) with reactive and proactive adaptation. Across all stressors and road types, proactive adaptation is projected to decrease costs by 98% under RCP8.5 and 83% under RCP4.5 relative to the scenario with reactive adaptation. For paved roads, proactive adaptation reduces temperature-related costs by 68% and 59% under RCP8.5 and RCP4.5, respectively, and reduces precipitation-related costs by 58% and 47%, respectively. For gravel and unpaved roads, precipitation-related costs are higher with proactive adaptation than with reactive adaptation. This is because the options for proactively adapting unpaved roads to increased precipitation risks are limited to upgrading the roads to paved or gravel, which are both very expensive. Proactive adaptation for gravel roads is also very expensive, as it essentially involves reconstructing the road with enhanced structural capacity. Costs associated with the freeze-thaw stressor do not change significantly between the reactive and proactive adaptation scenarios. In the proactive adaptation scenario, total, cumulative, discounted costs are higher under RCP4.5 than under RCP8.5 because the freeze-thaw related savings are greater under RCP8.5.

Table 10.3. Cumulative Change in Costs with Reactive and Proactive Adaptation

The table presents cumulative change in costs with reactive and proactive adaptation for the 2015-2099 period relative to the reference period (1950-2013) in billions $2015, discounted at 3%, for the five-GCM average.

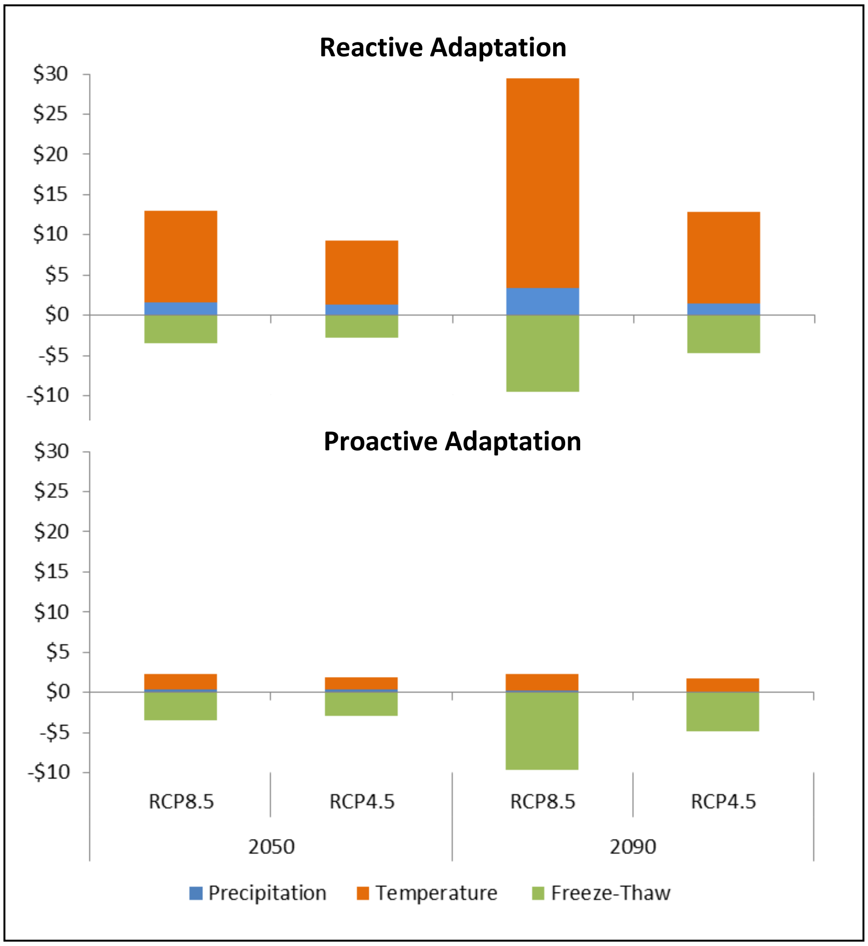
	RCP8.5		RCP4.5	
	Reactive Adaptation	Proactive Adaptation	Reactive Adaptation	Proactive Adaptation
Temperature				
Paved	$300	$95	$190	$78
Gravel	N/A*	N/A*	N/A*	N/A*
Unpaved	N/A*	N/A*	N/A*	N/A*
Subtotal	**$300**	**$95**	**$190**	**$78**
Freeze-Thaw				
Paved	-$120	-$120	-$77	-$80
Gravel	N/A*	N/A*	N/A*	N/A*
Unpaved	N/A*	N/A*	N/A*	N/A*
Subtotal	**-$120**	**-$120**	**-$77**	**-$80**
Precipitation				
Paved	$37	$15	$30	$16
Gravel	$6	$7	$5	$6
Unpaved	$3	$6	$2	$6
Subtotal	**$46**	**$28**	**$37**	**$28**
Total				
Paved	$220	-$8	$140	$14
Gravel	$6	$7	$5	$6
Unpaved	$3	$6	$2	$6
TOTAL	**$230**	**$5**	**$150**	**$26**

*The effects of the temperature and freeze-thaw climate stressors on gravel and unpaved roads are likely inconsequential and are therefore not modeled.

Figure 10.2 shows the change in total projected costs in 2050 and 2090 relative to the reference period with reactive and proactive adaptation, distributed across climate stressors. Temperature- and precipitation-related costs are significantly reduced in the proactive adaptation scenario relative to the reactive adaptation scenario, while freeze-thaw related savings do not change significantly between the two scenarios.

Figure 10.2. Change in Annual Costs for U.S. Roads with Reactive and Proactive Adaptation

The graphs present the change in annual costs for reactive and proactive adaptation in 2050 (2040-2059) and 2090 (2080-2099) relative to the historic reference period (1950-2013) in billions $2015, undiscounted, for the five-GCM averages.



10.5 DISCUSSION

The analysis estimates that climate change will result in increased costs of maintaining, repairing, and replacing roads, which is consistent with the findings of the assessment literature.[219] In particular, the analysis projects high costs associated with temperature- and precipitation-related impacts to paved roads. Total annual costs in 2090 are estimated at $20 billion under RCP8.5 and $8.1 billion under RCP4.5 ($2015, undiscounted, five-GCM average). With well-timed proactive adaptation, the analysis projects savings of $7.3 billion under RCP8.5 and $3 billion under RCP4.5 compared to the reference period. A previous study using a similar approach and different climate scenarios found that the estimated costs through 2100 were $10 billion under a high emissions scenario and $2.6 billion under a

[219] Schwartz, H. G., M. Meyer, C. J. Burbank, M. Kuby, C. Oster, J. Posey, E. J. Russo, and A. Rypinski, 2014: Ch. 5: Transportation. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 130-149. doi:10.7930/J06Q1V53.

global GHG mitigation scenario (discounted at 3%).[220] The difference between the current results and these previous estimates reflect two key differences between the two analyses. First, the savings reflected in the current results are due to the changes in the freeze-thaw stressor, as described above, which were modeled differently in the previous analysis. Second, the climate models used in the previous analysis project significantly wetter conditions across the U.S. compared to the models used in the current analysis, resulting in larger precipitation-related costs for unpaved roads.

The large reductions in costs due to proactive adaptation in this study are estimated under a scenario assuming well-timed and effective adaptation. As described in the Approach section, examples of proactive adaptation strategies include changing asphalt mixes to use binders with better temperature performance, or using gravel on unpaved roads that are subject to increasingly heavy precipitation. This proactive scenario is useful for evaluating how costs related to climate change impacts could be reduced. It is worthwhile to note, however, that the timing of road maintenance is important, and delays or deferred maintenance can decrease the potential effectiveness of adaptation, yielding smaller reductions in total costs than those reported under the proactive adaptation scenario which assumes well-timed investments to maintain levels of service.

Implementation of well-timed adaptation measures to maintain service levels is a potentially overly optimistic assumption given that infrastructure investments are oftentimes delayed and underfunded. Significant cases of delayed maintenance can result in road closure, which would lead to large public costs (e.g., increased travel time) not reported here. In addition, for unpaved roads, the effects of changes in precipitation are likely dependent on the amount of traffic on the road, which is not explicitly captured in the analysis. However, advancements in technology and changes in driving behavior are not directly modeled in the analysis, and could have long-term implications on the vulnerability of the road network to climate change. Lastly, among the three climate stressors examined in the analysis, freeze-thaw is the most complex and the most uncertain. The analysis assumes that areas fall neatly into climate zones with specific freeze-thaw risks (i.e., no-freeze or moderate-freeze) and that road maintenance decisions are made accordingly. In reality, areas that are close to the border between no-freeze and moderate-freeze zones will need to manage for some freeze events, which would lead to larger costs than those reported here. Specifically, there is a 61-70% increase in maintenance costs from no-freeze zones to moderate-freeze zones, so the cost for no-freeze zones can increase quickly if freeze events do in fact occur.

[220] EPA, 2015: Climate Change in the United States: Benefits of Global Action. U.S. Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-15-001.

11. BRIDGES

11.1 KEY FINDINGS

- By 2050, an estimated 4,600 inland bridges across the contiguous U.S. are projected to become vulnerable each year under RCP8.5. Under RCP4.5, this estimate is reduced to 2,500. By 2090, 6,000 bridges are projected to become vulnerable each year under RCP8.5, while 5,000 would be vulnerable under RCP4.5.
- National average annual proactive maintenance or rehabilitation costs under RCP8.5 are estimated at $1.7 billion by 2050 and $1.0 billion by 2090. Costs are reduced under RCP4.5 to $1.5 billion each year in 2050 and $510 million each year in 2090.

11.2 INTRODUCTION

Road bridges are a central component of the U.S. transportation system. With the average U.S. bridge now over 40 years old, however, vehicles cross structurally deficient bridges over 2 million times a day.[221] Similar to other transportation infrastructure, bridges are vulnerable to a range of threats from climate change.[222] Currently, most bridge failures caused by extreme events are due to scour, where swiftly moving water removes sediment from around bridge structural supports, weakening or destroying their foundations.[223] Increased flooding and long-term river flow changes caused by climate change are expected to increase the frequency of bridge scour, further stressing the aging U.S. transportation system.

11.3 APPROACH

The analysis estimates impacts on inland bridges that span bodies of water in the contiguous U.S. resulting from projected changes in peak flows from 100-year, 24-hour precipitation events in two future eras: 2050 (2035-2064) and 2090 (2070-2099),[224] as modeled by five GCMs under RCP8.5 and RCP4.5. Using data from the National Bridge Inventory, this method quantifies the costs associated with two levels of perfect-foresight responses for bridges determined to be vulnerable as a result of climate change: (1) the application of riprap to stabilize bridges, and (2) the strengthening of bridge piers and abutments with additional concrete. The analysis assumes that riprap is required when projected peak flows from a 100-year, 24-hour storm increase by 20%. Concrete strengthening is required when peak flows increase by 60% for bridges on non-sandy soils and by 100% for bridges on sandy soils. This study requires an estimate of peak flows from rainfall events and simulation of nonlinear watershed processes, accounting for watershed land use, soil type, and topography. The method adopted is the

---

[221] DOT, cited 2017: National Bridge Inventory. United States Department of Transportation, Federal Highway Administration. Available online at https://www.fhwa.dot.gov/bridge/nbi.cfm

[222] Schwartz, H. G., M. Meyer, C. J. Burbank, M. Kuby, C. Oster, J. Posey, E. J. Russo, and A. Rypinski, 2014: Ch. 5: Transportation. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 130-149. doi:10.7930/J06Q1V53.

[223] Briaud J.L., Hunt B.E. (2006) Bridge scour and the structural engineer. Structure December:58–61.

[224] The era referred to as 2090 is not centered on 2090 because the climate data was only available through 2099 and therefore the 30-year period required for the analysis had to begin in 2070.

U.S. Department of Agriculture's Natural Resources Conservation Service TR-20 model, used to convert 24-hour rainfall "design-storm" depths to peak flows, consistent with Wright et al. (2012).[225,226]

Based on the projections of bridge vulnerability, the analysis evaluates a response scenario in which bridges are proactively rehabilitated to avoid service disruption caused by climate-induced changes in extreme river flow.[227] Projected costs in this scenario include the costs of riprap installation and concrete strengthening based on engineering data from the reference period. Importantly, this analysis assumes perfect foresight, in that bridges are only rehabilitated if they are known to be threatened by a near-term river flow level that crosses one of the thresholds described above. This scenario may underestimate potential bridge damages, as the costs of proactive, well-timed rehabilitation are likely far lower than the costs associated with repairing or reconstructing bridge failures, and because this analysis does not estimate the damages associated with delays or disruption from loss of use. Also, this analysis focuses on the incremental effects due to climate change, and does not estimate the additional costs associated with retrofitting bridges that were structurally vulnerable in the reference period (i.e., there may be deficient bridges that are not projected to be rehabilitated because the climate projections do not suggest that they will be subjected to damaging high river flows).

For more information on the CIRA approach and results for the bridges sector, please refer to Neumann et al. (2014)[228] and Wright et al. (2012).[229]

11.4 RESULTS

Figure 11.1 shows the estimated percentage of bridges identified as vulnerable to climate change in each four-digit HUC of the contiguous U.S. In 2050 (2035-2064), the majority of HUCs across the U.S. are projected to contain 20% or fewer vulnerable bridges under both RCPs. By 2090 (2070-2099), there are a greater number of HUCs with 40% or more vulnerable bridges, particularly under RCP8.5. Table 11.2 summarizes the annual numbers of vulnerable bridges by region. By 2050, approximately 4,600 bridges are projected to be vulnerable each year under RCP8.5.[230] Under RCP4.5, this number is reduced by 46% to 2,500. Under both RCPs, the Southeast is projected to experience the highest number of vulnerable bridges in 2050, followed by the Midwest. By 2090, 6,000 bridges are projected to be vulnerable each year under RCP8.5, and this number is reduced to 5,000 per year under RCP4.5.[231] The Midwest is projected to experience the highest number of vulnerable bridges in 2090 under both RCPs.

---

[225] Wright, L., P. Chinowsky, K. Strzepek, R. Jones, R. Streeter, J. Smith, J. Mayotte, A. Powell, L. Jantarasami, and W. Perkins, 2012: Estimated effects of climate change on flood vulnerability of U.S. bridges. *Mitigation and Adaptation Strategies for Global Change*, **17**, 939-955, doi: 10.1007/s11027-011-9354-2.

[226] For this analysis, the ratio of peak precipitation that is used as an input to TR-20 is slightly different than past applications; it reflects identification of a 100-yr, 24-hour storm over a longer period (1980-2009; 30 years rather than 20 years) and also by fitting an extreme value Type 1 (Gumbel) distribution to the 30 year set of annual maximum precipitation values. The use of an extreme value Type 1 distribution differs from past applications, such as Wright et al. (2012), which have used the Log Pearson Type III distribution. The update in method for identifying the 100-year 24-hr precipitation event in each HUC reflects a desire to better match, and to not statistically overfit, the statistical characteristics of the precipitation distributions.

[227] Bridge overtopping, whereby extreme river flows rise higher than bridge decks, are an important effect not directly modeled in this analysis.

[228] Neumann, J., J. Price, P. Chinowsky, L. Wright, L. Ludwig, R. Streeter, R. Jones, J.B. Smith, W. Perkins, L. Jantarasami, and J. Martinich, 2014: Climate change risks to U.S. infrastructure: impacts on roads, bridges, coastal development, and urban drainage. *Climatic Change*, **131**, 97-109, doi: 10.1007/s10584-013-1037-4.

[229] Wright, L., P. Chinowsky, K. Strzepek, R. Jones, R. Streeter, J. Smith, J. Mayotte, A. Powell, L. Jantarasami, and W. Perkins, 2012: Estimated effects of climate change on flood vulnerability of U.S. bridges. *Mitigation and Adaptation Strategies for Global Change*, **17**, 939-955, doi: 10.1007/s11027-011-9354-2.

[230] Across the contiguous U.S., the analysis models impacts on a total of 440,000 bridges.

[231] The same bridge may be considered vulnerable in both 2050 and 2090; for example, a bridge may be subject to peak flows that surpass the threshold for riprap strengthening in 2050, and then in 2090 it may become subject to peak flows surpassing the threshold for concrete strengthening.

Figure 11.1. Percentage of Bridges Identified as Vulnerable to Climate Change

Estimated percentage of bridges in each four-digit HUC of the contiguous U.S. identified as vulnerable under each RCP in 2050 (2035-2064) and 2090 (2070-2099).

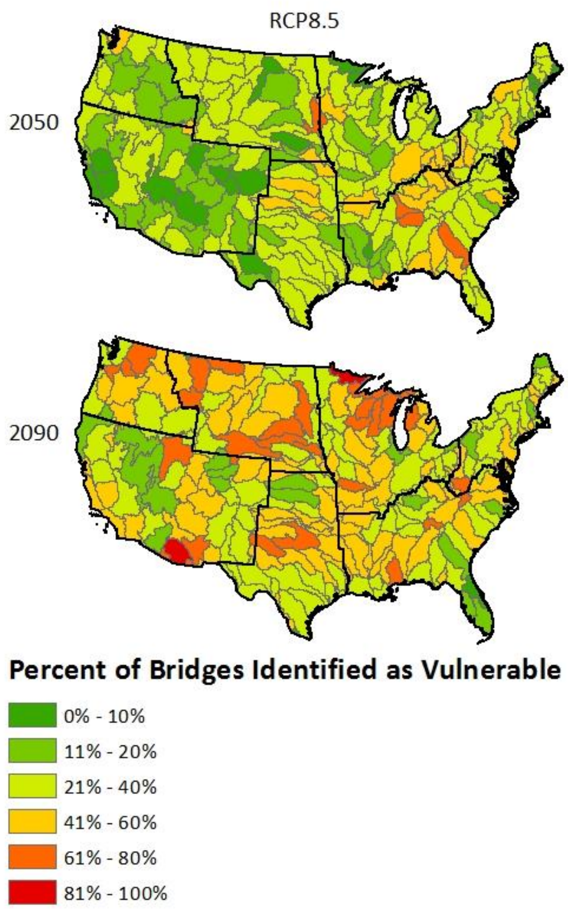


Table 11.1. Projected Number of Vulnerable Bridges per Year

Estimated number of bridges in each region identified as vulnerable each year by 2050 (2035-2064) and 2090 (2070-2099) under each RCP. Values represent averages of the five GCMs. Totals may not sum due to rounding.

	2050		2090	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Northeast	510	350	570	390
Southeast	1,400	750	1,600	1,200
Midwest	1,300	600	1,700	1,500
Northern Plains	260	160	410	430
Southern Plains	810	420	1,100	1,000
Southwest	160	120	360	260
Northwest	120	83	200	160
National Total	**4,600**	**2,500**	**6,000**	**5,000**

Table 11.2 presents the average proactive maintenance costs in 2050 and 2090. For the five-GCM average, annual costs under RCP8.5 are estimated at $1.7 billion by 2050 and $1.0 billion by 2090. Projected annual costs are reduced under RCP4.5 to $1.5 billion in 2050 and $510 million in 2090. Costs are smaller in 2090 than in 2050 under both RCPs because many bridges require repairs due to climate changes by 2050, and once repaired, are less susceptible to extreme river flow impacts in 2090. Of the five GCMs, GISS-E2-R, HadGEM2-ES, and MIROC5 project the highest impacts and CCSM4 projects the lowest impacts.

Table 11.2. Projected Proactive Maintenance Costs to U.S. Bridges Across Climate Models

Average annual costs (millions) in the contiguous U.S. in 2050 (2035-2064) and 2090 (2070-2099) (undiscounted, $2015).

GCM	2050		2090	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5
CanESM2	$1,700	$1,500	$1,100	$560
CCSM4	$950	$1,100	$670	$310
GISS-E2-R	$1,500	$1,500	$1,300	$390
HadGEM2-ES	$2,000	$1,700	$1,100	$740
MIROC5	$2,200	$1,600	$800	$530
5-GCM Average	**$1,700**	**$1,500**	**$1,000**	**$510**

Table 11.3 presents the estimated proactive maintenance costs at national and regional levels. At a national scale, projected proactive maintenance costs under RCP8.5 are estimated at $1.4 billion per year by 2050 and $1.1 billion by 2090, while under RCP4.5 costs are reduced to $1.2 billion per year by 2050 and $590 million by 2090. The Midwest and the Southeast incur the highest adaptation costs to maintain bridge service in both eras under both RCPs. Proactive maintenance costs are projected to be the smallest in the Northern Plains and Northwest, mostly due to the smaller number of bridges in those regions. Across the majority of regions, impacts are reduced under RCP4.5 relative to RCP8.5 (Table 11.3).

Table 11.3. Regional Proactive Maintenance Costs for Vulnerable Bridges

Average annual costs (millions) by region in 2050 (2035-2064) and 2090 (2070-2099) for the five-GCM average (undiscounted, $2015).

	2050		2090	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Northeast	$220	$180	$120	$77
Southeast	$430	$340	$300	$150
Midwest	$430	$390	$270	$110
Northern Plains	$89	$91	$42	$25
Southern Plains	$300	$300	$180	$83
Southwest	$120	$95	$54	$37
Northwest	$83	$71	$31	$22
National Total	**$1,700**	**$1,500**	**$1,000**	**$510**

11.5 DISCUSSION

The findings regarding near-term bridge vulnerability and proactive maintenance costs due to unmitigated climate change are consistent with the findings of the assessment literature,[232] but this work provides quantification of those risks in a consistent manner for a full lower 48 state domain. It is important to consider several limitations of the analysis. The analysis considers the effects of climate change on inland bridges, not coastal bridges, and also focuses only on high streamflow risks, and not other climatic stresses (e.g., extreme temperature) or synergistic effects of climate with other stresses, and therefore is likely an underestimate of future impacts of climate change on the nation's total bridge inventory. In addition, although there will likely be significant changes to the nation's bridges over the course of the century—some bridges will be strengthened for reasons separate from climate change risks, some will deteriorate, some will be removed, and new bridges will be added—this analysis estimates costs based on the existing bridge inventory in its current state. Further, this analysis assumes that proactive, well-timed adaptation will be taken to maintain the current level of bridge service. In reality, some bridges will likely fail in the future due to a combination of delayed maintenance and inadequate design to address future climate risks, resulting in loss of use and the associated public costs,

[232] Schwartz, H. G., M. Meyer, C. J. Burbank, M. Kuby, C. Oster, J. Posey, E. J. Russo, and A. Rypinski, 2014: Ch. 5: Transportation. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 130-149. doi:10.7930/J06Q1V53.

such as increased traffic and delays. Finally, the adaptation option evaluated here only consider a class of actions that could reduce physical impacts at the bridge facility. Other adaptation options to reduce the consequences of those physical impacts – such as re-routing of road traffic or building in other forms of network flexibility – could also be considered, and might in some cases be more cost-effective than bridge strengthening.

12. RAIL

12.1 KEY FINDINGS

- Increasing temperatures are projected to result in significant damages to the U.S. rail system. In response to increased risks of rail cracking, rail operators will be forced to reduce speeds, causing economic damages associated with delays to freight and passenger rail. Average cumulative discounted damages through 2100 are estimated at $50 billion under RCP8.5 and $40 billion under RCP4.5.
- Well-timed proactive adaptation is projected to reduce average cumulative discounted costs through 2100 to $12 billion under RCP8.5 and $4.5 billion under RCP4.5.

12.2 BACKGROUND

The U.S. rail network is a critical component of the nation's infrastructure system, connecting U.S. consumers with agricultural, economic, logistics, and manufacturing centers across the nation and the world.[233] Climate change affects the rail network principally through projected temperature increases across the U.S. Passenger and freight tracks are susceptible to damage during periods of extreme heat, which are expected to increase in frequency as a result of climate change. Specifically, when exposed to temperatures outside of the range of normal operating conditions, steel rail expands and can undergo a displacement or buckling called a "sun kink," increasing the risk of derailments and leading to costly maintenance expenditures and train delays.

12.3 APPROACH

The purpose of the analysis it to determine the potential risk of climate change to the Class I rail network in the U.S., which comprises 140,000 rail miles operated by seven railroad companies and carrying both freight and passenger trains.[234] To model the existing rail network, the analysis relies on geospatial data from the National Transportation Atlas Database (NTAD) for active main line and sub main line track.[235] Average daily train traffic volume is estimated based on highway-rail crossing data from the Federal Railroad Administration's (FRA's) Office of Safety Analysis.[236,237]

The analysis uses the Infrastructure Planning Support System (IPSS) tool, which incorporates engineering knowledge, stressor-response algorithms, and climate projections, to quantify potential vulnerabilities to the rail system resulting from climate change.[238] The tool quantifies the costs of reactive adaptation and proactive adaptation under RCP8.5 and RCP4.5 and for each of the five GCMs, and represent impacts above and beyond what is spent on periodic maintenance. The reactive adaptation costs are

---

[233] DOT, cited 2016: Freight Rail Overview. United States Department of Transportation, Federal Railroad Administration. Available online at https://www.fra.dot.gov/Page/P0528

[234] DOT, cited 2016: Freight Rail Today. United States Department of Transportation, Federal Railroad Administration. Available online at https://www.fra.dot.gov/Page/P0362

[235] DOT, cited 2016: Bureau of Transportation Statistics: National Transportation Atlas Databases 2015. [Available online at: http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_atlas_database/2015/index.html]

[236] FRA's Office of Safety Analysis provides data on daily highway-rail crossings for over 150,000 unique highway-rail crossings. Based on these data, the study estimated the average daily volume of train traffic per grid cell.

[237] DOT, cited 2016: Highway-Rail Crossings. United States Department of Transportation, Federal Railroad Administration, Office of Safety Analysis. Available online at http://safetydata.fra.dot.gov/OfficeofSafety/publicsite/Query/gxrtally1.aspx

[238] Chinowsky, P., and C. Arndt, 2012: Climate change and roads: a dynamic stressor-response model. *Review of Development Economics*, **16**, 448-462, doi: 10.1111/j.1467-9361.2012.00673.x

associated with delays resulting from increased temperatures under climate change, as current rail safety guidelines require reduced speed and traffic in areas where extreme temperatures are occurring or predicted. Delays are first quantified in minutes and then converted to dollars using a methodology that estimates the cost of delays for freight trains to the railroad company and the public.[239] The costs of delays include costs to the railroad companies (including the costs of crew, cars, locomotives, lading, and fuel), and costs to the public include costs of locomotive emissions attributed to additional operational time and car traffic delay at railroad crossings.[240]

The study also quantifies the costs of proactive adaptation measures that reduce the risk of rail line damage and the associated temperature-based delays.[241] The proactive adaptation measure modeled is the FRA-proposed installation and use of temperature sensors to identify the times and locations when speed and traffic reductions are required due to local conditions.[242] This is in contrast to the current practice of widespread restrictions over a predetermined number of hours, which corresponds to a broader set of delays. For more information on the approach to estimating impacts on rail infrastructure, please see Chinowsky et al. (2017).[243]

12.4 RESULTS

The projected cumulative reactive adaptation costs to the U.S. rail network are substantial, estimated at $50 billion under RCP8.5 and $40 billion under RCP4.5 for the five-GCM average (2016-2099, $2015, discounted at 3%). Table 12.1 shows the projected annual reactive adaptation costs for 2050 and 2090 for the five GCMs and the five-GCM average. As shown, costs are consistently higher in 2090 than in 2050 under both RCPs and across all five models. For the five-GCM average, annual costs in 2090 are $5.5 billion and $3.5 billion (undiscounted $2015) under RCP8.5 and RCP4.5, respectively. Projected costs are largest under the HadGEM2-ES model and smallest under the GISS-E2-R model, which, respectively, represent the hottest and coolest GCMs of the five analyzed.

---

[239] Lovett, A.H., C.T. Dick, and C.P. Barkan, 2015: Determining freight train delay costs on railroad lines in North America. In: Proceedings of the International Association of Railway Operations Research (IAROR) 6th International Conference on Railway Operations Modelling and Analysis, Tokyo, Japan. Available online at http://railtec.illinois.edu/articles/Files/Conference%20Proceedings/2015/Lovett-et-al-2015-IAROR.pdf

[240] The analysis quantifies the costs of conventional pollutants excluding CO_2.

[241] In this scenario with proactive adaptation, impacts include both the costs of the adaptation measure as well as any damages resulting from climate change that are not prevented by proactive adaptation.

[242] Kish, A. and G. Samavedam, 2013: Track Buckling Prevention: Theory, Safety Concepts, and Applications. United States Department of Transportation, Federal Railroad Administration. Technical Report No. DOT/FRA/ORD-13/16. Available online at https://www.fra.dot.gov/eLib/details/L04421

[243] Chinowsky, P., J. Helman, S. Gulati, J. Neumann, and J. Martinich, 2017: Impacts of Climate Change on Operation of the US Rail Network. *Transport Policy*. doi: 10.1016/j.tranpol.2017.05.007.

Table 12.1. Projected Annual Reactive Adaptation Costs to the U.S. Rail System

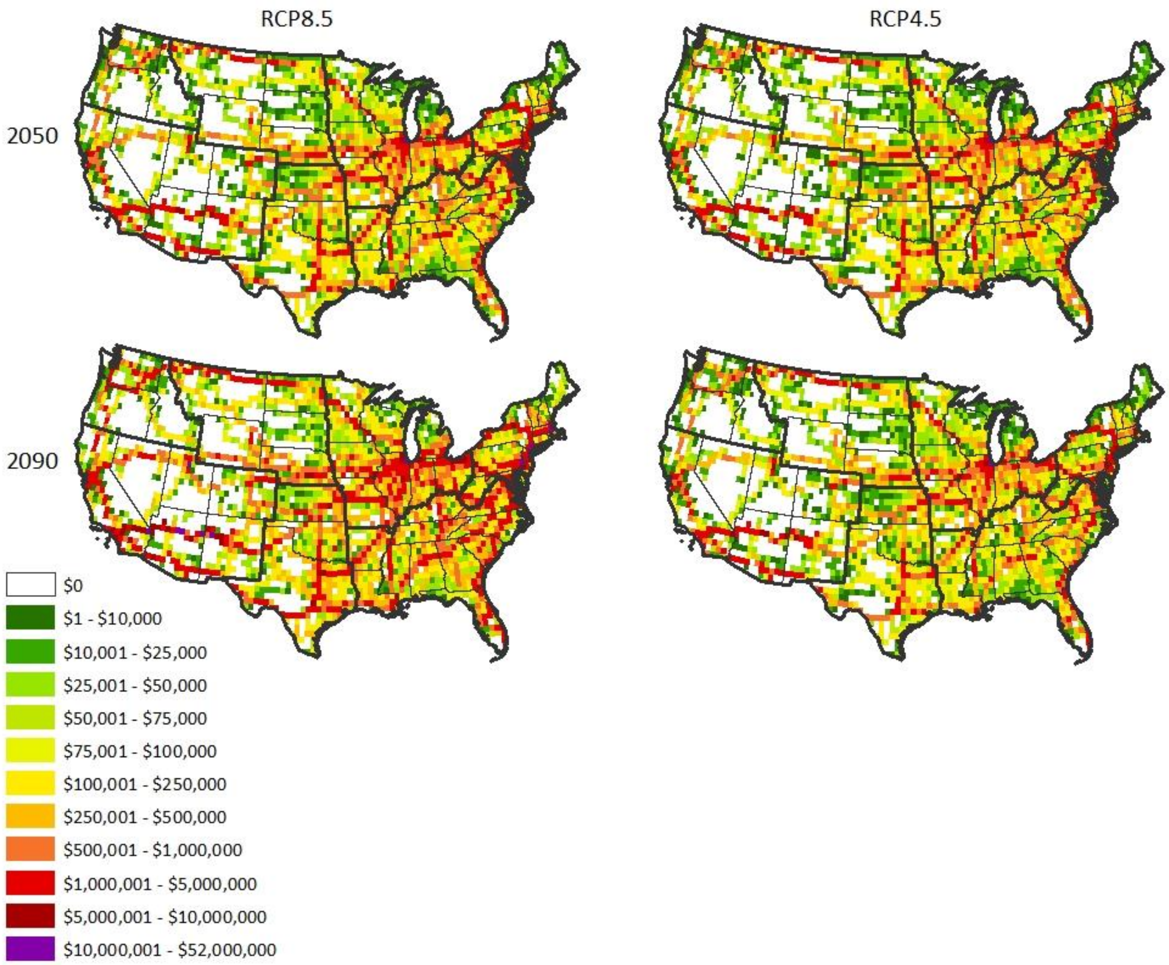
The table presents the change in reactive adaptation costs in 2050 (2040-2059) and 2090 (2080-2099) relative to the reference period (1950-2013) (billions $2015, undiscounted).

	2050		2090	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5
CanESM2	$1.9	$1.6	$6.1	$3.8
CCSM4	$1.7	$1.3	$5.1	$3.2
GISS-E2-R	$1.3	$1.1	$4.0	$2.4
HadGEM2-ES	$2.2	$1.8	$6.6	$4.4
MIROC5	$1.6	$1.6	$5.8	$3.7
5-GCM Average	**$1.8**	**$1.5**	**$5.5**	**$3.5**

Figure 12.1 displays the average annual reactive adaptation costs in 2050 and 2090 under both RCPs at the half-degree grid cell level (approximately 34 square miles). The white areas in the maps represent areas where no Class I rail is present in addition to where the costs of climate change are estimated to be near zero. The highest projected costs are mainly concentrated in the Northeast, Midwest, and Southwest, particularly under RCP8.5. These impacts are due to the relatively higher rail network density and/or the projected increases in temperature relative to the temperature at which the rails were designed to operate.

Figure 12.1. Average Annual Reactive Adaptation Costs to the U.S. Rail Network

The maps display the change in reactive adaptation costs relative to the reference period (1950-2013) for the five-GCM average ($2015, undiscounted) in 2050 (2040-2059) and 2090 (2080-2099).



Potential for Proactive Adaptation to Reduce Impacts

As described in the Approach section, the analysis also quantifies the impacts of climate change on the rail system in a scenario where proactive adaptation measures are implemented to reduce the temperature-delay effect on the rail system. Table 12.2 shows the estimated cumulative costs of climate change by region with reactive and proactive adaptation.[244] As shown, impacts are reduced significantly at the national level when proactive adaptation measures are taken. For the five-GCM average, estimated cumulative costs are reduced from $50 billion to $12 billion (77%) under RCP8.5 and from $40 billion to $4.5 billion (89%) under RCP4.5, for savings of $39 billion and $35 billion, respectively. At the regional level, reactive adaptation costs are highest in the Southeast and Southern Plains under both

[244] As described in the Approach section, impacts in the scenario with proactive adaptation include both the costs of making proactive adaptation measures and the climate-change related damages that are not prevented by the modeled adaptation.

RCPs. Proactive adaptation reduces these costs by 73% and 79%, respectively, under RCP8.5 and by 84% and 91%, respectively, under RCP4.5.

Table 12.2. Projected Cumulative Costs to U.S. Rail with Reactive and Proactive Adaptation

The table presents the cumulative reactive and proactive adaptation costs to the U.S. rail system by region for the period 2016-2099 relative to the reference period (five-GCM average, billions $2015, discounted at 3%).

	Total Costs (Billions $2015)		Costs Per Rail Mile (Thousands $2015)	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Reactive Adaptation				
Northeast	$8.7	$7.1	$410	$330
Southeast	$10	$7.7	$260	$200
Midwest	$4.6	$3.6	$100	$78
Northern Plains	$1.4	$1.0	$85	$62
Southern Plains	$14	$11	$620	$500
Southwest	$6.5	$5.2	$170	$130
Northwest	$5.2	$4.1	$600	$470
National Total	**$50**	**$40**	**$290**	**$230**
Proactive Adaptation				
Northeast	$1.6	$0.55	$77	$26
Southeast	$2.8	$1.2	$72	$31
Midwest	$0.63	$0.24	$14	$5
Northern Plains	$0.53	$0.23	$33	$14
Southern Plains	$2.9	$1.0	$130	$44
Southwest	$1.4	$0.60	$72	$30
Northwest	$1.6	$0.72	$180	$82
National Total	**$12**	**$4.5**	**$67**	**$26**

12.5 DISCUSSION

This analysis projects significant costs for the U.S. rail system associated with both reactive adaptation to increasing temperatures under climate change, which is consistent with the assessment literature.[245] Depending on the climate scenario selected and climate model used, the increase in cumulative reactive adaptation costs relative to the reference period range from $27 to $62 billion by 2099 (discounted at 3%) (see Appendix A.9). The study suggests that the use of sensor technology combined with changes in operating policy could reduce delays by limiting temperature-based speed restrictions for specific locations. These proactive adaptations could reduce costs to $1.1 to $26 billion by 2099 (discounted at 3%), depending on the climate scenario and model used.

Although national-scale analysis of climate change impacts on rail has not been done in the U.S., a recent study suggests that costs of climate-change related delays are projected to increase significantly across Europe under RCP8.5.[246] The study projects that Southern Europe will experience the highest increased risk for rail track buckling.

The proactive adaptation evaluated in this study is not the only approach to reduce train delays caused by climate change. Continuing innovations in track management and potential changes in track materials may provide additional opportunities. In addition, since rail lines must be replaced every 50 to 60 years, there may be scheduled opportunities to use more resilient infrastructure. Rail lines that anticipate implementing new rail technologies, such as high-speed rail, or that focus on specific types of freight, may implement new technologies optimized for those options.

Although the focus of this study was on temperature effects, additional climate change considerations can affect the vulnerability of the rail system. Precipitation changes could result in flooding that affect bridge or railbed stability, and thus require additional investment to stabilize the infrastructure. Similarly, increased threats from wildfires and hurricanes could exacerbate potential vulnerabilities.

---

[245] Schwartz, H.G., M. Meyer, C.J. Burbank, M. Kuby, C. Oster, J. Posey, E. J. Russo, and A. Rypinski, 2014: Ch. 5: Transportation. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J.M. Melillo, Terese (T.C.) Richmond, and G.W. Yohe, Eds., U.S. Global Change Research Program, 130-149. doi:10.7930/J06Q1V53.

[246] Nemry, F. and H. Demirel, 2012: Impacts of Climate Change on Transport: A focus on road and rail transport infrastructures. JRC Scientific and Policy Reports. European Commission. Available online at http://ftp.jrc.es/EURdoc/JRC72217.pdf

13. ALASKA INFRASTRUCTURE

13.1 KEY FINDINGS

- Under RCP8.5, climate-driven reactive adaptation costs (repairs to maintain service) to Alaska infrastructure are estimated at $4.5 billion through 2100 (cumulative, discounted). Under RCP4.5, cumulative reactive adaptation costs are reduced to $3.7 billion.
- The distribution of reactive adaptation costs varies across the state, with the largest effects projected for the interior and south central regions of Alaska.
- Road flooding associated with increased precipitation is projected to be the largest source of reactive adaptation costs, followed by impacts to buildings associated with permafrost thaw. Smaller costs are estimated for airports, railroads, and pipelines.
- Well-timed, proactive adaptation is projected to dramatically reduce total economic impacts relative to the reactive adaptation scenario.

13.2 BACKGROUND

In recent decades, the rate of temperature rise across the Arctic has been twice the global average. Sea and land ice has diminished, while coastal erosion and permafrost thaw have increased.[247] Climate change increases the vulnerability of infrastructure by creating additional strains on structures beyond what is expected from normal conditions and use. Permafrost thaw and subsequent ground subsidence, particularly where permafrost is ice-rich, negatively affect buildings, roads, railroads, pipelines, and oil and gas infrastructure. Warmer temperatures can also alter the frequency of freeze-thaw cycles, affecting foundations and underground infrastructure stability. As climate change continues, the extent of infrastructure damage, as well as the costs to maintain, replace, and adapt the built environment, are expected to rise.

13.3 APPROACH

This analysis estimates two types of adaptation costs associated with climate change impacts to public infrastructure in Alaska:

- Reactive adaptation- in the form of rehabilitation and repairs to infrastructure in response to climate-driven damages, with the goal of maintaining current levels of service and ensuring that infrastructure is functional through its intended lifespan. The estimated reactive adaptation costs represent the incremental change in maintenance costs due to climate change relative to those simulated for the baseline period (1950-1999). Many parts of the Alaskan public infrastructure network are under-maintained today, which can increase overall vulnerability to climate change. However, this analysis focuses on the additional impacts due to climate change independent of this underlying vulnerability.
- Proactive adaptation- in the form of investments and modifications of infrastructure to improve its resiliency and reduce vulnerability prior to the occurrence of climate change-related damages. This approach assumes that well-designed, well-timed adaptation measures are taken early in the

[247] Christensen, J.H., K. Krishna Kumar, E. Aldrian, S.-I. An, I.F.A. Cavalcanti, M. de Castro, W. Dong, P. Goswami, A. Hall, J.K. Kanyanga, A. Kitoh, J. Kossin, N.-C. Lau, J. Renwick, D.B. Stephenson, S.-P. Xie and T. Zhou, 2013: Climate Phenomena and their Relevance for Future Regional Climate Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

century and continue to provide economic benefits into later eras. Proactive adaptation cost estimates represent both the costs of the adaptive actions and repair costs associated with impacts that are not avoided by proactive adaptation.

The reactive and proactive adaptation costs are estimated using the Infrastructure Planning Support System (IPSS) software tool, which integrates stressor-response algorithms, engineering data on the Alaska public infrastructure network, and climate projections.[248,249] For this analysis, IPSS analyzes the following specific infrastructure assets: roads, buildings, airports, railroads, and pipelines.[250] The numbers, locations, and levels of use of these infrastructure types were compiled from numerous sources to create the inventory of public infrastructure used for this analysis. The IPSS model accounts for climate change impacts unique to northern latitudes, including near-surface permafrost thaw, extreme freeze-thaw dynamics, and the effects of precipitation and precipitation-induced flooding. Due to unique climate conditions and infrastructure present in Alaska, these infrastructure types are separately modeled and reported from those for the contiguous U.S. (see Roads and Rail sections).

The analysis uses the SNAP Alaska climate projections[251,252] described in the Modeling Framework section of this Technical Report. Reactive and proactive adaptation costs are estimated for 2030 (2020-2039), 2050 (2040-2059), 2070 (2060-2079), and 2090 (2080-2099), and represent the incremental change in expenditures associated with projected climate change for each relevant environmental stressor and infrastructure type analyzed.[253] As such, the effect of climate change can be isolated from maintenance costs in the reference period (1950-1999). IPSS simulations were aggregated to the scale of Alaska boroughs, which are shown in Figure 13.1. For more information on the approach used in this analysis, please refer to Melvin et al (2016).[254]

---

[248] Schweikert, A., P. Chinowsky, X. Espinet, and M. Tarbert, 2014: Climate change and infrastructure impacts: comparing the impact on roads in ten countries through 2100. *Procedia Engineering*, **78**, 306-316.

[249] Chinowsky, P., A. Schweikert, G. Hughes, C.S. Hayles, N. Strzepek, K. Strzepek, and M. Westphal, 2015: The impact of climate change on road and building infrastructure: a four-country study. *International Journal of Disaster Resilience in the Built Environment*, **6**, 382-396.

[250] The approach described in Melvin et al. (2016) also developed a novel approach to generate first-order estimates of projected coastal erosion rates and evaluated how alternative climate scenarios may influence erosion in twelve coastal communities where immediate actions to manage erosion or relocate have been recommended. Because this coastal erosion component did not feed into the economic damage calculations, these results are not included in this Technical Report.

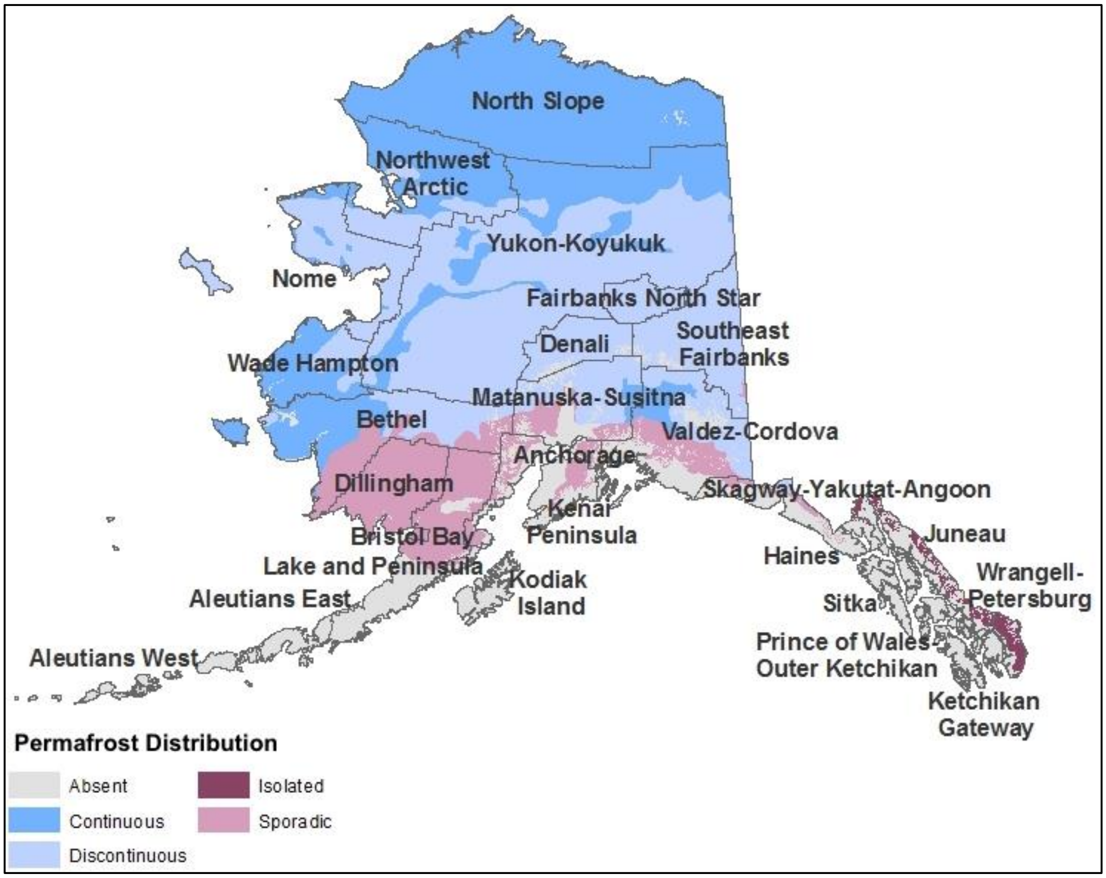
[251] Climate variables used include projected minimum and maximum annual temperature, precipitation, and change in mean annual ground temperature, which were then used to project active layer thickness, compared to reference period permafrost and ground ice content.

[252] As noted in the Modeling Framework section, the SNAP downscaled database contains projections for five climate models, two of which (CCSM4 and GISS-E2-R) overlap with the five LOCA GCMs applied throughout the other sectors of this Technical Report. The results presented in this section represent the mean results for CCSM4 and GISS-E2-R only, and therefore differ modestly from the results of the five SNAP models reported in Melvin et al. (2016).

[253] For some infrastructure-type/climate-stressor combinations, no adaptation measures are modeled.

[254] Melvin, A.M., P. Larsen, B. Boehlert, J.E. Neumann, P. Chinowsky, X. Espinet, J. Martinich, M.S. Baumann, L. Rennels, A. Bothner, D.J. Nicolsky, and S.S. Marchenko, 2016: Climate change damages to Alaska public infrastructure and the economics of proactive adaptation. *Proceedings of the National Academies of Sciences*, doi:10.1073/pnas.1611056113.

Figure 13.1. Distribution of Current Permafrost across Alaska's Boroughs



13.4 RESULTS

The reactive adaptation (repair) cost estimates presented in this section represent the incremental change in expenditures due to climate change that are required to maintain current levels of service and allow infrastructure to be functional through its intended lifespan. Total cumulative reactive adaptation costs resulting from projected climate change this century are estimated at approximately $4.5 billion under RCP8.5 and $3.7 billion under RCP4.5 (Table 13.1). Under RCP8.5 and RCP4.5, flooding (associated with changes in precipitation) accounts for about 44% and 46%, respectively, of costs while near-surface permafrost thaw is responsible for 38% and 35%, respectively. Repair costs from precipitation account for about 17% and 19%, respectively, of cumulative costs. The largest total costs are projected for roads ($2.5 billion and $2.1 billion for RCP8.5 and RCP4.5, respectively) and buildings ($1.5 billion and $1.3 billion, respectively). However, the environmental stressors responsible for the reactive costs differ, with approximately 75% of road damages caused by flooding and 85% of building damages by near-surface permafrost thaw under both RCPs. Airports, railroads, and pipelines account for a smaller fraction of the overall public infrastructure inventory, which contributed to considerably lower projected reactive adaptation costs, collectively accounting for less than 12% of total costs under both RCPs. Figure 13.2 shows the regional distribution of cumulative costs through 2100, while Figure 13.3 shows projected annual costs by infrastructure type for four future time periods.

Table 13.1. Costs under Reactive and Proactive Adaptation

Cumulative costs are presented for the period 2015-2099 for each infrastructure type and environmental stressor considered (millions $2015, discounted at 3%). Values may not sum due to rounding.

Reactive Adaptation (Repair) Costs						
	RCP	**Flooding**	**Permafrost Thaw**	**Precipitation**	**Freeze-Thaw**	**Total**
Roads	RCP8.5	$1900	$100	$530	-$13	**$2500**
	RCP4.5	$1600	-$1	$490	-$16	**$2100**
Buildings	RCP8.5	Not Modeled	$1300	$120	Not Modeled	**$1500**
	RCP4.5		$1100	$110		**$1300**
Airports[†‡]	RCP8.5	$150	$140	$100	-$4	**$380**
	RCP4.5	$120	$97	$92	-$4	**$310**
Railroads	RCP8.5	Not Modeled	$130	Not Modeled	Not Modeled	**$130**
	RCP4.5		$30			**$30**
Pipelines	RCP8.5	Not Modeled	$15	Not Modeled	Not Modeled	**$15**
	RCP4.5		-$4			**-$4**
Total	**RCP8.5**	**$2000**	**$1700**	**$750**	**-$17**	**$4500**
	RCP4.5	**$1700**	**$1300**	**$690**	**-$20**	**$3700**

Proactive Adaptation Costs*						
	RCP	**Flooding**	**Permafrost Thaw**	**Precipitation**	**Freeze-Thaw**	**Total**
Roads	RCP8.5	$320	Reactive[‡]	$320	Reactive[‡]	**$730**
	RCP4.5	$300		$310		**$590**
Buildings	RCP8.5	Not Modeled	Reactive[‡]	$5.6	Not Modeled	**$1400**
	RCP4.5			$5.1		**$1100**
Airports[†]	RCP8.5	$44	Reactive[‡]	$71	Reactive[‡]	**$250**
	RCP4.5	$44		$64		**$200**
Railroads	RCP8.5	Not Modeled	Reactive[‡]	Not Modeled	Not Modeled	**$130**
	RCP4.5					**$30**
Pipelines	RCP8.5	Not Modeled	Reactive[‡]	Not Modeled	Not Modeled	**$15**
	RCP4.5					**-$4**
Total	**RCP8.5**	**$360**	**$1700**	**$400**	**-$17**	**$2500**
	RCP4.5	**$340**	**$1300**	**$380**	**-$20**	**$2000**

[*]Includes the sum of the costs for proactively adapting those infrastructure units where impacts are projected to occur, plus any impacts incurred to infrastructure units where adaptation was not applied. For infrastructure type-climate stressor combinations where adaptation was not modeled, the reactive adaptation cost estimates were used in the calculations shown in the total columns in the 'Proactive Adaptation Costs' section.

[†]Airports values include the sum of expenditures for airport buildings and runways.

[‡]Proactive adaptation costs were quantified for these infrastructure types, however, adaptation was found to be more expensive than reactive adaptation repairs, and therefore, reactive values are used when calculating total costs.

Figure 13.2. Cumulative Reactive Adaptation Costs to Infrastructure by Borough

Cumulative costs (2015-2099, discounted at 3%) to infrastructure and per capita costs for each borough across Alaska under RCP8.5 and RCP4.5.

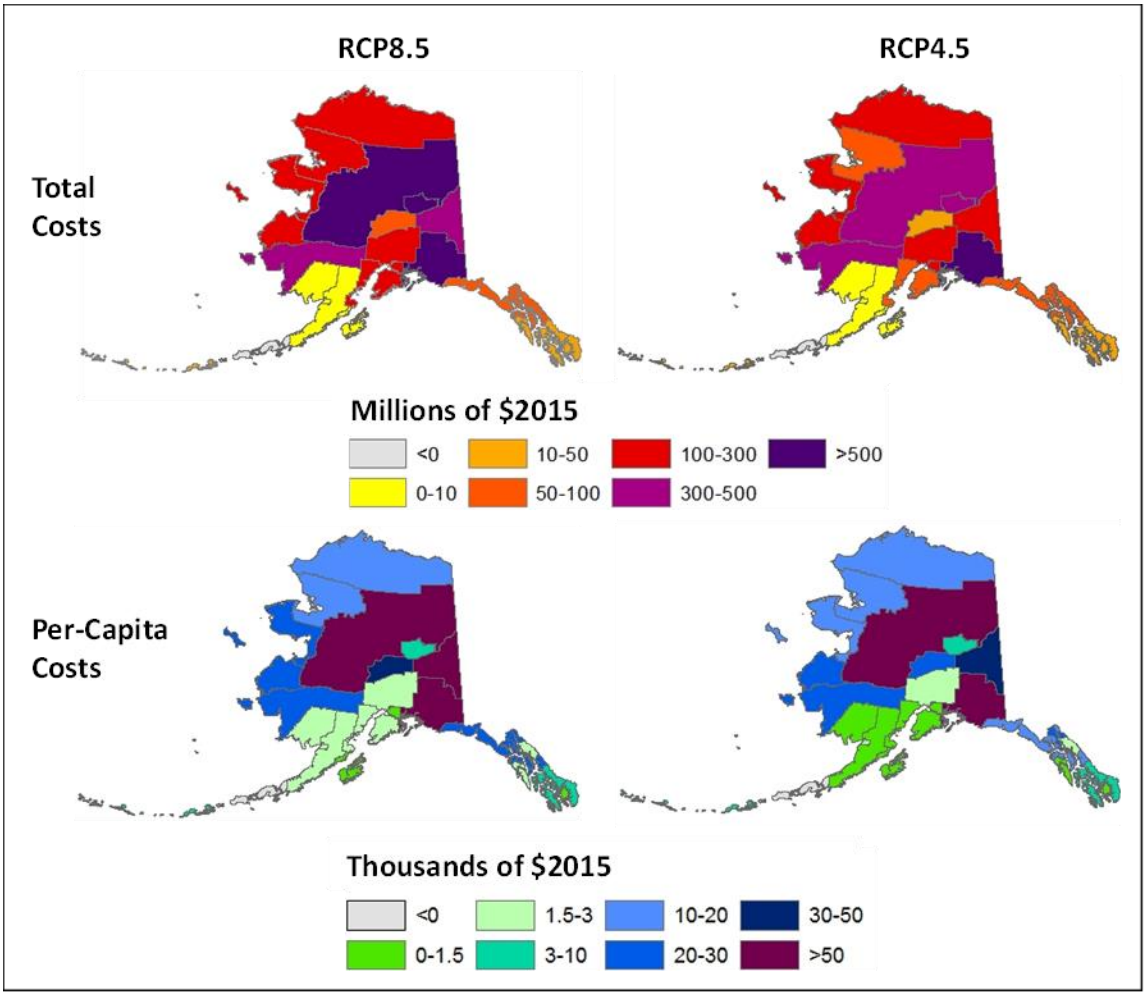
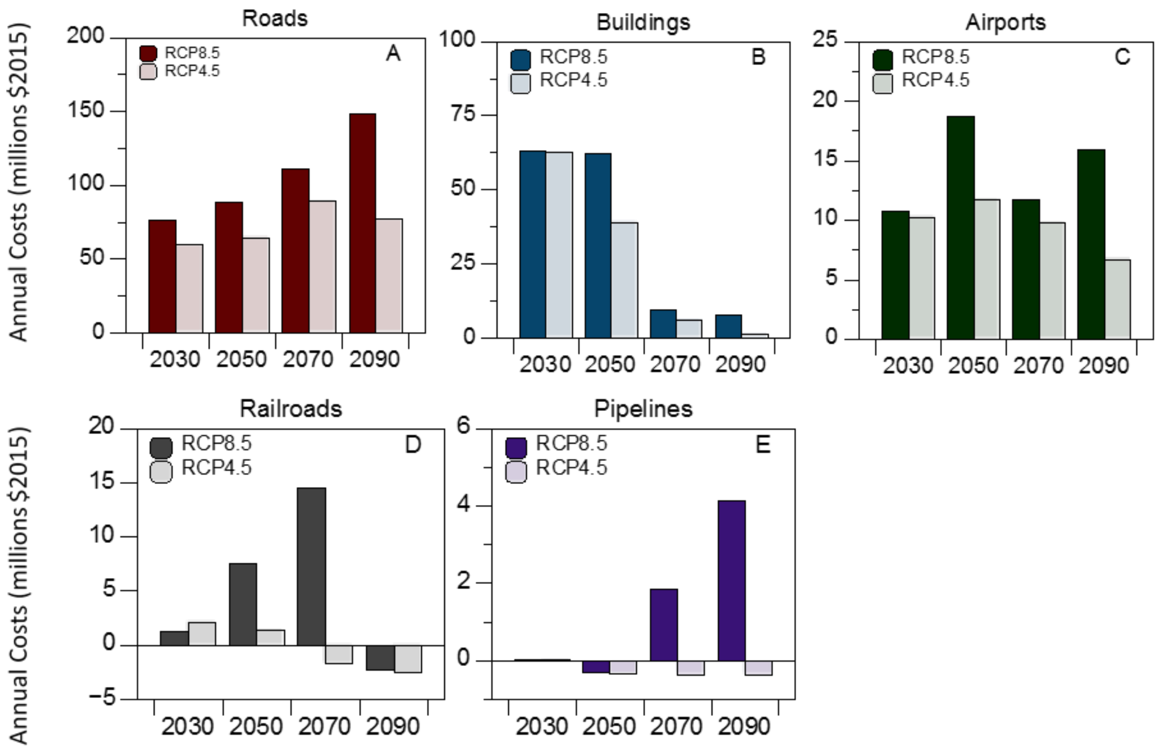


Figure 13.3. Projected Annual Reactive Adaptation Costs by Infrastructure Type

Annual costs to each infrastructure type (roads, A; buildings, B; airports, C; railroads, D; and pipelines, E) for the four study eras and two RCPs. Values represent the mean annual undiscounted costs for the twenty years included in each time period. Note the difference in scale among panels.

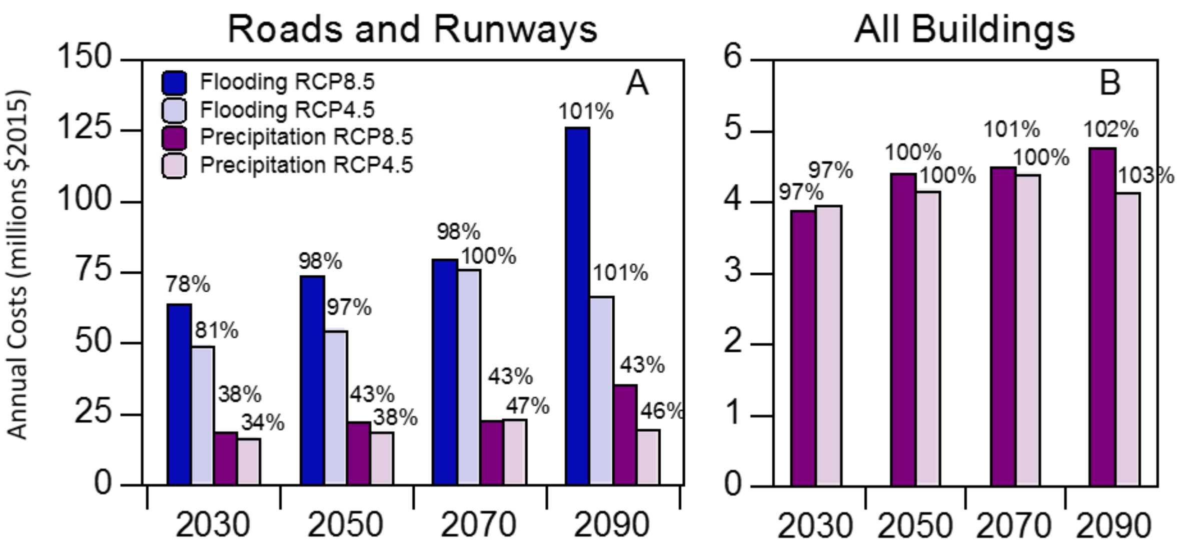


Proactive adaptation to flooding (modeled for roads and runways) and precipitation (modeled for roads, buildings, and airport buildings and runways) reduces the expected cumulative impacts of climate change this century for both RCPs (Table 13.1). Total cumulative impacts assuming proactive adaptation are estimated to be $2.5 billion under RCP8.5 and $2.0 billion under RCP4.5. The benefits of proactive adaptation are largest for flooding to roads, with a projected reduction in expenditures of $1.6 and 1.3 billion under RCP8.5 and RCP4.5, respectively, this century. Proactive adaptation to precipitation nearly halves the total expenses to roads and also provides a large reduction in estimated building expenses, although the reactive adaptation costs to buildings are relatively small. In contrast, there are limited cost-effective options for adapting infrastructure to near-surface permafrost thaw. The analysis considered permafrost thaw-related adaptation costs for roads, runways, and railroads, and determined that adapting is more expensive than incurring climate-related damages.

Figure 13.4 presents the effect of proactive adaptation by infrastructure type across four time periods. Proactive adaptation costs are smaller than estimated reactive costs for the environmental stressors (flooding and precipitation) and infrastructure types shown.

Figure 13.4. Effect of Adaptation on Vulnerability

Annual reactive adaptation costs to roads and runways (A) and buildings (B) from flooding (blue) and precipitation (purple) under the two RCPs. Percentages represent the percent savings in expenditures from proactive adaptation compared to mean estimated reactive costs. Percentages greater than 100 indicate instances where estimated proactive adaptation costs fell below the reference period maintenance costs. Note the difference in scale between panels.



13.5 DISCUSSION

Damages to Alaska public infrastructure from climate change are projected to be large and widespread. This analysis did not estimate impacts to ports, electricity transmission structures, telecommunications, and other infrastructure types, whose inclusion would provide a more comprehensive evaluation of potential vulnerabilities and associated damages. Quantification of loss of use impacts would also inform estimates of potential damages, and could be particularly meaningful in Alaska where there is a lack of infrastructure redundancy across most of the state.

Many previous assessments and studies have recognized the risks of permafrost thaw to infrastructure in Alaska;[255, 256] however, few studies have sought to quantify the physical and economic risks to multiple infrastructure types in response to a broad list of climate stressors. The results presented for this sector are similar in both direction and magnitude to other studies that have projected climate-related increases in costs in Alaskan infrastructure. Those studies project an estimated $50 million

[255] Chapin, F. S., III, S. F. Trainor, P. Cochran, H. Huntington, C. Markon, M. McCammon, A. D. McGuire, and M. Serreze, 2014: Ch. 22: Alaska. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 514-536, doi:10.7930/J00Z7150.

[256] U.S. Arctic Research Commission, 2003: Climate change, permafrost, and impacts on civil infrastructure. U.S. Arctic Research Commission, Permafrost Task force Report, Special Report 01-03. Available online at https://storage.googleapis.com/arcticgov-static/publications/other/permafrost.pdf

annually in costs by 2080 from a subset of climate stressors for the roads and electricity sectors,[257] and approximately $7.3-15 billion through 2080 (note cumulative estimate) above 'normal' operations and maintenance due to permafrost thaw, flooding, and coastal erosion impacts on a variety of infrastructure types.[258]

[257] Cole, H., V. Colonell, and D. Esch, 1999: The Economic Impact and Consequences of Global Climate Change on Alaska's Infrastructure. In Assessing the Consequences of Climate Change for Alaska and the Bering Sea Region, summarized workshop proceedings (Center for Global Change and Arctic System Research, University of Alaska Fairbanks), pp 43-57.

[258] Larsen, P.H., S. Goldsmith, O. Smith, M. Wilson, K. Strzepek, P. Chinowsky, and B. Saylor, 2008: Estimating future costs for Alaska public infrastructure at risk from climate change. *Global Environmental Change-Human and Policy Dimensions*, **18**, 442-457.

14. URBAN DRAINAGE

14.1 KEY FINDINGS

- Climate change is projected to result in costs for adapting urban drainage infrastructure to increased runoff associated with more intense rainfall events.
- Under RCP8.5, annual average adaptation costs of 10-, 25-, and 50-year storms in 100 major U.S. cities in 2090 are estimated at $2.5, $3.9, and $5.6 billion, respectively. Projected costs in 2090 under RCP4.5 are lower ($1.6, $2.7, and $4.1, respectively). Inclusion of all U.S. cities would likely increase costs.
- Under both RCP8.5 and RCP4.5, projected weighted average costs for a 50-year storm event are highest in the Southern Plains at $460,000 and $230,000 per square mile, respectively. High adaptation costs are also projected for 50-year storm events in the Southeast under RCP8.5 ($380,000 per square mile).

14.2 BACKGROUND

Urban drainage systems capture and treat stormwater runoff and prevent urban flooding. During storm events, the volume of runoff flowing into drainage systems and the ability of these systems to manage runoff depend on a variety of site-specific factors, such as the imperviousness of the land area in the drainage basin. Changes in storm intensity associated with climate change have the potential to overburden drainage systems, which may lead to flood damage, disruptions to local transportation systems, discharges of untreated sewage to waterways, and increased human health risks from waterborne illness and fish kills.[259] In areas where precipitation intensity increases significantly, adaptation investments may be necessary to prevent runoff volumes from exceeding system capacity.

14.3 APPROACH

The analysis estimates the costs of proactive adaptation for urban drainage systems in 100 major coastal and non-coastal cities of the contiguous U.S. to meet future demands of increased runoff associated with more intense rainfall under climate change. Adaptive actions focus on the use of best management practices to limit the quantity of runoff entering stormwater systems and maintain current level of service (i.e., proactive adaptation to avoid damages), instead of expanding formal drainage networks of basins and conveyance systems. These best management practices generally include temporary storage above or below ground (e.g., bioswails, retention ponds), or infiltration (e.g., permeable pavement), and are based on EPA guidelines and construction cost estimates.[260]

While many site-specific factors influence the effect of climate change on a given drainage system, this analysis uses a streamlined approach that allows for the assessment of potential impacts in multiple U.S. cities under future climate scenarios RCP4.5 and RCP8.5. Specifically, the analysis uses a reduced-form approach for projecting changes in flood depth and the associated costs of flood prevention, based on

---

[259] Trtanj, J., L. Jantarasami, J. Brunkard, T. Collier, J. Jacobs, E. Lipp, S. McLellan, S. Moore, H. Paerl, J. Ravenscroft, M. Sengco, and J. Thurston, 2016: Ch. 6: Climate Impacts on Water-Related Illness. The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment. U.S. Global Change Research Program, Washington, DC, 157-188, doi:10.7930/J03F4MH.

[260] See the following for more information: Price, J., L. Wright, C. Fant, and K. Strzepek, 2014: Calibrated Methodology for Assessing Climate Change Adaptation Costs for Urban Drainage Systems. *Urban Water Journal*, **13**, doi:10.1080/1573062X.2014.991740.

an approach derived from EPA's Storm Water Management Model (SWMM). The simplified approach[261] yields impact estimates in units of average adaptation costs per square mile for a total of 100 cities across the contiguous U.S. (see Figure 14.1) for three categories of 24-hour storm events (those with precipitation intensities occurring every 10, 25, and 50 years—metrics commonly used in infrastructure planning) and two future time periods: 2050 (2040-2059) and 2090 (2080-2099).[262] Inclusion of all U.S. cities with stormwater conveyance systems would provide a more comprehensive characterization of future impacts. The analysis also assumes that the systems are able to manage runoff associated with historical climate conditions, and estimates the costs of implementing the adaptation measures necessary to manage increased runoff due to climate change.[263] For more information on the CIRA approach and results for the urban drainage sector, please refer to Neumann et al. (2014)[264] and Price et al. (2014).[265,266]

14.4 RESULTS

Table 14.1 presents the projected proactive adaptation costs for urban drainage infrastructure in the 100 modeled cities across the contiguous U.S. In 2050, the projected costs are slightly higher under RCP4.5 than RCP8.5 in a few cases, particularly with the CCSM4 model. For example, for 25- and 50-year storms, costs under RCP4.5 are higher than RCP8.5 for CCSM4, GISS_E2_R (50-year storm only), MIROC 5, and the five-GCM average.[267] However, by 2090, the climate signal is clearer, and the projected adaptation costs are higher under RCP8.5 for all three storm types and across all five models with the one exception of GISS_E2_R for the 50-year storm. For the five-GCM average, annual costs in 2090 for RCP8.5 for 10-, 25-, and 50-year storms are estimated at \$2.5, \$3.9, and \$5.6 billion (\$2015), respectively. Projected costs under RCP4.5 are lower (\$1.6, \$2.7, and \$4.1, respectively).

---

[261] Although more detailed models, such as SWMM, are often used by municipalities for local stormwater management planning, applying these models across the 100 cities examined in this analysis was not practicable.

[262] The analysis assumes that adaptation investments are made at the beginning of each time period analyzed.

[263] Because this analysis does not model damages due to urban flooding or combined sewer overflow events, a reactive adaptation scenario was not modeled. For estimates of damages due to Inland Flooding, please see that section.

[264] Neumann, J., J. Price, P. Chinowsky, L. Wright, L. Ludwig, R. Streeter, R. Jones, J. Smith, W. Perkins, L. Jantarasami, and J. Martinich, 2014: Climate change risks to U.S. infrastructure: impacts on roads, bridges, coastal development, and urban drainage. *Climatic Change*, **131**, 97-109, doi:10.1007/s10584-013-1037-4.

[265] Price, J., L. Wright, C. Fant, and K. Strzepek, 2014: Calibrated Methodology for Assessing Climate Change Adaptation Costs for Urban Drainage Systems. *Urban Water Journal*, **13**, doi:10.1080/1573062X.2014.991740.

[266] The results presented here apply the methods described in Price et al. (2014) and Neumann et al. (2014), with an expansion of the number of cities modeled.

[267] This is likely due to the fact that the analysis relies on climate projections for extreme events, and in some cases the changes in extremes under RCP4.5 are higher than under RCP8.5.

Table 14.1. Projected Annual Proactive Adaptation Costs for Urban Drainage Infrastructure in 100 Cities in the U.S.

Total costs for 10-, 25-, and 50-year storms under RCP8.5 and RCP4.5 in 2050 (2040-2059) and 2090 (2080-2099) (billions $2015, undiscounted).

	2050						2090					
	10-year		25-year		50-year		10-year		25-year		50-year	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
CanESM2	$1.5	$1.4	$2.4	$2.4	$3.5	$3.5	$2.5	$1.3	$3.7	$2.0	$5.2	$2.9
CCSM4	$1.0	$1.3	$1.5	$2.6	$2.1	$4.2	$1.5	$1.2	$2.3	$2.0	$3.3	$3.3
GISS_E2_R	$1.7	$1.5	$2.9	$2.8	$4.3	$4.5	$2.5	$1.6	$3.9	$3.4	$5.8	$5.9
HadGEM2	$2.0	$1.8	$3.2	$3.0	$4.6	$4.6	$3.3	$2.3	$5.0	$3.6	$7.0	$5.1
MIROC5	$2.0	$1.7	$3.0	$3.2	$4.2	$4.9	$2.7	$1.6	$4.5	$2.4	$6.6	$3.4
5-GCM Average	**$1.7**	**$1.6**	**$2.6**	**$2.8**	**$3.7**	**$4.3**	**$2.5**	**$1.6**	**$3.9**	**$2.7**	**$5.6**	**$4.1**

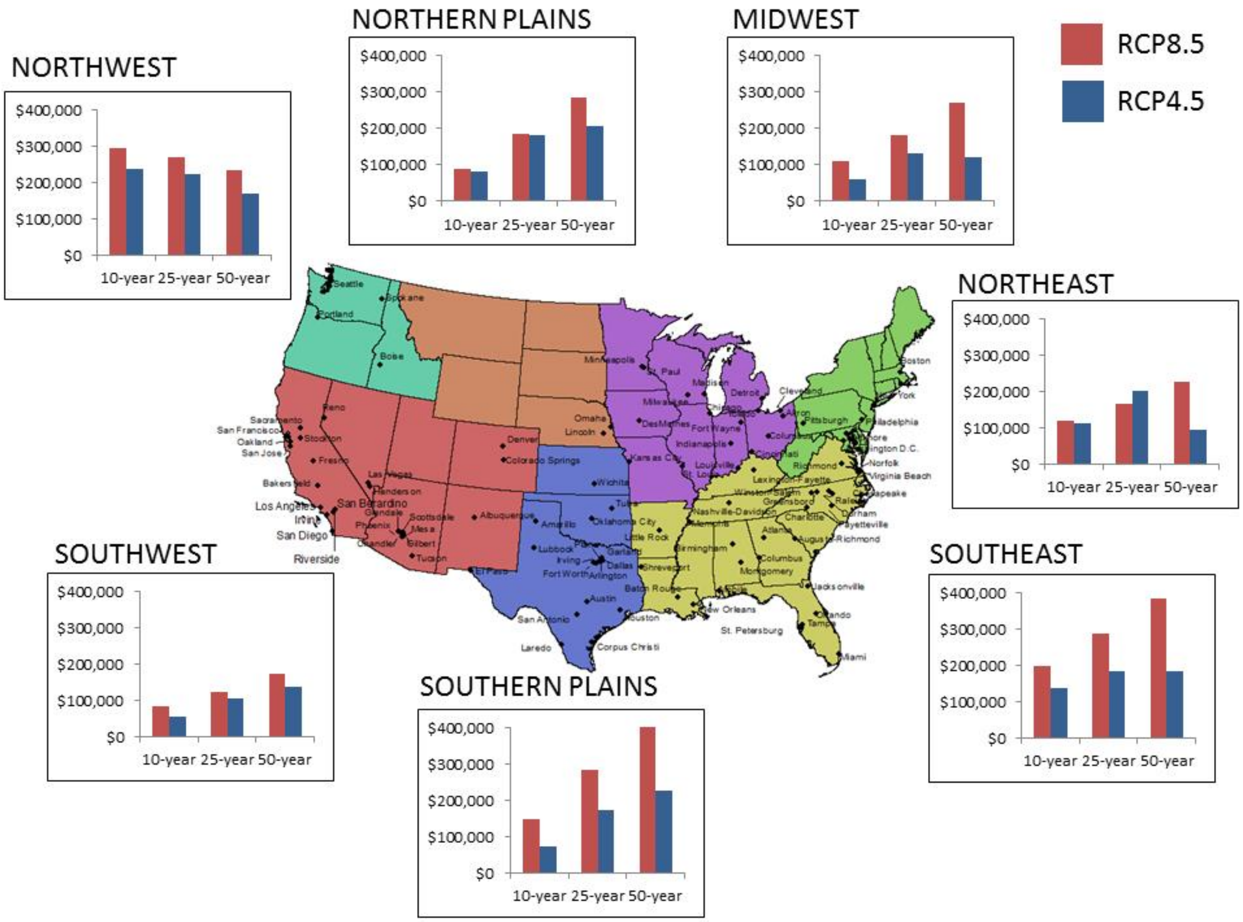
Figure 14.1 presents the projected costs for each of the 100 modeled cities, aggregated to seven regions used in the NCA4. The costs presented in Figure 14.1 are weighted average costs per square mile.[268] As shown, for a 10-year storm, costs are projected to be highest in the Northwest under both RCP8.5 and RCP4.5 ($300,000 and $240,000 per square mile, respectively). In all other regions except for the Southeast, the projected costs for a 10-year storm are less than half of the costs in the Northwest. For a 25-year storm, costs are projected to be highest in the Southeast and Southern Plains under RCP8.5, at approximately $290,000 and $280,000, respectively, per square mile. Under RCP4.5, costs for a 25-year storm are projected to be highest in the Northwest (approximately $220,000 per square mile).

As expected, the highest projected costs for urban drainage infrastructure are associated with a 50-year storm. Under both RCP8.5 and RCP4.5, projected costs for a 50-year storm are highest in the Southern Plains at $460,000 and $230,000, respectively, per square mile. The second highest costs for a 50-year storm under RCP8.5 are projected to occur in the Southeast ($380,000 per square mile) while the second highest costs under RCP4.5 are projected to occur in the Northern Plains ($200,000 per square mile).

[268] The adaptation costs per square mile, calculated by city, storm, scenario, and year, were aggregated to the regions used in the Fourth National Climate Assessment and weighted by area. For example, for a region with 2 cities, each with an area of 100 square miles, each city's area is divided by the sum of the areas, resulting in a proportion value of 0.5 for each city. This proportion value is then multiplied by each calculation of per-square-mile adaptation costs (calculated by storm, scenario, and year) to produce a weighted average adaptation cost per square mile.

Figure 14.1. Projected Regional Proactive Adaptation Costs for Urban Drainage Infrastructure

Weighted average per-square-mile adaptation costs in 2090 (2080-2099) for 10-, 25-, and 50-year storms under RCP8.5 and RCP4.5 (five-GCM average, $2015, undiscounted). Costs for each of the 100 modeled cities (shown) are aggregated to the NCA4 regions.



14.5 DISCUSSION

The results presented above suggest that climate change will stress the nation's aging water infrastructure to varying degrees by location and over time. These results are consistent with the findings of the assessment literature, which describes much of the country's current drainage infrastructure as already overwhelmed during heavy precipitation and high runoff events – an impact that is projected to be exacerbated as a result of climate change, land-use change, and other factors.

There are several important considerations worth noting. First, the use of best management practices in this analysis to address all future increases in runoff may be overly optimistic, and therefore might underestimate total risk. In some instances, these practices may not be sufficient to handle all increases in stormwater volume, and therefore construction and expansion of existing conveyance networks may be necessary under a future climate. In addition, this analysis only estimated adaptation costs for 100 cities; inclusion of all U.S. cities with stormwater conveyance systems would provide a more comprehensive characterization of future impacts and would likely increase costs substantially.

15. COASTAL PROPERTY

15.1 KEY FINDINGS

- A large area of U.S. coastal land and property is at risk of inundation from sea level rise, and an even larger area is at risk of damage from storm surge, which will intensify as sea levels continue to rise.
- Without adaptation, cumulative discounted damages to coastal property in the contiguous U.S. are estimated at $3.6 trillion through 2100 under both RCPs. Damages under RCP4.5 are reduced by $92 billion compared to RCP8.5.
- Well-timed adaptation measures significantly reduce cumulative discounted costs to an estimated $820 billion under RCP8.5 and $800 billion under RCP4.5. In comparison, reductions in damages under RCP4.5 are modest, with the majority of benefits projected to occur late in the century.
- Projected sea level rise and storm surge have environmental justice implications. In the example of Tampa Bay, nearly all of the area inhabited by the most socially vulnerable is projected to be abandoned as opposed to approximately half of the area inhabited by the least socially vulnerable.

15.2 BACKGROUND

Coastal areas in the U.S. are some of the most densely populated, developed areas in the nation, and contain a wealth of natural and economic resources. Sea level rise threatens to inundate many low-lying coastal areas and increase flooding, erosion, wetland habitat loss, and saltwater intrusion into estuaries and freshwater aquifers. Climate change will increase exposure risk to coastal flooding due to increases in extreme precipitation and in hurricane intensity and rainfall rates, as well as sea level rise and the resulting increases in storm surge.[269] Rising temperatures are causing ice sheets and glaciers to melt and ocean waters to expand, contributing to global sea level rise at increasing rates. The combined effects of sea level rise and other climate change factors, such as increased intensity of storms, may cause rapid and irreversible change across the contiguous U.S. coastline. Nationally important assets, such as ports, tourism and fishing sites, water supply and energy infrastructure, and evacuation routes in already-vulnerable coastal locations, are increasingly exposed to sea level rise, storm surges, inland flooding, and erosion.[270] In the Gulf Coast, home to more than 50% of the nation's petroleum refining capacity, impacts to liquid fuels infrastructure can disrupt distribution and availability of products, with effects on consumer prices.

15.3 APPROACH

This analysis identifies at-risk coastal property and land-based energy infrastructure across the contiguous U.S. and projects costs incurred due to sea level rise and storm surge, with and without adaptation.[271] Coastal property considered in the analysis includes residential, commercial, industrial, institutional, and government properties, as well as energy infrastructure and facilities. Importantly, impacts to other coastal assets (e.g., transportation and telecommunication infrastructure) and ecological resources are not estimated.

---

[269] Bell, J.E., S.C. Herring, L. Jantarasami, C. Adrianopoli, K. Benedict, K. Conlon, V. Escobar, J. Hess, J. Luvall, C.P. Garcia-Pando, D. Quattrochi, J. Runkle, and C.J. Schreck, III, 2016: Ch. 4: Impacts of Extreme Events on Human Health. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 99–128, doi: 10.7930/J0BZ63ZV.

[270] Moser, S. C., M. A. Davidson, P. Kirshen, P. Mulvaney, J. F. Murley, J. E. Neumann, L. Petes, and D. Reed, 2014: Ch. 25: Coastal Zone Development and Ecosystems. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 579-618, doi:10.7930/J0MS3QNW.

[271] The additional risks to coastal flooding events caused by precipitation are not included in this analysis.

The EPA's National Coastal Property Model is used to estimate how areas along the coast may respond to sea level rise and storm surge and calculates the economic impacts of adaptation decisions (i.e., damages due to climate change associated with costs of protection strategies or lost value of inundated property). The approach uses four primary responses to the threat of climate change: beach nourishment, property elevation, shoreline armoring, or property abandonment. The model projects an adaptation response for areas at risk based on sea level rise, storm surge height, property value, and costs of protective measures. The model is also run assuming no adaptation to compare the risks of inaction with the net costs of adaptation.

This analysis uses regional sea level rise scenarios based on projections from NOAA (2017), described in the Modeling Framework section of this Technical Report. The National Coastal Property Model then uses a tropical cyclone simulator[272] and a storm surge model[273] to estimate the joint effects of sea level rise and storm surge for East and Gulf Coast sites, and an analysis of historic tide gauge data to project future flood levels for West Coast sites.[274]

The adaptation responses projected by the National Coastal Property Model are developed using a cost-benefit framework comparing the costs of protection relative to the property value. Developed using a simple metric to estimate potential adaptation responses in a consistent manner for the entire coastline, the estimates presented here should not be construed as recommending any specific policy or adaptive action. Further, additional adaptation options not included in this analysis, such as marsh restoration, may be appropriate, and potentially more cost-effective, for some locales. Importantly, this analysis assumes that development in the coastal flood plan remains fixed at current locations, with growth in economic value at those locations consistent with past trends in national property appreciation. Increased development at the extensive margin in coastal communities, which follows observed patterns over the past several decades, or faster rates of property appreciation in coastal versus inland sites, could compound the economic impacts of sea level rise and storm surge. For more information on the National Coastal Property Model, please refer to Neumann et al. (2014)[275] and Neumann et al. (2014).[276]

15.4 RESULTS

Sea level rise and storm surge pose increasingly large risks to coastal property, including costs associated with property abandonment, residual storm damages,[277] and protective adaptation measures, such as property elevation, beach nourishment, and shoreline armoring. As shown in Figure 15.1, cumulative damages to coastal property across the contiguous U.S. are significantly reduced if protective adaptation measures are implemented compared to a scenario where no adaptation occurs. Without adaptation,

---

[272] Emanuel, K., R. Sundararajan, and J. Williams, 2008: Hurricanes and Global Warming: Results from Downscaling IPCC AR4 Simulations. *Bulletin of the American Meteorological Society*, doi:10.1175/BAMS-89-3-347.

[273] Jelesnianski, C.P., J. Chen, and W.A. Shaffer, 1992: SLOSH: Sea, lake, and overland surges from hurricanes. NOAA Technical Report NWS 48, National Oceanic and Atmospheric Administration, U. S. Department of Commerce, Washington, DC.

[274] Tebaldi, C., B. Strauss, and C. Zervas, 2012: Modeling sea-level rise impacts on storm surges along U.S. coasts. *Environmental Research Letters*, **7,** 014032, doi:10.1088/1748-9326/7/1/014032.

[275] Neumann, J., K. Emanuel, S. Ravela, L. Ludwig, P. Kirshen, K. Bosma, and J. Martinich, 2014: Joint Effects of Storm Surge and Sea-level Rise on U.S. Coasts. *Climatic Change*, **129**, 337-349, doi: 10.1007/s10584-014-1304-z.

[276] Neumann, J., J. Price, P. Chinowsky, L. Wright, L. Ludwig, R. Streeter, R. Jones, J.B. Smith, W. Perkins, L. Jantarasami, and J. Martinich, 2014: Climate change risks to U.S. infrastructure: impacts on roads, bridges, coastal development, and urban drainage. *Climatic Change*, **131**, 97-109, doi:10.1007/s10584-013-1037-4.

[277] Residual damages in this analysis are those that cause property damages smaller than the value of the property and any potential protective measures. Therefore the model estimates that the economically efficient response is to incur these smaller damages.

cumulative damages under RCP8.5 are estimated at $3.6 trillion through 2100 (discounted at 3%), compared to $820 billion in the scenario where cost-effective adaptation measures are implemented. Under RCP4.5, costs without adaptation are estimated at $3.6 trillion through 2100 (discounted 3%) (a reduction of $92 billion relative to RCP8.5), compared to $800 billion with adaptation.[278]

Figure 15.1. Cumulative Costs of Sea Level Rise and Storm Surge to Coastal Property

Costs are presented with and without adaptation under RCP8.5 and RCP4.5[279] in trillions of $2015, discounted at 3%.

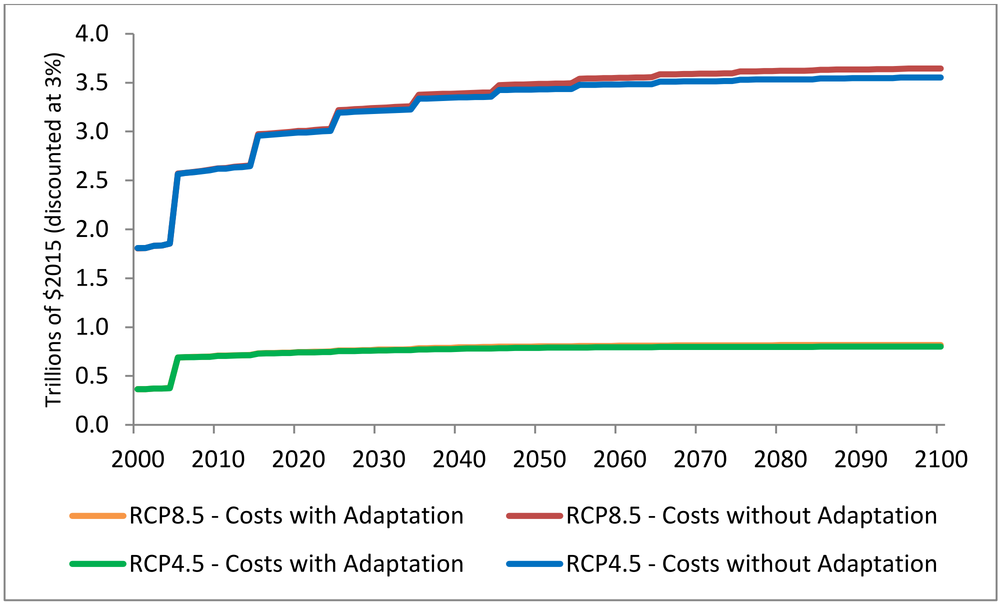


Figure 15.2 shows the total estimated costs (including the value of abandoned property, costs of protective adaptation measures, and residual costs of storm surge damage) for 17 key sites under both RCPs. Costs vary across sites primarily due to the value of property at risk and the severity of the storm surge threats. For example, adaptation costs are comparatively higher in sites such as Tampa and Miami, where there are many high-value properties in low-lying areas and high levels of storm surge are projected in the future.

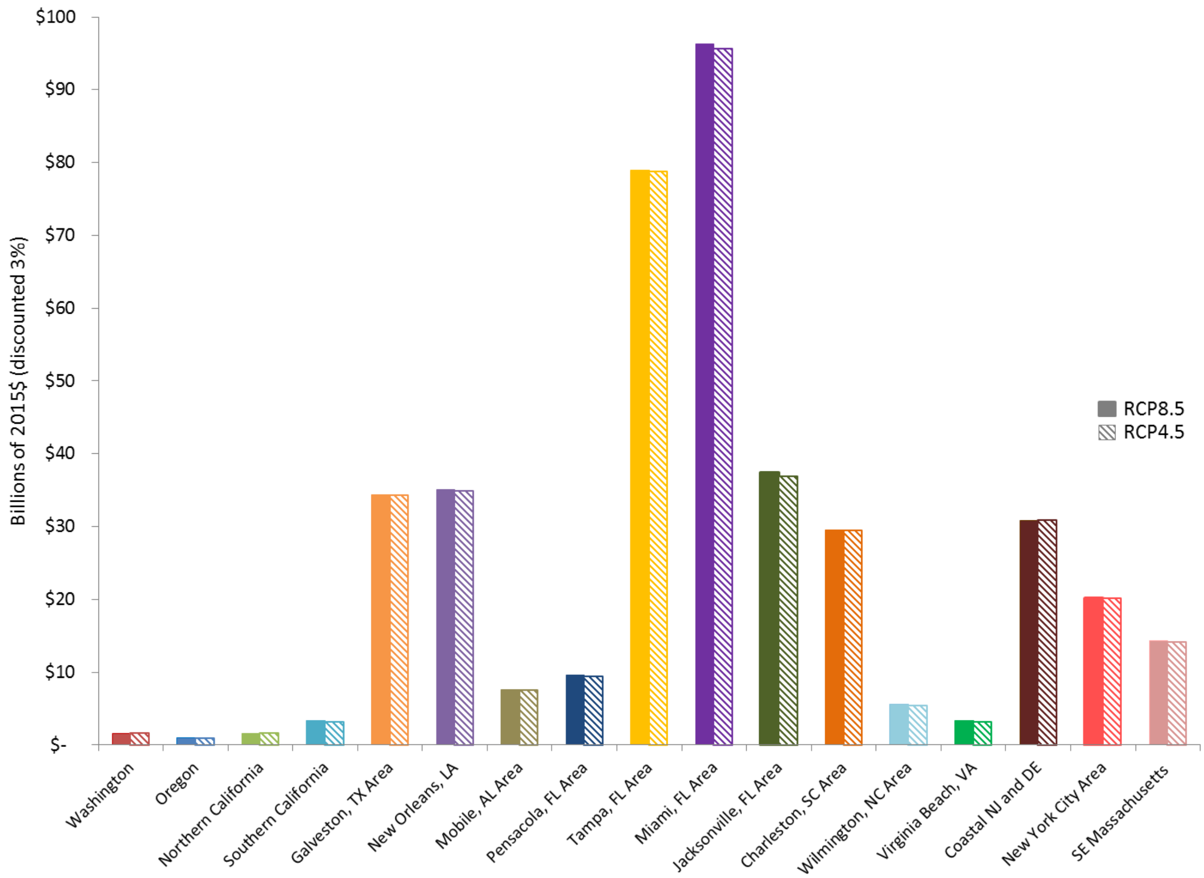
---

[278] Global sea level rise is similar under the RCPs scenarios through mid-century. It is not until the second half of the century when the benefits of reduced sea level rise under RCP4.5 become apparent, which are more heavily affected by discounting. In addition, some of the effects on coastal property are due to land subsidence which is assumed to occur at an equal rate under the sea level rise projections of the two RCPs.

[279] The step-wise nature of the graph is due to the fact that the analysis evaluates storm surge risks every ten years, beginning in 2005.

Figure 15.2. Projected Costs to Coastal Property of Sea Level Rise and Storm Surge

Costs are shown for 17 multi-county coastal areas (see map below) that were modeled for sea level rise and storm surge impacts and potential adaptation responses through 2100 (billions $2015, discounted at 3%).



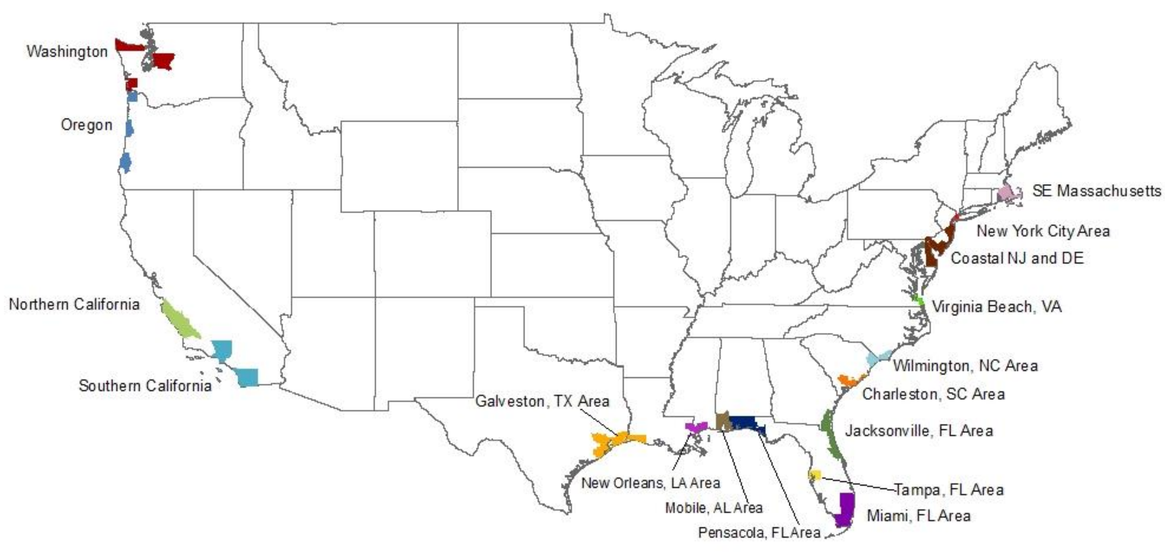


Table 15.1 presents the breakdown of projected costs for the 17 sites under RCP8.5.[280] In general, the largest costs are associated with shoreline armoring and incurred residual storm surge damages.

Table 15.1. Projected Costs of Sea Level Rise and Storm Surge Damages

Projected costs are for the period 2000-2100 under RCP8.5 at 17 sites, and are presented in millions $2015, discounted at 3%. See Figure 15.2 for the geographic extent of each coastal area.

Coastal Area	Value of Abandoned Property	Cost of Armoring	Cost of Nourishment	Cost of Elevation	No Adaptation (Storm Surge Damage)	Total Costs
SE Massacusetts	$4,000	$8,900	$530	$140	$790	$14,000
Charleston, SC area	$23,000	$4,100	$640	$8	$1,400	$30,000
Galveston, TX area	$30,000	$2,200	$330	$28	$2,300	$34,000
Jacksonville, FL area	$19,000	$10,000	$1,800	$420	$6,200	$37,000
Miami, FL area	$57,000	$13,000	$1,600	$2,000	$23,000	$96,000
Mobile, AL area	$4,700	$900	$420	$18	$1,600	$7,600
New Orleans, LA area	$29,000	$2,600	$440	$0	$3,100	$35,000
New York City are	$15,000	$3,100	$150	$110	$2,000	$20,000
Northern California	$1,000	$450	$50	$7	$110	$1,600
Coastal NJ and DE	$19,000	$9,600	$0	$480	$2,300	$31,000
Oregon (parts of)	$450	$430	$28	$2	$54	$960
Pensacola, FL area	$3,100	$4,400	$600	$150	$1,300	$9,600
Southern California	$480	$1,800	$570	$35	$410	$3,300
Tampa, FL area	$63,000	$7,600	$580	$150	$7,600	$79,000
Virginia Beach VA area	$930	$1,200	$320	$5	$870	$3,300
Washington (state)	$690	$730	$0	$0	$190	$1,600
Wilmington, NC area	$1,400	$2,300	$630	$160	$1,100	$5,600

Environmental Justice Case Study: Tampa Bay

The analysis also explores the potential impact of sea level rise and storm surge on socially disadvantaged populations in the Tampa Bay area. The approach, based on the methodology described in Martinich et al. (2013),[281] quantifies how sea level rise and storm surge risks are distributed across

[280] The projected costs under RCP4.5 are not significantly different than the costs under RCP8.5 (approximately 1% lower across the 17 sites).

[281] Martinich, J., J. Neumann, L. Ludwig, and L. Jantarasami, 2013: Risks of sea level rise to disadvantaged communities in the United States. *Mitigation and Adaptation Strategies for Global Change*, **18**, 169-185, doi: 10.1007/s11027-011-9356-0.

different socioeconomic populations; how these populations are likely to respond; and what adaptation costs (i.e., property damage and protection investments) will potentially be incurred. The analysis uses the Social Vulnerability Index (SoVI)[282] to identify socially vulnerable coastal communities. It calculates census tract-level SoVI values based on data on gender, age, race, employment, and wealth from the 2010 Census and 2014 American Community Survey.

Figure 15.3 presents the at-risk areas in each SoVI category under RCP8.5. As shown, 96% of the area inhabited by the high-vulnerability population is likely to be abandoned as opposed to 54% of the area inhabited by the low-vulnerability population. Results under RCP4.5 show similar patterns.

Figure 15.3. Tampa Bay Areas at Risk from Sea Level Rise and Storm Surge

The chart displays the areas (in square miles) within each SoVI category at risk from sea level rise and storm surge through 2100 under RCP8.5 in the Hillsborough and Pinellas Counties of Florida. The chart identifies the adaptation measures for each SoVI category.

15.5 DISCUSSION

Projections of increasing risks to coastal property of sea level rise and storm surge, and of the potential for adaptation to reduce overall costs, are consistent with the findings of the assessment literature,[283] and other recent reports. Assuming no protective measure are taken, The American Climate

---

[282] Cutter, S., B.J. Boruff, and W.L. Shirley, 2003: Social Vulnerability to Environmental Hazards. *Social Science Quarterly, **84**, 242-261.*

[283] Moser, S. C., M. A. Davidson, P. Kirshen, P. Mulvaney, J. F. Murley, J. E. Neumann, L. Petes, and D. Reed, 2014: Ch. 25: Coastal Zone Development and Ecosystems. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 579-618. doi:10.7930/J0MS3QNW.

Prospectus[284] found that $66-106 billion worth of current coastal property will likely be below mean sea level by 2050 under RCP8.5 ($62-85 billion under RCP4.5), which could grow to $238-507 billion by 2100 ($175-339 billion under RCP4.5). Values from the American Climate Prospectus presented are undiscounted, at 2011 property prices, using mean sea level measures, while the estimates presented in this section are based on mean high water levels (as adopted by other analyses, such as Strauss et al. 2015[285]), and using projected property prices that grow with projected GDP per capita. A recent Congressional Budget Office report[286] found that annual hurricane damages to coastal development, considering both flooding and wind damages, currently amount to approximately $28 billion, but that by 2075, the figure could reach approximately $39 billion. Results are undiscounted, and incorporate both adaptation to these risks and a projection of future property prices. This CBO analysis estimated the joint effects of hurricanes and increased coastal development on future damages, concluding that roughly 45% of their projected increase is attributable to climate change, and 55% to coastal development. Both of these efforts rely on coastal damage functions from a model of insured losses developed by Risk Management Solutions, so not all aspects of the approach used in those studies, some of which reflect proprietary data and methods, can be compared to those adopted in this analysis.

It should also be noted that none of these analyses, including the results of this section, incorporate findings from recent Antarctic research[287] suggesting that 6 feet or more of global sea level rise may be possible this century under RCP8.5. Consideration of this possibility would roughly double most of the estimates presented in this section, and may have an unknown (nonlinear) effect on property damages.

The effect of global GHG mitigation in reducing damages and adaptation costs is not significant in this study, and is likely underestimated for several reasons. In terms of projected damages, global sea level rise is similar under the RCPs scenarios through mid-century. It is not until the second half of the century when the benefits of reduced sea level rise under RCP4.5 become apparent. In terms of adaptation costs, when considering the total present value estimates under the RCPs, avoided adaptation costs accrued in later years are more heavily affected by discounting.[288] In addition, costs under both RCPs are projected with the assumption that coastal areas will implement cost-efficient and well-timed adaptation measures in response to risks. Since many parts of the coastline are not sufficiently protected today, and because adaptation measures that are taken are oftentimes not well-timed, estimates for this sector likely underestimate damages.[289] Also, this analysis holds constant the level of development in the coastal floodplain, which likely leads to underestimates of reported risk.[290] Finally, the inclusions of impacts of sea level rise and storm surge on other coastal assets (e.g., transportation and telecommunication infrastructure) and ecological resources would increase total potential damages.

---

[284] Hsiang, S., R. Kopp, D. Rasmussen, M. Mastrandrea, A. Jina, J. Rising, R. Muir-Wood, P. Wilson, M. Delgado, S. Mohan, K. Larsen, T. Houser, 2014. American Climate Prospectus: Economic Risks in the United States. Goldman School of Public Policy Working Paper. Available online at https://gspp.berkeley.edu/research/working-paper-series/american-climate-prospectus-economic-risks-in-the-united-states

[285] Strauss, B.H., S. Kulpa, and A. Levermann, 2015: Carbon choices determine US cities committed to futures below sea level. *Proceedings of the National Academy of Sciences*, **112**, 13508–13513, doi: 10.1073/pnas.1511186112.

[286] Dinan, T., 2016: CBO's Approach to Estimating Expected Hurricane Damage: Working Paper 2016-02. Congressional Budget Office. Available online at https://www.cbo.gov/publication/51610

[287] DeConto, R. M., and D. Pollard, 2016: Contribution of Antarctica to past and future sea-level rise. *Nature*, **531**, 591-597.

[288] Without discounting, the cumulative effect of mitigation is larger, reducing impacts by about 8% (from $1.2 trillion to $1.1 trillion), and the annual benefits rise from approximately $450 million in 2050 to nearly $1.6 billion in 2100.

[289] However, climate change amplification of flood risk may also trigger proactive adaptation, such as people choosing not to move into flood-prone areas, or where zoning or insurance markets present clear barriers to moving there. These dynamics are not captured in this analysis.

[290] Dinan, T., 2016: CBO's Approach to Estimating Expected Hurricane Damage: Working Paper 2016-02. Congressional Budget Office. Available online at https://www.cbo.gov/publication/51610

ELECTRICITY

16. ELECTRICITY DEMAND AND SUPPLY

16.1 KEY FINDINGS

- Higher temperatures due to climate change are projected to increase demand for electricity to meet cooling needs across the contiguous U.S.
- Electricity demand rises under both RCPs. Nationally, electricity demand increases 2.4-2.9% in 2050 under RCP8.5 and 1.7-2.0% under RCP4.5, though increases in regional demand vary.
- Electric power sector capacity and generation will increase to meet these higher demands, resulting in national cumulative costs of tens to hundreds of billions of dollars through mid-century. Warming temperatures are projected to increase national power system costs by 2.4-4.0% under RCP8.5 and 1.8-3.1% under RCP4.5 through 2050.
- The Southeast is projected to experience the highest costs associated with meeting increased electricity demands, with high costs also projected in the Northeast, Midwest, and Southern Plains.

16.2 BACKGROUND

Electricity is an essential element of modern life. It lights and cools our homes, powers our appliances and electronics, supports the production of goods and services, and enables critical infrastructure services such as water treatment and telecommunications. The generation of electricity in the U.S., most of which comes from fossil fuels, also contributes to climate change, accounting for approximately 30 percent of U.S. greenhouse gas emissions.[291]

As air temperatures rise due to climate change, electricity demands for cooling are expected to increase in every U.S. region.[292] Higher summer temperatures, particularly during heat waves, will likely increase peak electricity demand, placing more stress on the electricity grid and increasing electricity costs. Although the majority of U.S. residential and commercial cooling demand is met with electricity, less

---

[291] U.S. Department of Energy, 2014: Electric Power Monthly: Table 1.1. Net Generation by Energy Source: Total (All Sectors), 2004-February 2014.

[292] Dell, J., S. Tierney, G. Franco, R. G. Newell, R. Richels, J. Weyant, and T. J. Wilbanks, 2014: Ch. 4: Energy Supply and Use. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 113-129. doi:10.7930/J0BG2KWD

than nine percent of heating demand is met with electricity.[293,294] Therefore, although higher average temperatures are expected to reduce electricity demands for heating, net electricity use is projected to increase under climate change. Meeting these higher demands for electricity has cost and operating implications for the electric sector as additional capacity and generation are required. At the same time, higher temperatures reduce the capacity of both thermal power plants and transmission lines.[295]

16.3 APPROACH

The analysis projects how rising temperatures under climate change will affect electricity demand in the contiguous U.S., and how system costs in the electric power sector will change in response to these shifts in demand. To estimate changes in demand, the approach applies downscaled temperature projections from the five GCMs under RCP8.5 and RCP4.5 to two models of the U.S. electric power sector:

- Regional Electricity Deployment System Model (ReEDS): a technology-rich model of the deployment of electric power generation technologies and transmission infrastructure for the contiguous U.S.[296,297]
- Global Change Assessment Model (GCAM-USA, referred to as "GCAM" hereafter): a detailed, service-based building energy model for the 50 U.S. states[298,299,300,301]

The models project changes in electricity demand as functions of changes in heating and cooling degree-days (HDDs/CDDs).[302] To assess the effect of rising temperatures, changes in heating and cooling degree days and electricity demand are compared to a control scenario that assumes temperatures do not change over time but does incorporate future population growth.[303]

In addition to estimating the change in electricity demand, this analysis assesses impacts on the U.S. electricity sector's supply side using the same two models. The models project changes in the

---

[293] U.S. Department of Energy, U.S. Energy Information Administration, 2009: 2009 Residential Energy Consumption Survey (RECS): Table CE4.1. Available online at http://www.eia.gov/consumption/residential/data/2009/index.cfm

[294] U.S. Department of Energy, U.S. Energy Information Administration, 2003: 2003 Commercial Buildings Energy Consumption Survey (CBECS): Tables E1A and E3A. Available online at http://www.eia.gov/consumption/commercial/data/2003/index.cfm

[295] Dell, J., S. Tierney, G. Franco, R. G. Newell, R. Richels, J. Weyant, and T. J. Wilbanks, 2014: Ch. 4: Energy Supply and Use. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 113-129. doi:10.7930/J0BG2KWD

[296] Eurek, K., W. Cole, D. Bielen, N. Blair, S. Cohen, B. Frew, J. Ho, V. Krishnan, T. Mai, B. Sigrin and D. Steinberg, 2016: Regional Energy Deployment System (ReEDS) Model Documentation. Version 2016. National Renewable Energy Laboratory Technical Report NREL/TP-6A20-67067. [Available online at www.nrel.gov/docs/fy17osti/ 67067.pdf]

[297] Sullivan, P., J. Colman, and E. Kalendra, 2015: Predicting the Response of Electricity Load to Climate Change. National Renewable Energy Laboratory Technical Report NREL/TP-6A20-64297. Available online at www.nrel.gov/docs/fy15osti/64297.pdf

[298] Iyer, G. et al., 2017: U.S. electric power sector transitions required to achieve deep decarbonization targets: Results based on a detailed state-level model of the U.S. energy system. *PNNL Report* (forthcoming).

[299] Kyle, P., L. Clarke, F. Rong, and S.J. Smith, 2010: Climate policy and the long-term evolution of the U.S. buildings sector. The Energy Journal, 31, 145-172.

[300] Zhou, Y., J. Eom, and L. Clarke, 2013: The effect of global climate change, population distribution, and climate mitigation on building energy use in the U.S. and China. *Climatic Change*, doi:10.1007/s10584-013-0772-x.

[301] Zhou Y., L. Clarke, J. Eom, P. Kyle, P. Patel, S. Kim, J.A. Dirks, E.A. Jensen, Y. Liu, J.S. Rice, L.C. Schmidt, T.E. Seiple, 2014: Modeling the effect of climate change on U.S. state-level buildings energy demands in an integrated assessment framework. *Applied Energy*, **113**, 1077-1088.

[302] HDDs and CDDs are one way to measure the influence of temperature change on energy demand. They measure the difference between outdoor temperatures and a temperature that people generally find comfortable indoors. These measurements suggest how much energy people might need to use to heat and cool their homes and workplaces. The approach used a fixed balance point of 65°F.

[303] The HDD/CDD values were smoothed using 4th degree polynomial curves to capture long-term climate effects as opposed to interannual variability.

generation and generation mix needed to meet increasing demand due to future warming. The two models also estimate the corresponding system costs comprised of capital (e.g., expenditures related to bring new capacity online), operations and maintenance, and fuel costs over time. Note that ReEDS includes the effects of transmission capacity losses due to high air temperatures. In both the demand and supply analyses of this section, the ReEDS model is simulated through 2050, while the GCAM model runs through 2100. While ReEDS' electricity demand path is fixed, the GCAM demand path responds to changes in power prices. For more information on the methodology for estimating impacts to electricity demand and supply, please refer to McFarland et al. (2015).[304]

In an extension to the approach taken in McFarland (2015), the ReEDS analysis incorporates the effects of changes in precipitation on hydropower generation. Changes in hydropower generation are estimated using the US Basins modeling framework, a linked water systems model designed to evaluate the impacts of climate change on water resources.[305,306] Precipitation and temperature from each RCP/GCM combination are inputs into: (a) a rainfall-runoff model (CLIRUN-II), which is used to simulate monthly runoff; and (b) a water demand module, which projects the water requirements of the municipal and industrial (M&I) and agriculture sectors across the GCMs. With these runoff and demand projections, US Basins produces a time series of reservoir storage, release, and allocation to the various demands in the system, which include M&I, agriculture, transboundary flows, and hydropower. See Figure A10-1 of the Appendix to this Technical Report for projected changes in flow aggregated to the scale of four-digit hydrologic unit codes. The changes in hydropower generation estimated by the US Basins framework are then applied to ReEDS. For more information on the hydropower methodology, please refer to Boehlert et al. (2016).[307,308]

16.4 RESULTS

The projected changes in regional CDD and HDD over time and across the GCMs are shown in Figures 16.1 and 16.2, respectively. The increase in CDDs are more pronounced in the northern regions, rising by a factor of 3 to 5 by 2100 under RCP8.5 versus a doubling in the southern regions over the same timeframe. The smaller change in the southern regions is primarily due to the higher number of CDDs in the reference year. The change in CDD under RCP4.5 is more modest, rising by factor of less than two in

---

[304] ReEDS and GCAM employ different techniques and underlying datasets for estimating the sensitivity of electricity demand to changes in HDD/CDD. See: McFarland, J., Y. Zhou, L. Clarke, P. Sullivan, J. Colman, W. Jaglom, M. Colley, P. Patel, J. Eom, S. Kim, G. Kyle, P. Schultz, B Venkatesh, J. Haydel, C. Mack, and J. Creason, 2015: Impacts of rising air temperatures and emissions mitigation on electricity demand and supply in the United States: a multi-model comparison. *Climatic Change*, doi: 10.1007/s10584-015-1380-8.

[305] Boehlert, B., K.M. Strzepek, Y. Gebretsadik, R. Swanson, A. McCluskey, J. Neumann, J. McFarland, and J. Martinich, 2016: Climate change impacts and greenhouse gas mitigation effects on U.S. hydropower generation. *Applied Energy*, **183**, 1511-1519.

[306] Boehlert, B., K.M. Strzepek, S.C. Chapra, C. Fant, Y. Gebretsadik, M. Lickley, R. Swanson, A. McCluskey, J. Neumann, J. Martinich, 2015: Climate change impacts and greenhouse gas mitigation effects on US water quality. *Journal of Advances in Modeling Earth Systems*, **7**, 1326-1338.

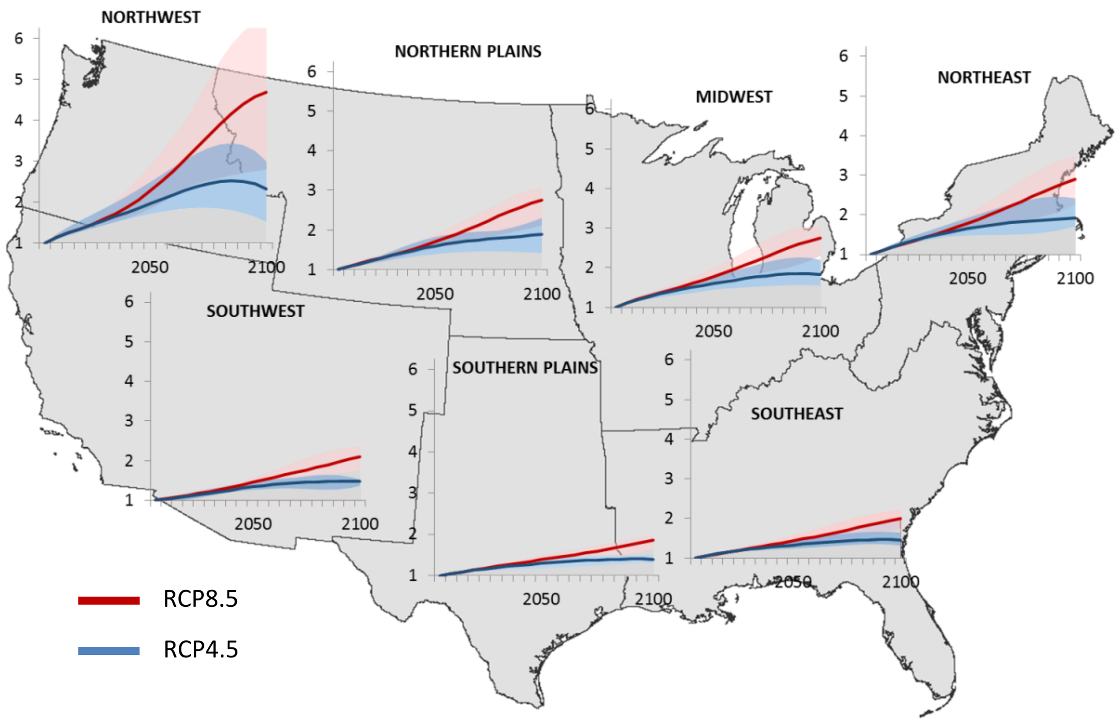
[307] Boehlert, B., K.M. Strzepek, Y. Gebretsadik, R. Swanson, A. McCluskey, J. Neumann, J. McFarland, and J. Martinich, 2016: Climate change impacts and greenhouse gas mitigation effects on U.S. hydropower generation. *Applied Energy*, **183**, 1511-1519.

[308] While not presented in detail in this section, additional sensitivity cases were run in ReEDS to assess the effects of climate-induced changes in thermo-electric cooling water availability on system costs. The climate-induced changes to thermal cooling water availability in ReEDS are determined through iteration with the US Basins model (See Water Quality section of this Technical Report for more information). Whereas ReEDS constrains only quantities of water withdrawn in each season and balancing area, US Basins represents detailed hydrology and plant-specific cooling water constraints such as thermal discharge limits. ReEDS scenarios are first run with cooling water availability based solely on the evolution of the hydrological system as projected by US Basins. The resulting electric power sector generation and capacity expansion in ReEDS are then used as input to a second iteration of the US Basins model, which evaluates the feasibility of ReEDS results given its additional thermal cooling water constraints. Any constraint violations are fed back to ReEDS by multiplying the initial water available by the fraction of ReEDS proposed water demand that is met in US Basins to form updated cooling water availability data. ReEDS is then run with this second iteration of cooling water availability data to produce the final results.

the northern regions and under 1.5 in the southern regions by 2100. Higher temperatures reduce HDDs by approximately 30% in the northern regions and 50% in the southern regions by 2100 under RCP8.5. Because electricity comprises less than 10 percent of heating demand, changes in HDD have only a small effect on electricity demand.[309]

Figure 16.1. Change in Cooling Degree-Days

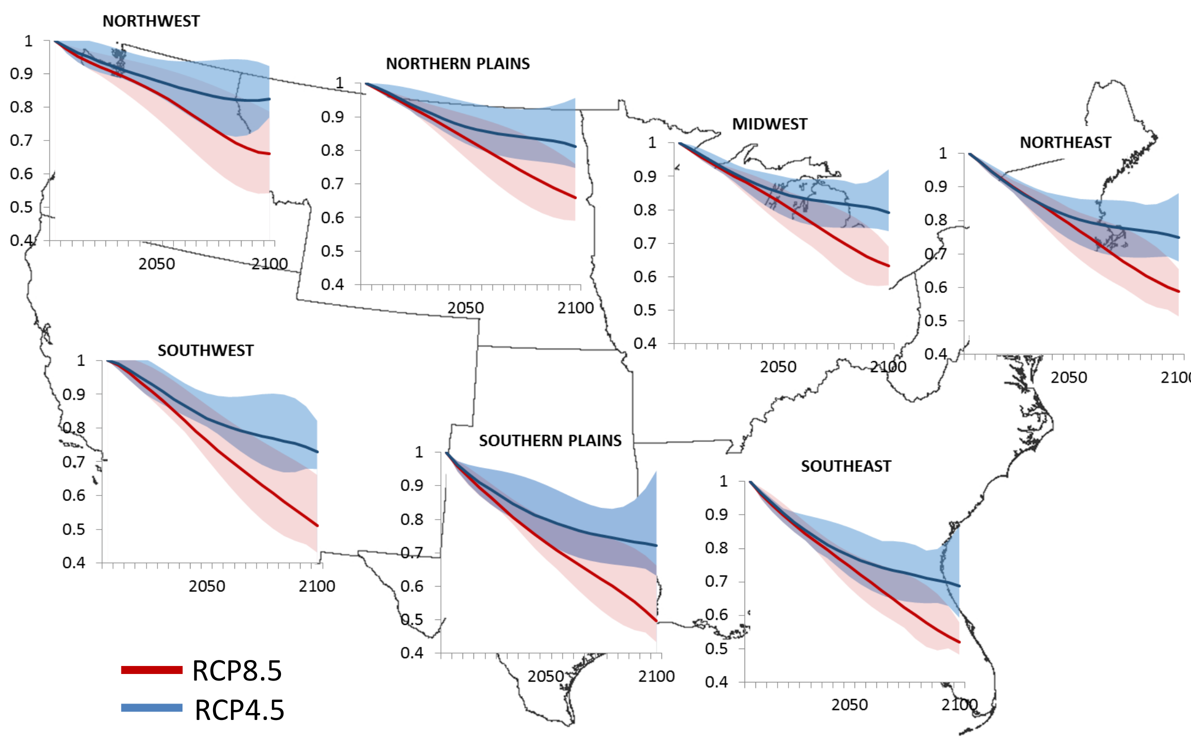
Results shown by region through 2100 as compared to 2005 (2005=1), with a value of 2 representing a 100% increase in CDDs.



309 HDD reductions will have a larger effect on reducing natural gas and fuel oil consumption during the winter months, however those effects are not modeled here.

Figure 16.2. Change in Heating Degree-Days

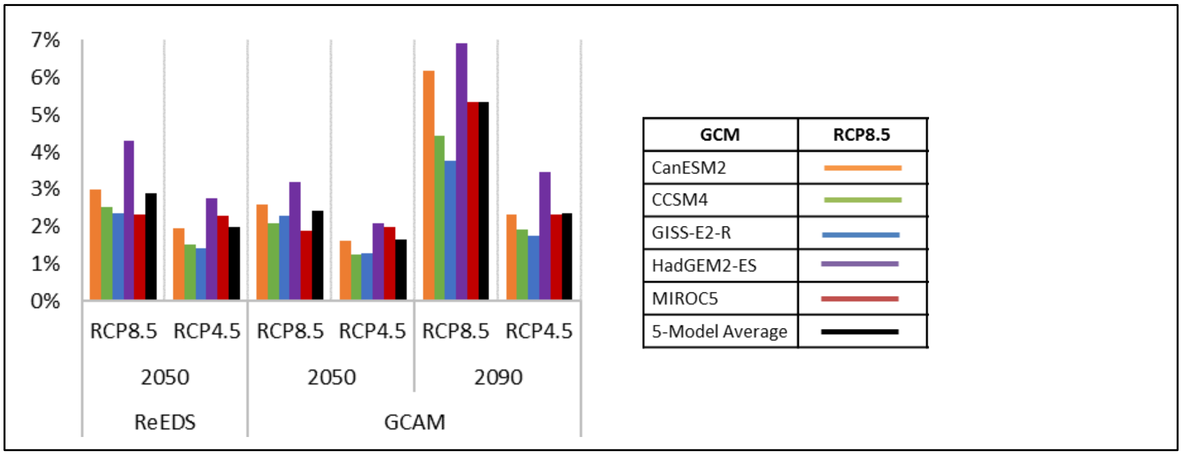
Results shown by region through 2100 as compared to 2005 (2005=1), with a value of 0.5 representing a 50% decrease in HDDs.



At the national level, both the ReEDS and GCAM models estimate that the HDD/CDD changes result in average increases in electricity demand of 2.9% and 2.4%, respectively in 2050 under RCP8.5 (Figure 16.3). Under RCP4.5, average change in demand in 2050 increases across both models by 2.0% and 1.7%, respectively. National average electricity demand is projected by GCAM to increase 5.3% under RCP8.5 in 2090, and 2.4% under RCP4.5. Figure A.10.2 of the Appendix to this Technical Report provides projected changes in regional demand. As shown there, the largest regional increases in demand by 2050 occur in the Northeast, Southeast, Midwest, and Southern Plains in the ReEDS model; the largest increases in demand in the GCAM model occur in the Southeast, Southern Plains, and Northwest, especially by 2090.

Figure 16.3. Percent Change in National Electricity Demand

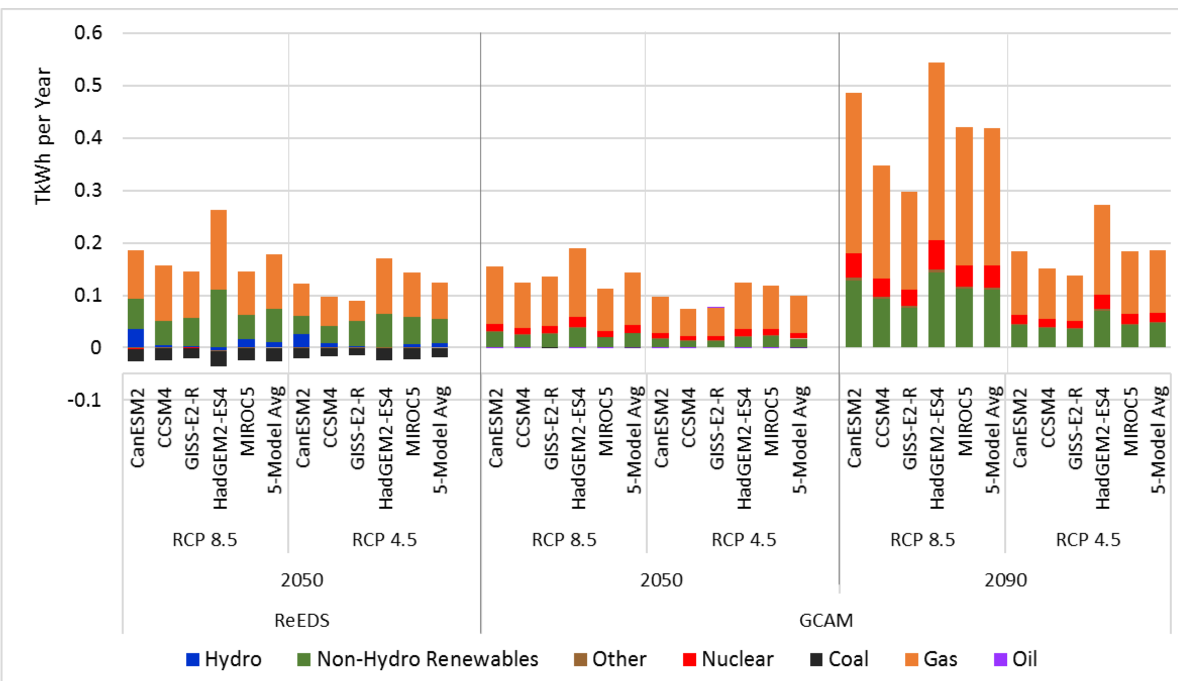
Values across RCPs and the five GCMs are shown relative to a control scenario without climate change for the year 2050 (ReEDS and GCAM) and 2090 (GCAM only).



To meet the increase in demand, ReEDS and GCAM primarily expand generation of natural gas, non-hydro renewables, and, to a lesser extent, nuclear in GCAM (Figure 16.4). However, the CanESM2 climate model, which projects large increases in precipitation in the Northwest and Southwest, leads to an expansion of hydropower in 2050, by as much as 12%, under both climate scenarios in the ReEDS results.

Figure 16.4. Change in National Electricity Generation by Technology Type

Values across RCPs and the five GCMs are shown for 2050 (ReEDS and GCAM) and 2090 (GCAM only) and are relative to a control scenario without climate change.



Discounted cumulative system costs by region and RCP from both power system models are shown in Table 16.1. In the ReEDS model, projected national system costs increase by 4.0% under RCP8.5 and 3.1% under RCP4.5 through 2050,[310] with most regions showing increases in costs. Notably, system costs in ReEDS are estimated to decrease in the Northwest by 6.9% and 7.0% through 2050 under RCP8.5 and RCP4.5, respectively, due to increased hydropower availability. Under the GCAM model, national system costs are projected to increase by 2.4% and 1.8% under RCP8.5 and RCP4.5, respectively, through 2050—a smaller increase due in part to GCAM's less-sensitive demand response to temperature change. System costs in GCAM are estimated to increase by 3.4% and 2.0% through 2100 under RCP8.5 and RCP4.5, respectively. In both models and under all scenarios, the Southeast is projected to experience some of the highest costs associated with meeting changing electricity demand. For example, increased cumulative costs of $57 billion and $15 billion through 2050 are projected under RCP8.5 in the ReEDS and GCAM models, respectively. High costs are also projected in the Northeast, Midwest, and Southern Plains. The Northern Plains is projected to have the lowest increases in cumulative costs.

Table 16.1. Projected Change in Cumulative System Costs

Values relative to a control scenario without climate change are shown by region and the national (contiguous U.S.) in billions of discounted (3%) $2015 and percent change. Values represent average of the five GCMs over the 2015-2050 period (ReEDS and GCAM) and 2015-2100 (GCAM only). Totals may not sum due to rounding.

Region	2050								2100			
	ReEDS				GCAM				GCAM			
	RCP8.5		RCP4.5		RCP8.5		RCP4.5		RCP8.5		RCP4.5	
Northeast	$35	5.2%	$30	4.4%	$2.6	1.1%	$1.9	0.8%	$7.4	1.7%	$4.1	0.9%
Southeast	$57	4.3%	$43	3.2%	$15	3.6%	$11	2.7%	$36	4.6%	$21	2.7%
Midwest	$37	4.5%	$29	3.6%	$5.6	1.9%	$4.1	1.4%	$13	2.4%	$7.9	1.4%
Northern Plains	$2.0	1.4%	$2.0	1.3%	$0.2	0.5%	$0.2	0.5%	$0.5	1.4%	$0.3	0.9%
Southern Plains	$27	4.4%	$21	3.4%	$5.7	2.7%	$4.4	2.1%	$16	4.1%	$10	2.6%
Southwest	$18	4.0%	$15	3.2%	$4.7	2.1%	$3.8	1.7%	$14	3.3%	$8.8	2.0%
Northwest	-$6.1	-6.9%	-$6.2	-7.0%	$1.2	2.2%	$0.9	1.8%	$4.3	5.3%	$2.4	2.9%
National Total	**$170**	**4.0%**	**$130**	**3.1%**	**$35**	**2.4%**	**$26**	**1.8%**	**$92**	**3.4%**	**$55**	**2.0%**

16.5 DISCUSSION

Consistent with findings of the assessment literature,[311] the analysis presented in this section shows that rising temperatures due to climate change are projected to increase demand for electricity and affect the operation and planning of the power system.[312] The results are also consistent with another recent national-scale study,[313] which found that average electricity demand in the residential and commercial sectors increase by 2.3-4.9% by 2050 under RCP8.5 and 1.2-4.1% under RCP4.5.

It is important to note several limitations of this analysis when interpreting the above results. First, the two electric power system models only resolve the system to annual or seasonal levels. This coarse

---

[310] When thermo-cooling constraints are added to ReEDS simulations, the cumulative, discounted system costs from 2015 through 2050 increase by up to $10-13 billion nationally.

[311] Dell, J., S. Tierney, G. Franco, R. G. Newell, R. Richels, J. Weyant, and T. J. Wilbanks, 2014: Ch. 4: Energy Supply and Use. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 113-129. doi:10.7930/J0BG2KWD

[312] Importantly, the analyses described in this Technical Report do not examine implementation of any specific policy.

[313] Rhodium Group, 2014: American Climate Prospectus: Economic Risks in the United States. Input to the Risky Business Project. Available online at http://climateprospectus.org/publications/

temporal resolution does not fully capture the potential effects of frequent temperature peaks in electricity demand that hourly or sub-hourly dispatch models are designed to address. As such, the present analysis underestimates some impacts of climate change on the power system. Second, the approach only estimates electricity demand, and does not consider impacts on demand for other fuel sources used in residential cooling or heating, such as oil, natural gas, or wood. Third, consistent with the focus of the Technical Report to estimate the impacts of climate change on U.S. sectors, this analysis does not estimate costs associated with reducing greenhouse gas emissions from the electric power sector.[314] Fourth, costs on power systems and the distribution of electricity (i.e., power interruptions) due to changes in extreme weather events (e.g., high winds, tropical storms) are not estimated in this analysis. Finally, although the estimates described in this sector do not include impacts to the electric power system of changes in cooling water availability for thermo-electric generation, a side-case modeled only in ReEDS indicates that discounted national system costs from 2015 through 2050 would increase by 6% to 10% to adapt to water constraints.

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

WATER RESOURCES

17. INLAND FLOODING

17.1 KEY FINDINGS

- The frequency of historical "100-year" floods across the contiguous U.S. is projected to increase over the 21st century, with approximately twice as many flood events projected under RCP8.5 compared to RCP4.5 by the end of the century.
- Under RCP8.5, projected annual damages from "100-year" floods approximately double over the 21st century, whereas estimated flood damages under RCP4.5 change only modestly. By 2100, the difference between projected damages under RC8.5 and RCP4.5 is estimated to be approximately $4 billion per year.
- Changes in flood frequency and increases in associated flood damages are not evenly distributed geographically through the U.S. The most significant difference between projected inland flood damages under RCP8.5 and RCP4.5 is in the Southeast, where the difference between the two scenarios approaches $2 billion per year by the end of the century.

17.2 INTRODUCTION

Extreme precipitation events have intensified in recent decades across most of the U.S., and this trend is projected to continue.[315] Heavier downpours can result in more extreme flooding and increase the risk of costly damages.[316] Flooding affects human health and safety, property, infrastructure, and natural resources. In the U.S., inland flooding caused over 4,500 deaths between 1959 and 2005 and flood-related property and crop damages averaged nearly $8.5 billion per year[317] from 1981 to 2011.[318] The potential for increased damages is large, given that climate change is projected to continue to increase the frequency of extreme precipitation events and amplify risks from non-climate factors such as

---

[315] Georgakakos, A., P. Fleming, M. Dettinger, C. Peters-Lidard, Terese (T.C.) Richmond, K. Reckhow, K. White, and D. Yates, 2014: Ch. 3: Water Resources. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J.M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 69-112. doi:10.7930/J0G44N6T.

[316] Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M. Wehner, J. Willis, D. Anderson, S. Doney, R. Feely, P. Hennon, V. Kharin, T. Knutson, F. Landerer, T. Lenton, J. Kennedy, and R. Somerville, 2014: Ch. 2: Our Changing Climate. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 19-67. doi:10.7930/J0KW5CXT.

[317] Based on the National Weather Service database, the median value is approximately $4.5 billion per year, while the annual values over this period range from $500 million to $55 billion.

[318] Georgakakos, A., P. Fleming, M. Dettinger, C. Peters-Lidard, Terese (T.C.) Richmond, K. Reckhow, K. White, and D. Yates, 2014: Ch. 3: Water Resources. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J.M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 69-112. doi:10.7930/J0G44N6T.

expanded development in floodplains, urbanization, and land-use changes. People in flood-prone regions are expected to be at greater risk of exposure to flood hazards due to climate change.[319]

17.3 APPROACH

This analysis evaluates how climate change could affect precipitation-driven inland flooding damages in the contiguous U.S. Catchment hydrology is simulated using the variable infiltration capacity (VIC) hydrologic model, driven by downscaled precipitation fields from five GCMs under RCP8.5 and RCP4.5. The VIC model simulates the range of hydrologic processes relevant to generating runoff, including interception on the forest canopy, evapotranspiration, water storage and melt from snowpack, infiltration, and direct runoff. For this analysis, VIC-projected runoff is routed through a national-scale river network using a tool that incorporates both hillslope and river channel processes. See Figure A.11.1 of the Appendix to this Technical Report for a map showing the average annual maximum flows across the contiguous U.S. in the reference period (2001-2020). For each of the 10 GCM/RCP combinations in the hydrologic model output, the time-series of annual maximum flow is then extracted at each of the approximately 57,000 stream segments in the contiguous U.S. To estimate future flood frequency and damages through 2100, the analysis compares the full transient of future annual streamflow maxima for each GCM/RCP combination to the modeled 1% annual exceedance probability (AEP) flood event in the reference period (i.e., the “100-year flood”). At each stream segment, an ensemble average probability of exceeding the 1% AEP event in each year is calculated by tabulating the fraction of models experiencing a flood and smoothing these probabilities over a 20-year moving window. The analysis then links these time and ensemble-averaged flood probabilities to the assets exposed within each floodplain to calculate projected annual damages.

Asset damages resulting from 1% AEP floods are calculated using data from a tool under development for the U.S. Army Corps of Engineers (USACE). The tool compiles all of the 100-year (1% AEP) floodplains mapped by the U.S. Federal Emergency Management Agency (FEMA) and estimates the distribution of flood depths within each floodplain using digital topographic data from the U.S. Geologic Survey’s National Elevation Dataset (NED). Floodplain polygons are intersected with residential and commercial building inventories from FEMA’s HAZUS-MH software to estimate the number of buildings exposed to inundation within each floodplain. Damages to buildings exposed to the 1% AEP flood event are estimated using published depth-damage functions from the USACE and FEMA, and assuming that assets are evenly distributed within all urbanized portions of the floodplain/census block intersection areas. See Figure A11-2 of the Appendix to this Technical Report for a map of total expected damages from a 1% AEP flood event in each 12-digit HUC of the contiguous U.S. The analysis uses a Monte Carlo approach to estimate both a mean and a variance in regional and national-scale flood damages throughout the 21st century. One thousand 100-year time-series of flood damages in the CONUS are simulated using the ensemble average probability of exceeding the 1% AEP event at each node in each year. For each flood event, expected damages are tabulated within the 12-digit HUC corresponding to

---

[319] Bell, J.E., S.C. Herring, L. Jantarasami, C. Adrianopoli, K. Benedict, K. Conlon, V. Escobar, J. Hess, J. Luvall, C.P. Garcia-Pando, D. Quattrochi, J. Runkle, and C.J. Schreck, III, 2016: Ch. 4: Impacts of Extreme Events on Human Health. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 99–128.

that node.[320] For more information on the approach and results for flooding damages, please refer to Wobus et al. (2017).[321]

17.4 RESULTS

Climate change is projected to increase the frequency of inland flooding in most watersheds of the U.S. As shown in Figure 17.1, the annual number of 100-year floods across the contiguous U.S. across all five GCMs averages approximately 500 events from 2000-2020. This average number of floods increases substantially to approximately 1,300 events per year by 2100 under RCP8.5, with a smaller increase to approximately 600 events per year under RCP4.5. Climate-driven changes in flood risk are not evenly distributed across the contiguous U.S. See Figure A.11.3 of the Appendix to this Technical Report for maps of projected changes in the frequency of historical 100-year flood events based on the full CMIP-5 ensemble results.

[320] Data on built assets were taken from FEMA's HAZUS-MH General Building Stock inventory, which provides estimates of the number and aggregate dollar value of multiple types of residential, commercial, and industrial buildings for each Census block. For the developed portion of each Census block/floodzone intersection, damage estimates were created using depth-damage functions from USACE and FEMA. A separate depth-damage function was used for each of 28 different categories of buildings (e.g., residential one-story homes without a basement). Each depth-damage function describes the percent loss as a function of depth. The depth-damage functions were applied to the aggregate value for each building category within each NFHL-Census block intersection, using the depth exposure results described above. See Wobus et al. (2017) for additional detail and citations to these inventories and functions. These estimates represent physical damages to residential, commercial, and industrial buildings, but do not include the costs of reconstruction or rehabilitation. Further, this analysis is not linked with the Urban Drainage analysis described in this Technical Report, which quantifies the effect of proactive adaptation measures (best management practices) in reducing urban runoff entering stormwater systems.

[321] Wobus, C., E. Gutmann, R. Jones, M. Rissing, N. Mizukami, M. Lorie, H. Mahoney, and J. Martinich, 2017: Modeled changes in 100 year flood risk and asset damages within mapped floodplains of the contiguous United States. Natural Hazards and Earth System Sciences. doi: 10.5194/nhess-2017-152.

Figure 17.1. Number of 100-Year Floods

In each plot, black dots are the median value across the five GCMs throughout the contiguous U.S. in each year of the 21st century, thick blue bars are the middle 50% of models, whiskers extend to the 95th percentile of values, and dots represent outliers. Thick black lines are five-year moving averages across all models.

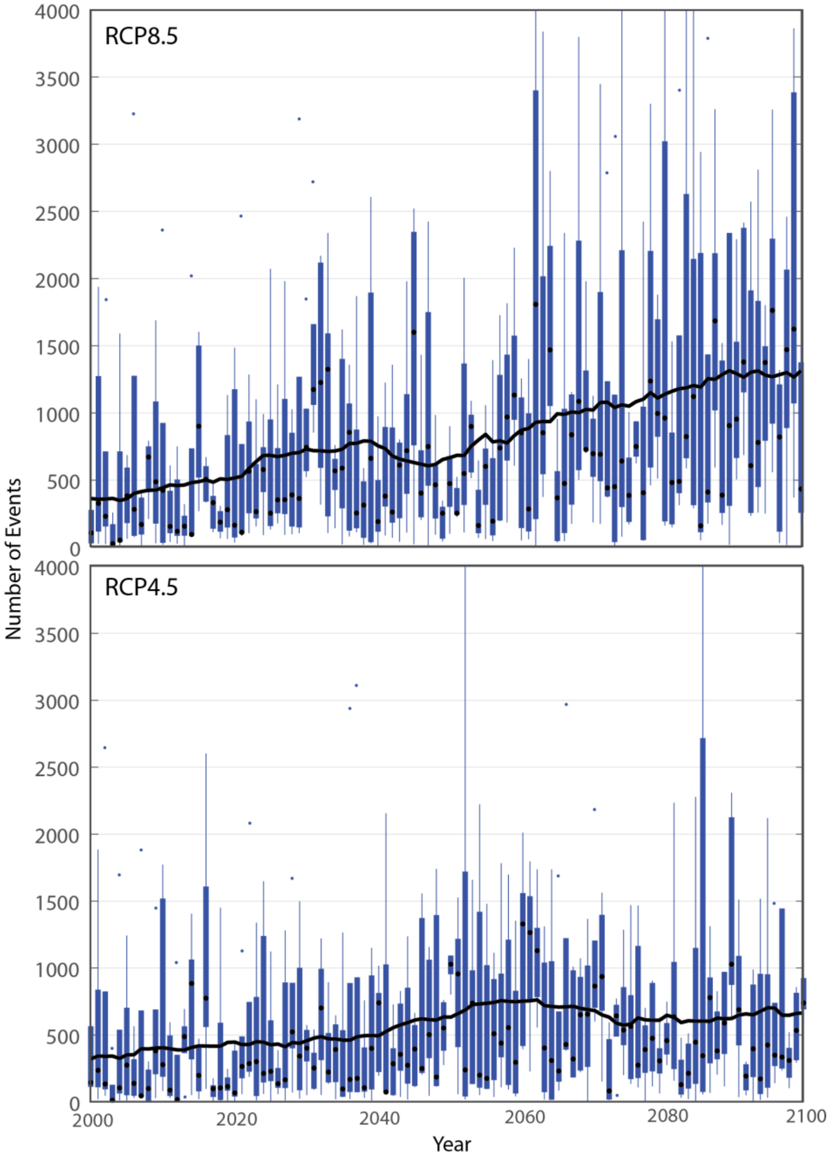
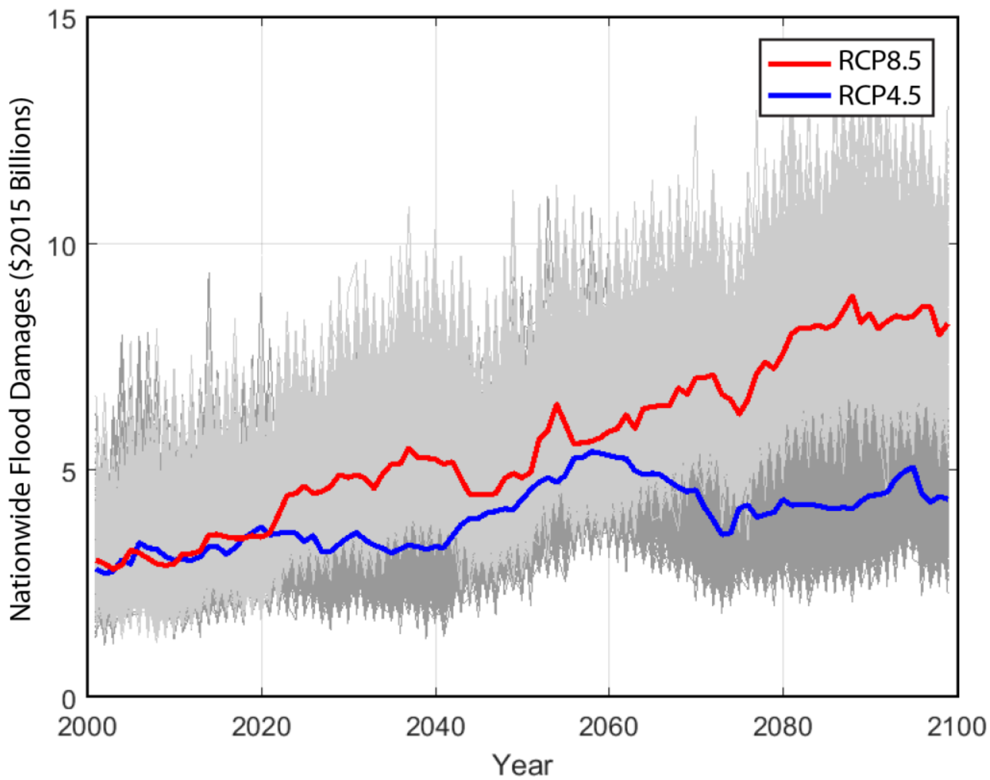


Figure 17.2 below shows the full time-series of projected changes in flood damages across the contiguous U.S. through 2100, generated by combining changes in frequency of flooding at each stream segment with the asset exposure and damage associated with a 100-year event in each floodplain. As shown, changes in flood damages broadly mimic changes in flood frequency, with Figure 17.2 also highlighting the difference in trajectories under the two RCPs. While the RCP8.5 and RCP4.5 pathways are generally similar through mid-century, the trajectories begin to diverge in the latter half of the 21st century. Under RCP8.5, estimated annual flood damages increase from approximately $3.0 billion in the early 21st century to over $8.1 billion by 2100. Projected damages under RCP4.5 increase modestly to approximately $4.3 billion per year by 2050 and remain at this level through the end of the century.

Figure 17.2. Projected National Flood Damages within 100-Year Flood Zones

Thin grey lines represent results across 1,000 simulations of damages under RCP8.5 (light grey) and RCP4.5 (dark grey). Red and blue lines are means of simulations for the two RCPs. All results represent the average of the five GCMs.



Similar to changes in flood frequency, the increasing flood damages under RCP8.5 relative to RCP4.5 are not evenly distributed through the U.S. Figure 17.3 shows the time-series of average annual damages in each NCA4 region, calculated from the 1,000 Monte Carlo simulations described above. Regional changes shown in Figure 17.3 are primarily driven by the projected changes in precipitation-based flood risk. As shown in Figure 17.3 and Table 17.1, the most significant difference between projected flood damages under the RCPs is in the Southeast, where the difference between the two trajectories approaches $2 billion per year by the end of the century, though substantial inter-annual variability is also observed.

Figure 17.3. Average Annual Damages by Region

Results represent the average of the five GCMs under RCP8.5 and RCP4.5.

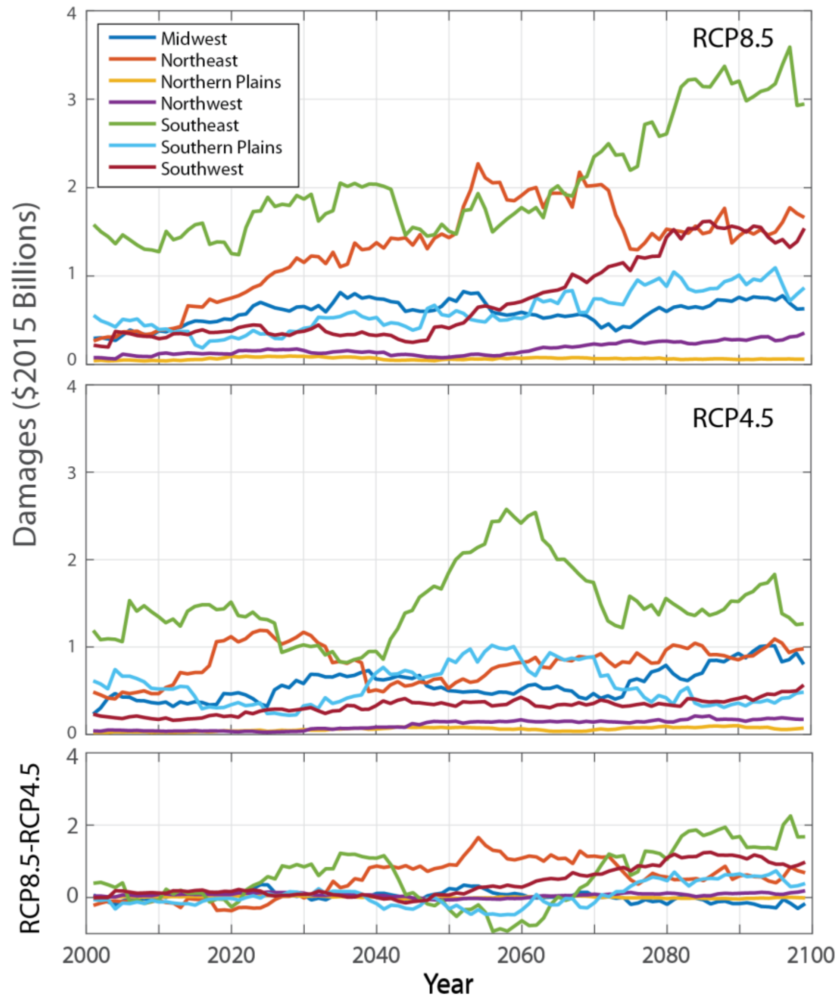


Table 17.1. Annual Damages from Flooding

Results for 2050 (2040-2059) and 2090 (2080-2099) represent the average annual damages from flooding of the five GCMs in billions of $2015.

Region	2050		2090	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Northeast	$1.6	$0.62	$1.5	$0.95
Southeast	$1.7	$1.8	$3.1	$1.5
Midwest	$0.67	$0.54	$0.69	$0.83
Northern Plains	$0.06	$0.07	$0.06	$0.08
Southern Plains	$0.51	$0.81	$0.90	$0.38
Southwest	$0.45	$0.36	$1.5	$0.41
Northwest	$0.10	$0.13	$0.28	$0.17
National Total	**$5.1**	**$4.3**	**$8.1**	**$4.3**

17.5 DISCUSSION

Increasing risks of flooding associated with climate change are consistent with the findings of the assessment literature[322] and other national scale analyses projecting flooding damages using different methodologies.[323,324] Projecting changes in local flood risk at a national scale can be challenging, and as such, several important caveats are important to note. First, the downscaling method used in developing the climate projections for this analysis was designed in part to improve GCM resolution of historical precipitation, but this method also introduces artifacts associated with the transition from the historical to future period (see Wobus et al. 2017 for more detail). An improved representation of precipitation extremes would improve confidence in the results. Second, the method is limited by available data on assets exposed to inland flooding. Because the 1% AEP floodplains are the only flood risk zones consistently mapped at a national scale, the approach only tabulates damages within these mapped floodplains, therefore missing damages in other areas, including pluvial (direct rainfall-driven) flooding. Third, this approach does not estimate flood damages from more frequent floods (e.g., 10- and 50-year events), nor does it account for the fact that larger flood events above the historical "100-year" event threshold will cause more significant damages than smaller ones. These factors combined signify that the results presented in this section are likely underestimates to total potential damages. Fourth, the estimated damages do not include impacts on human health or economic disruption, which are likely to increase the total economic impacts from flooding. Finally, the approach does not account for future adaptations to protect against changing flood risk; nor does it account for population growth or increasing development within flood risk zones. Future demographic and infrastructure changes could either increase or decrease damages from flooding in the future: flood protection could decrease damages,[325] while increases in development in the floodplain could increase them. Without reasonable means of predicting future flood development and protection changes, the analysis assumes that floodplain development and protection will on average remain static.

---

[322] Georgakakos, A., P. Fleming, M. Dettinger, C. Peters-Lidard, Terese (T.C.) Richmond, K. Reckhow, K. White, and D. Yates, 2014: Ch. 3: Water Resources. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J.M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 69-112. doi:10.7930/J0G44N6T.

[323] Das, T., Maurer, E. P., Pierce, D. W., Dettinger, M. D., and Cayan, D. R., 2013: Increases in flood magnitudes in California under warming climates, *Journal of Hydrology*, **501**, 101–110.

[324] Wobus, C., M. Lawson, R. Jones, J. Smith, and J. Martinich, 2013: Estimating monetary damages from flooding in the United States under a changing climate. *Journal of Flood Risk Management*, **7**, 217-229, doi: 10.1111/jfr3.12043.

[325] Climate change amplification of flood risk may also trigger proactive adaptation, such as people choosing not to move into flood-prone areas, or where zoning or insurance markets present clear barriers to moving there. These dynamics are not captured in this analysis.

18. WATER QUALITY

18.1 KEY FINDINGS

- Climate change is projected to have negative impacts on water quality in the U.S. as measured by water temperature, dissolved oxygen, phosphorous, and nitrogen levels. Water quality is projected to decrease across a large majority of the country under all models, scenarios, and time periods, but particularly under RCP8.5 in the Northeast, Southeast, and Midwest.
- Important regional differences are observed across the two water quality models used in the analysis, owing primarily to differences in model structure. Despite these regional differences, there is good agreement in changes of overall water quality, both in terms of the direction and magnitude of climate impacts.
- By 2090, national water quality damages are estimated at $4.3-4.8 billion per year under RCP8.5, and $2.6-3.3 billion annually under RCP4.5.

18.2 INTRODUCTION

Climate change is likely to have far-reaching effects on water quality in the U.S. due to increases in river and lake temperatures and changes in the magnitude and seasonality of river flows, both of which will affect the concentration of water pollutants. Rising water temperatures, reduced lake mixing, and increased biotic consumption of dissolved oxygen each reduce water quality. These physical impacts on water quality will have potentially substantial economic impacts, since water quality is valued for drinking water and recreational and commercial activities such as boating, swimming, and fishing.[326,327] The analysis presented in this section estimates the economic value associated with changes in the quality of recreation opportunities (e.g., swimming, boating, fishing), but does not quantify health effects.

18.3 APPROACH

This analysis estimates climate change effects on water quality at the eight-digit HUC scale of the contiguous U.S. using two biophysical models: Hydrologic and Water Quality System (HAWQS) and US Basins. HAWQS advances the functionality of the widely used and accepted Soil and Water Assessment Tool (SWAT), providing a platform for water quality modeling, primarily by minimizing the necessary initialization time.[328] This improves the ease of application to national scale analyses while still simulating a large array of watershed processes for a defined period of record. Originally developed by the U.S. Department of Agriculture (USDA), SWAT has been the core simulation tool for numerous U.S. national and international assessments of soil and water resources. The model follows a broad modeling

---

[326] Georgakakos, A., P. Fleming, M. Dettinger, C. Peters-Lidard, Terese (T.C.) Richmond, K. Reckhow, K. White, and D. Yates, 2014: Ch. 3: Water Resources. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J.M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 69-112. doi:10.7930/J0G44N6T.

[327] Luber, G., K. Knowlton, J. Balbus, H. Frumkin, M. Hayden, J. Hess, M. McGeehin, N. Sheats, L. Backer, C. B. Beard, K.L. Ebi, E. Maibach, R. S. Ostfeld, C. Wiedinmyer, E. Zielinski-Gutiérrez, and L. Ziska, 2014: Ch. 9: Human Health. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G.W. Yohe, Eds., U.S. Global Change Research Program, 220-256. doi:10.7930/J0PN93H5.

[328] Yen, H., P. Daggupati, M.J. White, R. Srinivasan, A. Gossel, D. Wells, and J.G. Arnold, 2016: Application of large-scale, multi-resolution watershed modeling framework using the hydrologic and water quality system (HAWQS). *Water*, **8**, 164, doi:10.3390/w8040164.

sequence: (1) the landscape phase, where the primary processes are climate, soil water balance, nutrient and sediment transport and fate, land cover, plant growth, farm management, and (2) the main channel phase, where the main processes are river routing, sediment and nutrient transport through the rivers and reservoirs.

US Basins is a linked water systems and water quality model designed to evaluate the impacts of climate change on water quantity and quality outcomes.[329] Precipitation and temperature from each climate scenario are inputs into: (a) a rainfall-runoff model (CLIRUN-II), which is used to simulate monthly runoff; and (b) a water demand model, which projects the water requirements of the municipal and industrial (M&I) and agriculture sectors. With these runoff and demand projections, a water resources systems model produces a time series of reservoir storage, release, and allocation to the various demands in the system, which include M&I, agriculture, transboundary flows, and hydropower. The water quality model (QUALIDAD[330]) uses managed flows and reservoir states from the water resources systems model to simulate a number of water quality constituents in rivers and reservoirs. Since US Basins does not include a representation of loading transport across the landscape, nonpoint loadings from the HAWQS landscape (phosphorus, nitrogen, and biological oxygen demand) are used directly in US Basins, equally distributed across each segment within the eight-digit HUC.

Each water quality model projects changes in water quality parameters, along with simulated changes in river flow, which are projected for five climate models under RCP8.5 and RCP4.5, with future municipal wastewater treatment plant loadings (point source) scaled to account for population growth.[331] Changes in overall water quality are estimated using changes in a Climate-oriented Water Quality Index (CWQI), a metric that combines multiple pollutant and water quality measures. Four water quality parameters (water temperature, dissolved oxygen (DO), total nitrogen, and total phosphorus) are aggregated from the eight-digit HUC level to the Level-III Ecoregions, weighted by area.[332] Finally, a relationship between changes in the CWQI and changes in the willingness to pay (WTP) for improving water quality is used to estimate the economic implications of projected water quality changes. For more information on the approach and results for the water quality sector, please refer to Fant et al. (2017),[333] Boehlert et al. (2015), and Yen et al. (2016).

18.4 RESULTS

Climate change will lead to the warming of rivers, lakes, and reservoirs across the country. Since water temperature is primarily driven by changes in air temperature, this water quality parameter shows the most similarity between the two water quality models (Figure 18.1).[334] The differences in spatial patterns that can be observed between the models are due to how future temperatures are simulated

---

[329] Boehlert, B., K.M. Strzepek, S.C. Chapra, C. Fant, Y. Gebretsadik, M. Lickley, R. Swanson, A. McCluskey, J. Neumann, and J. Martinich, 2015: Climate change impacts and greenhouse gas mitigation effects on US water quality. *Journal of Advances in Modeling Earth Systems*, **7**, 1326-1338. This paper includes a detailed flow diagram showing the suite of nested models involved in this analysis.

[330] Chapra, S.C., 2014: QUALIDAD: A parsimonious modeling framework for simulating river basin water quality, Version 1.1, Documentation and user's manual. Civil and Environmental Engineering Dept., Tufts University, Medford, MA.

[331] Key differences between the HAWQS and US Basins modeling frameworks are described in Fant et al. (2017).

[332] Designed to serve as a spatial framework for environmental resource management, ecoregions denote areas within which ecosystems (and the type, quality, and quantity of environmental resources) are generally similar. Ecoregions were originally created to support the development of regional biological criteria and water quality standards, and to set management goals for nonpoint source pollution.

[333] Fant, C., R. Srinivasan, B. Boehlert, L. Rennels, S.C. Chapra, K.M. Strzepek J. Corona, A. Allen, and J. Martinich, *2017*: Climate change impacts on US water quality using two models: HAWQS and US Basins. *Water,* **9**, 118, doi: 10.3390/w9020118

[334] Fant et al. (2017) describe the main differences in the reference period water quality parameters from both models, which can affect comparisons of future projections, and identifies the main causes for these differences.

in the two approaches and the influence of different projected changes in runoff and flow on water temperature.

Since DO is largely influenced by temperature through levels of DO saturation (i.e., higher temperatures reduce DO saturation levels, thereby reducing DO aeration),[335] decreases in DO are generally projected in the future. In both water quality models, there are consistent decreases in DO in the East (Figure 18.1). HAWQS shows large decreases in the Northeast, Southeast, and coastal regions of the Pacific Northwest, with areas of increases in the Midwest. Conversely, US Basins shows the largest decrease in DO in the Midwest. In both water quality models, changes in DO are largest for 2090 compared to 2050 and larger under RCP8.5 than RCP4.5.

Figure 18.1 shows percent change in total nitrogen concentrations. Both water quality models show increases in total nitrogen in the south-central U.S. and the area around the Great Lakes. HAWQS shows large increases in total nitrogen in the Southwest, while US Basins shows decreases in this region. As for changes in total phosphorus concentrations, HAWQS projects increases in phosphorus levels along the Southwest coast and Texas. In contrast, US Basins projects larger increases in the central U.S., especially in 2090, as well as in the East. Differences in nitrogen and phosphorus concentration changes can be explained primarily by the differences in flow changes for these two water quality models.

Reflecting changes in the underlying water quality parameters discussed above, Figure 18.2 shows changes in CWQI across the contiguous U.S. in 2050 and 2090 under the two RCPs. The CWQI serves as a measure of water quality; the higher the CWQI, the higher the water quality. Importantly, water quality is projected to decrease across a large majority of the country under all models, RCPs, and time periods. For both water quality models, changes in CWQI are more pronounced in the Northeast, Southeast, and Midwest regions of the country, primarily due to loadings and temperature being higher in this area. For HAWQS, changes in CWQI are largest along the East coast and in parts of the Southeast, although this pattern can also be seen in US Basins under RCP8.5. Compared to HAWQS, US Basins tends to show larger decreases in CWQI in the central U.S. and around the Great Lakes.

[335] DO is also influenced by changes in nitrogen, phosphorus, and BOD loadings, as well as changes in flow.

Figure 18.1. Change in Water Quality Parameters

The maps show the change in water quality parameters under RCP8.5 in 2050 (2040-2059) and 2090 (2080-2099) relative to the reference period (1986-2005). Results for each eight-digit HUC represent the average values across the five GCMs, and are aggregated to the Level-III Ecoregions.

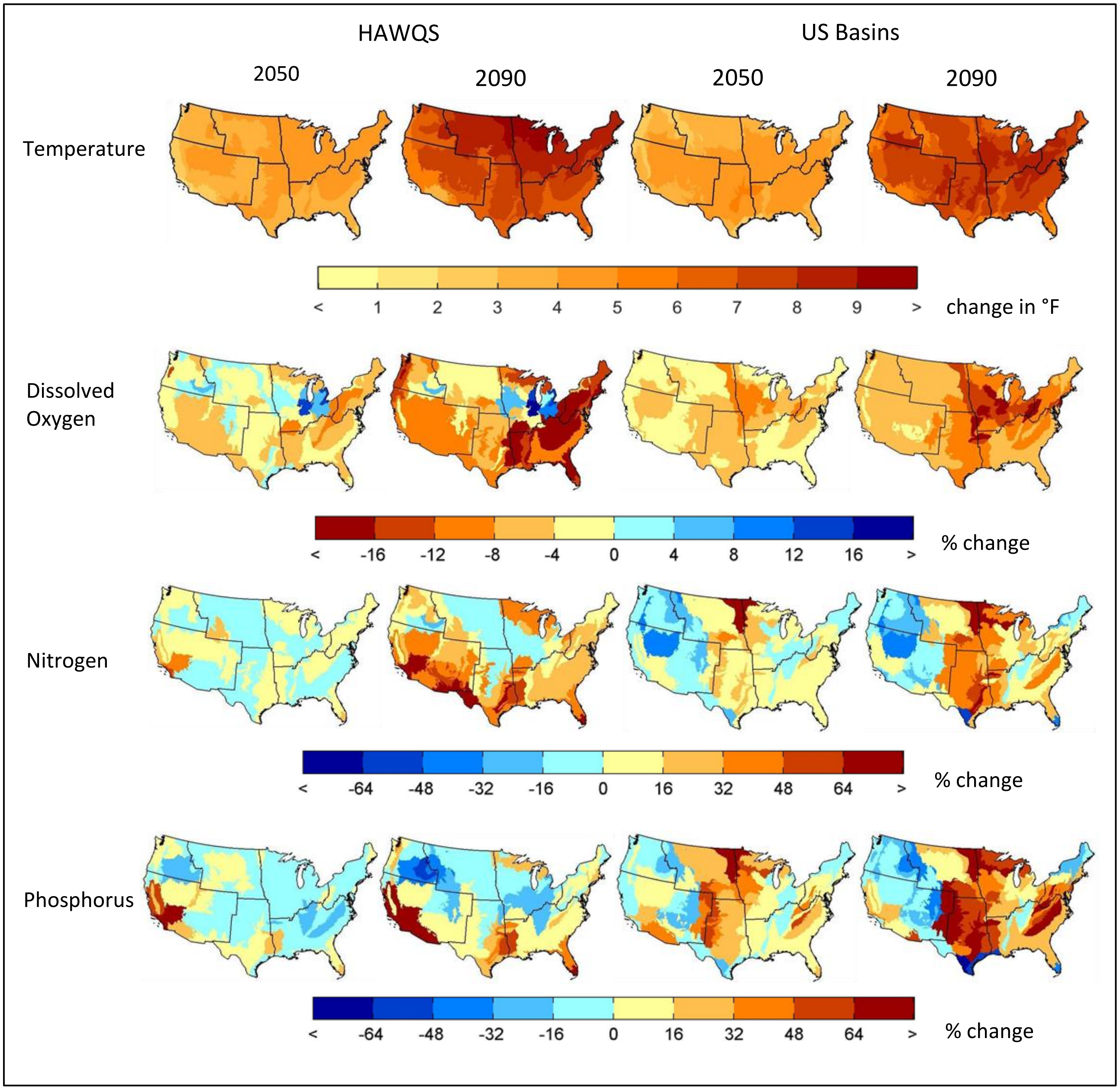
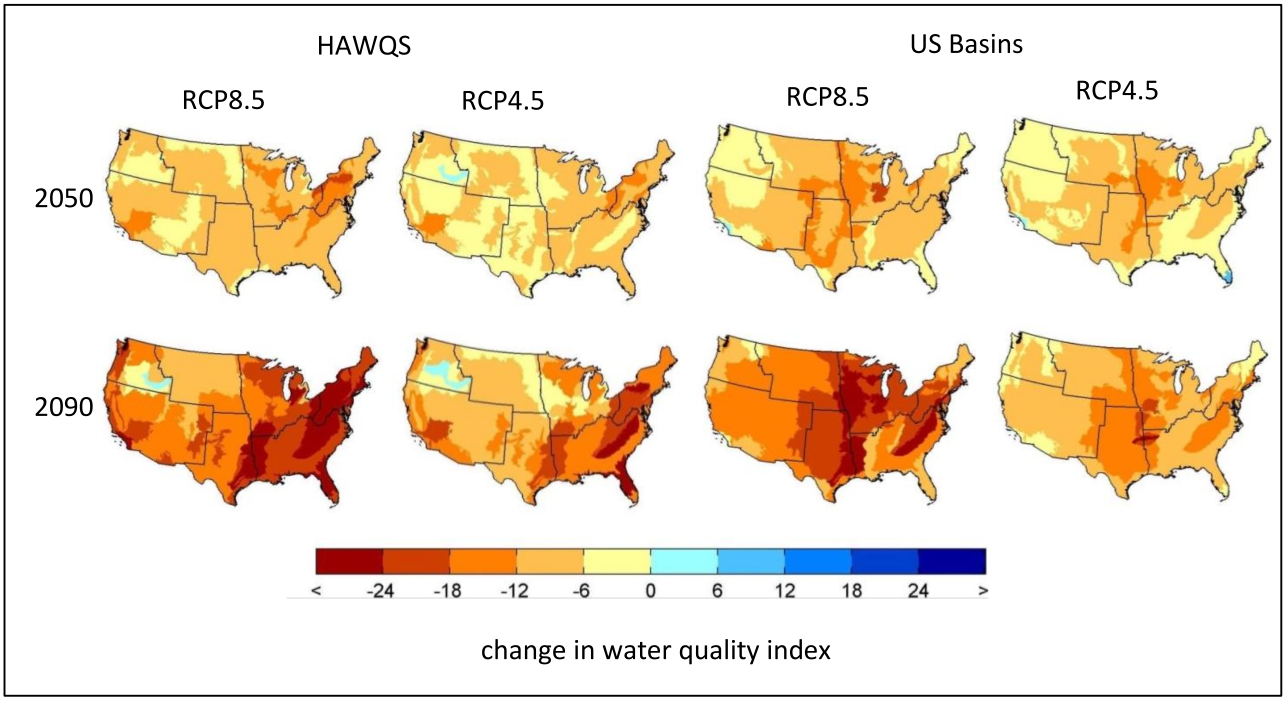


Figure 18.2. Changes in Mean Water Quality Index

Projected values for 2050 (2040-2059) and 2090 (2080-2099) represent changes relative to the reference period (1986-2005) across the contiguous U.S. The results are averages across the five GCMs, and are aggregated to the Level-III Ecoregions. For reference, the water quality index is based on a 100-point scale.



Total WTP is shown in in Table 18.1 for all five GCMs, RCPs, time periods, and the two water quality models. In all GCMs and water quality models, WTP decreases most for RCP8.5 compared to RCP4.5. Under RCP8.5, water quality damages for the five-GCM average are estimated at $4.3-4.8 billion annually by 2090, and $2.6-3.3 billion under RCP4.5 (with values solely representing recreational impacts). The largest changes in WTP are shown in the HadGEM2-ES GCM (on average, the hottest GCM modeled), with the least projected under GISS-E2-R (the coolest, comparatively). Table 18.2 presents WTP results across the NCA4 regions. Under results from both water quality models, projected damages are largest in the Northeast, Southeast, and Midwest, though substantial damages are also estimated for the Southwest under HAWQS.

Table 18.1. National Water Quality Damages to Recreation

The table presents estimated damages in 2050 (2040-2049) and 2090 (2080-2099). Results represent the national willingness to pay for improving water quality each (in billions $2015) for all five GCMs under RCP8.5 and RCP4.5.

	HAWQS				US Basins			
	2050		2090		2050		2090	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
CanESM2	$2.0	$1.6	$5.3	$3.1	$1.9	$1.6	$4.4	$2.6
CCSM4	$1.6	$1.2	$4.8	$3.1	$1.5	$1.2	$3.9	$2.3
GISS-E2-R	$1.4	$1.1	$3.6	$2.6	$1.3	$0.8	$3.2	$1.7
HadGEM2-ES	$2.8	$2.2	$5.7	$4.2	$2.5	$2.0	$5.2	$3.5
MIROC5	$2.0	$1.7	$4.8	$3.6	$2.2	$1.9	$4.8	$3.1
5-GCM Average	**$2.0**	**$1.6**	**$4.8**	**$3.3**	**$1.9**	**$1.5**	**$4.3**	**$2.6**

Table 18.2. Regional Water Quality Damages to Recreation

The table presents estimated damages in 2050 (2040-2049) and 2090 (2080-2099). Results are shown in billions of $2015 per year, and represent the average of the five GCMs for each RCP. Values may not sum due to rounding.

	HAWQS				US Basins			
	2050		2090		2050		2090	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Northeast	$0.47	$0.40	$1.1	$0.75	$0.39	$0.33	$0.88	$0.55
Southeast	$0.45	$0.35	$1.5	$1.0	$0.53	$0.39	$1.3	$0.85
Midwest	$0.32	$0.25	$0.61	$0.33	$0.45	$0.37	$0.89	$0.51
Northern Plains	$0.05	$0.04	$0.10	$0.05	$0.06	$0.05	$0.12	$0.08
Southern Plains	$0.20	$0.14	$0.55	$0.35	$0.24	$0.19	$0.52	$0.35
Southwest	$0.39	$0.33	$0.86	$0.67	$0.18	$0.15	$0.43	$0.24
Northwest	$0.07	$0.06	$0.17	$0.12	$0.05	$0.03	$0.11	$0.06
National Total	**$2.0**	**$1.6**	**$4.8**	**$3.3**	**$1.9**	**$1.5**	**$4.3**	**$2.6**

18.5 DISCUSSION

Projections that climate change will decrease river and lake water quality are consistent with the findings of the assessment literature,[336] and with a previous analysis focused on specific U.S. watersheds to characterize the sensitivity of streamflow, nutrient, and sediment loading to a range of climate and urban development scenarios.[337] The analysis presented in this section of the Technical Report

[336] Georgakakos, A., P. Fleming, M. Dettinger, C. Peters-Lidard, Terese (T.C.) Richmond, K. Reckhow, K. White, and D. Yates, 2014: Ch. 3: Water Resources. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program. doi:10.7930/J0G44N6T.

[337] U.S. EPA. Watershed Modeling to Assess the Sensitivity of Streamflow, Nutrient, and Sediment Loads to Potential Climate Change and Urban Development in 20 U.S. Watersheds (Final Report). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-12/058F, 2013.

contributes to the literature on water quality impacts by using two impact models to project long-term changes. Differences in these water quality projections between the two models point to dissimilarities in their structure and inherent bias of each water quantity and quality modeling component. As these are complex systems modeled over large geographic areas, inconsistencies in the outcomes of the two models are expected. Despite regional differences in projected water quality parameters between the two models, good agreement in water quality index was observed, both in terms of direction and magnitude of climate impacts.

Decreases in water quality due to climate change will likely have adverse effects on human health and the environment that are not represented in the results of this section. For example, climate change impacts to water quality may affect ecological dynamics of freshwater systems, with cascading effects on ecosystem services and recreational opportunities.[338] Also, this analysis only considers four water quality parameters, and omits other constituents, such as sediment and heavy metals, that may be affected by changes in the climate system. In addition, the methods underlying the analysis do not consider the effects of climate change-induced extreme events on water quality, such as increased siltation and runoff following wildfire events. Finally, the analysis considers only a subset of all use/non-use values linked to water quality changes, therefore the damages reported here are likely underestimates.

Simulation results illustrate a high degree of variability in the response of different streamflow and water quality attributes to climate change throughout the nation. Results also illustrate sensitivity to methodological choices such as different approaches for downscaling global climate change simulations and use of different watershed models.

[338] Please see the Harmful Algal Blooms section of this report, which projects changes in bloom activity and resulting effects on recreation.

19. MUNICIPAL AND INDUSTRIAL WATER SUPPLY

19.1 KEY FINDINGS

- Climate change is projected to alter precipitation patterns across the contiguous U.S., when combined with changes in temperature, will likely cause water shortages in some areas while increasing water availability in others.
- Estimated annual welfare losses at a national level are projected to be $320 million per year by 2090 under RCP8.5 and $210 million under RCP4.5, compared to the no-climate change control scenario.
- The effects of climate change on municipal and industrial water supply and demand vary over space. Cumulative discounted regional welfare impacts through 2100 range from a loss of $1.2 billion in the Southern Plains to a gain of $540 million in the Southeast under RCP8.5.

19.2 INTRODUCTION

Climate change is projected to affect municipal and industrial (M&I) water supply and demand due to changing temperatures and precipitation patterns.[339] Water supplied for industrial uses can include a broad range of activities, such as process water for manufacturing processes, industrial cleaning operations, cooling, and food processing. In this study, the industrial category excludes uses for cooling of thermoelectric power plants, which are discussed in the Electricity Demand and Supply section. Municipal (sometimes called "domestic") uses of water include two broad categories: outdoor uses (primarily for landscaping) and indoor uses (for bathing, cleaning, cooking, drinking, and sanitation). Indoor uses tend to require a lower volume on an annual basis, but are of higher economic value to consumers compared to outdoor uses. For example, when municipal water supplies run low, outdoor municipal uses are often the first to be curtailed. In 2010, public water supply withdrawals for municipal uses accounted for about 8 percent of all water withdrawals in the U.S.[340] Industrial uses (excluding thermoelectric cooling and mining) account for about 4 percent of all water withdrawals. Because of its high economic value, water supplied to the M&I sector is often the last sector to experience water shortages (as opposed to commercial agricultural irrigation, for example). The high value of M&I water also means that when unmet demands do occur, the economic impacts of these shortages tend to be large. The impacts of climate change on water supply and demands for sectors other than M&I, namely hydropower and irrigation are captured in the Electricity Demand and Supply and Agriculture sections of this Technical Report.

19.3 APPROACH

This analysis estimates the welfare loss to consumers of water associated with unmet M&I water demands (i.e., shortages) from climate change in the contiguous U.S. To develop these estimates, the analysis defines demand functions for three categories of M&I water demand: municipal indoor use, municipal outdoor use, and industrial use. Each demand is defined by a constant elasticity of demand

---

339 Georgakakos, A., P. Fleming, M. Dettinger, C. Peters-Lidard, Terese (T.C.) Richmond, K. Reckhow, K. White, and D. Yates, 2014: Ch. 3: Water Resources. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J.M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 69-112. doi:10.7930/J0G44N6T..

340 Maupin, M.A., J.F. Kenny, S.S. Hutson, J.K. Lovelace, N.L. Barber, and K.S. Linsey, 2014: Estimated use of water in the United States in 2010. U.S. Geological Survey, Circular 1405. Available online at https://dx.doi.org/10.3133/cir1405

where elasticity varies by category (outdoor elasticity = -0.6; indoor elasticity = -0.2; industrial elasticity= -0.4).[341,342]

Total demand data values are derived from the U.S. Geological Survey (USGS) National Water-Use Science Project.[343] These data are used for baseline water demand, as well as proportions used for allocating demand and unmet demand among use categories. Return flow fractions from the Water Supply Stress Index (WaSSI) Ecosystem Services Model from the USDA Climate Change Resource Center are used to assign unmet demand based on consumptive use.[344] All projected demands are scaled using population projections from EPA's Integrated Climate and Land-Use Scenarios (ICLUS) Version 2 model.[345] Unmet demands at the eight-digit HUC level are distributed among the three categories of demand based on a prioritization scheme where shortages are first expected to be absorbed by outdoor use. If unmet demand is greater than landscape demand, the remaining shortage is absorbed by industry. Finally, any remaining unmet demand after both outdoor and industry uses have been exhausted is taken from indoor municipal demand. [346]

Surface water supply estimates, and the water balance of supply and demand for all sectors, are generated using the US Basins model. US Basins characterizes the effects of climate change and water infrastructure on flow volumes, as well as water balance across demand sectors, at the eight-digit HUC level. The US Basins system employs GCM projections of precipitation and temperature as inputs to a rainfall-runoff model, which is used to simulate monthly runoff in each of the eight-digit HUCs, and a water demand model which projects the water requirements of the M&I and agriculture sectors. With these runoff and demand projections, the US Basins water resources systems model produces a time series of reservoir storage, release, and allocation to the various demands in the system, which include

---

[341] The demand function is $ln(Q) = \propto -\varepsilon \times ln(P)$. For examples of previous uses of this demand function for water see: Henderson, J., C. Rodgers, R. Jones, J. Smith, K. Strzepek, and J. Martinich, 2015: Economic impacts of climate change on water resources in the coterminous United States. *Mitigation and Adaptation Strategies for Global Change*, **20**, 135-157; and Cai, X., C. Ringler, and M.W. Rosegrant, 2006: Modeling water resources management at the basin level. Methodology and application to the Maipo River Basin. Research Report 149. International Food Policy Research Institute, Washington, DC.

[342] Elasticities derived from ranges provided in: 1) Renzetti, S., 1992: Estimating the structure of industrial water demands: the case of Canadian manufacturing. Land Economics, 396-404; 2) Espey, M., J. Espey, and W.D. Shaw, 1997: Price elasticity of residential demand for water: a meta-analysis. *Water Resources Research*, **33**, 1369-1374; and 3) Dalhuisen, J.M., R.J.G.M. Florax, H.L.F. de Groot, and P. Nijkamp, 2003: Price and income elasticities of residential water demand: a meta-analysis. *Land Economics*, **79**, 292-308.

[343] U.S. Geological Survey, cited 2017: The National Water-Use Science Project. Available online at http://water.usgs.gov/watuse/wunwup.html

[344] U.S. Department of Agriculture, cited 2017: WaSSI Ecosystem Services Model. Available online at https://www.wassiweb.sgcp.ncsu.edu/s

[345] EPA, 2017: Updates to the Demographic and Spatial Allocation Models to Produce Integrated Climate and Land Use Scenarios (Iclus) (Version 2). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-16/366F. Available online at https://cfpub.epa.gov/ncea/iclus/recordisplay.cfm?deid=322479

[346] Before calculating economic welfare loss, several eight-digit HUCs are removed from consideration in the analysis because the underlying model calculating unmet demand is unable to effectively simulate complexities of the water system supplies in those locations, either due to water connections (i.e., interbasin transfers) that are not modeled or to storage and groundwater access contingency plans for water supply in densely populated areas. This includes all HUCs with unmet demand in the reference period of over 20 percent, all HUCs adjacent or one-removed from a Great Lake, and any HUC with the majority of its area in a metropolitan statistical area (MSA) with a population of over 1 million people (where back up plans for unmet demand would be in place). A sensitivity analysis was run where the last group (HUCs with majority of area in an MSA) was included in the results. The five GCM average cumulative welfare losses were $55 billion and $37 billion in RCP8.5 and RCP4.5, respectively, about a fifteen-fold increase over the results presented in this assessment. While these areas are likely to incur some costs due to water shortages, it is unlikely that they would see the levels of unmet demand originally modeled that yield these large damage results due to existing emergency water source planning typical in highly populated areas.

M&I, agriculture, environmental flows, transboundary flows, hydropower, and others. US Basins is described more fully in Boehlert et al. (2015).[347,348]

Welfare losses are calculated at the eight-digit HUC level for each of the five GCMs and two RCPs, and a control scenario, which includes changes in demand due to population and per capita water use but no changes in the climate. Welfare change is estimated using M&I water supply prices from over 300 utilities nationwide,[349] with a willingness-to-pay cap set at five times the price. Final welfare loss estimates due to climate change for each scenario are calculated as the difference in consumer surplus loss between the control and climate scenario summed across the three demand categories.[350]

19.4 RESULTS

Future unmet M&I demands are a function of both climate change impacts on water supply and socioeconomic changes affecting demand (e.g. population growth, population shifts, and per capita water demand). The results of this analysis measure the incremental impacts of climate change only. National average unmet demand projections do not change dramatically due to climate change (a 0.16% change in unmet demand is projected annually by 2090 under RCP8.5, 5-model average). However, even small amounts of unmet demand, often concentrated in certain areas and time periods, can produce large welfare losses because of the high value of M&I water. As seen in Table 19.1, by 2090 the national annual average welfare loss estimates due to unmet M&I water demands for the five-GCM average is $320 million, with estimates for each model ranging from $190 million to $640 million under RCP8.5. The corresponding 2090 five-GCM average is $210 million for RCP4.5, reflecting individual model results that range from a gain of $9.0 million to a loss of $410 million. As would be expected, the GCMs projecting generally wetter futures (CanESM2 and GISS-E2-R) show lower damages than those projecting generally drier futures (MIROC5 and HadGEM2-ES).

Table 19.1. National Average Annual Welfare Loss

Results for 2030 (2020-2039), 2050 (2040-2059), 2070 (2060-2079), and 2090 (2080-2099) are shown in millions of $2015. Totals may not sum due to use of two significant figures and rounding.

	2030		2050		2070		2090	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
CanESM2	$120	$94	$68	$96	$170	$89	$220	$140
CCSM4	$100	$80	$100	$71	$140	$180	$190	$220
GISS-E2-R	-$22	$58	$26	$27	$160	$38	$190	-$9
HadGEM2-ES	$95	$120	$240	$150	$390	$180	$340	$310
MIROC5	$81	$61	$150	$240	$540	$310	$640	$410
5-GCM Average	**$76**	**$83**	**$120**	**$120**	**$280**	**$160**	**$320**	**$210**

[347] Boehlert, B., K. M. Strzepek, S. C. Chapra, C. Fant, Y. Gebretsadik, M. Lickley, R. Swanson, A. McCluskey, J. E. Neumann, and J. Martinich, 2015: Climate change impacts and greenhouse gas mitigation effects on U.S. water quality. *J. Adv. Model. Earth Syst.*, **7**, 1326–1338, doi:10.1002/2014MS000400.

[348] In most of the 8-digit HUCs (or basins), the demands and sources are assumed to be within the basin. However, the water systems model does include all major basin transfers (totaling over 100 transfers), the most significant of which are from the Colorado River to southern California. M&I supply is driven by the water demand in each HUC, which is taken from the U.S. Geological Survey's "Estimated Use of Water in the United States in 2005" report (Kenny et al. 2009). Municipal and industrial demands were aggregated from among the numerous categories of demands provided by Kenny et al. Changes in M&I over time are projected based on population changes and estimates of changes in consumption rates. See Boehlert et al. (2015) for more detail on these data and methods. Reference: Kenny, J. F., N. L. Barber, S. S. Hutson, K. S. Linsey, J. K. Lovelace, and M. A. Maupin (2009), Estimated use of water in the United States in 2005, U.S. Geological Survey Circular 1344, 52 p.

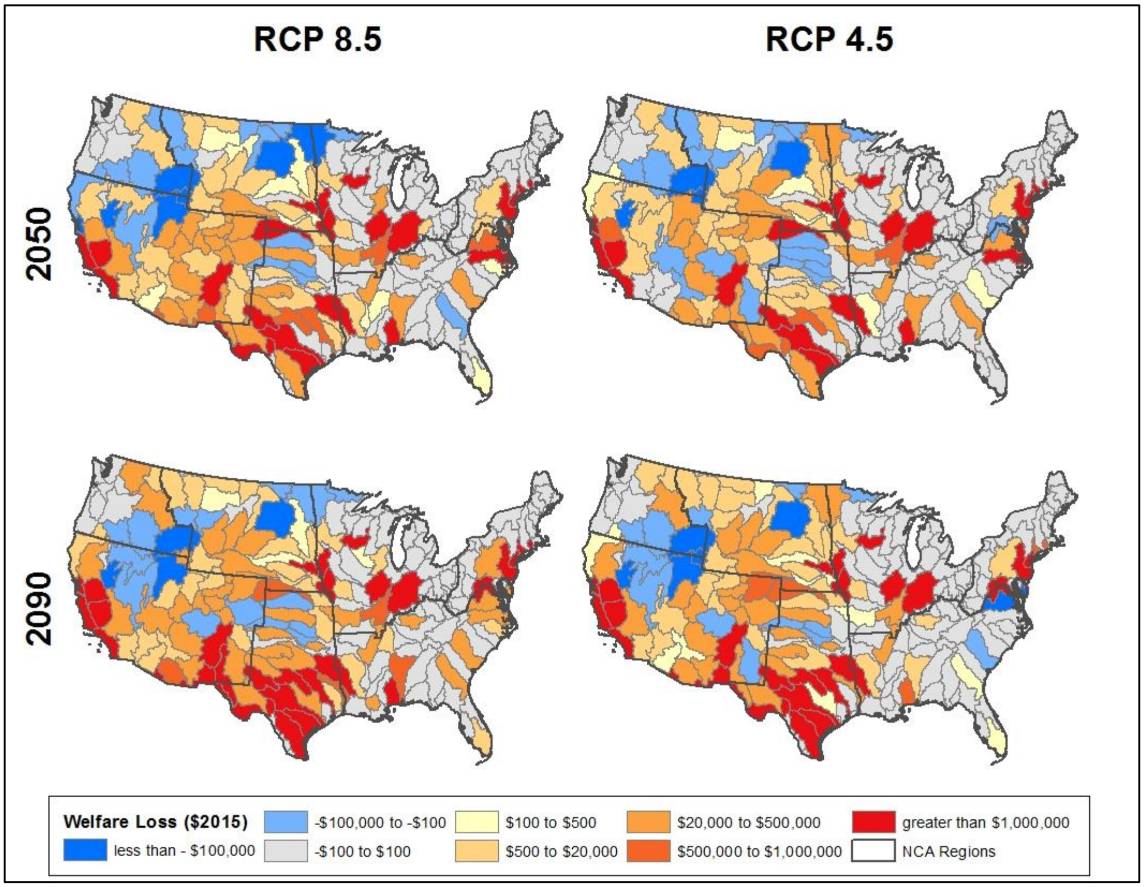
[349] Water prices from: American Water Works Association and Raftelis Financial Consultants. 2015. 2014 Water and Wastewater Rate Survey.

[350] A flat supply curve is assumed; therefore, no producer surplus is lost due to supply shortages. The consumer surplus loss is the value (price times quantity) of the quantity demanded less the quantity supplied.

Welfare impacts also vary by region, as changes in both future demands and climates vary over space. Figure 19.1 presents the average annual welfare loss by 2050 for the 5-model average under RCP8.5 by four-digit HUC. Lost welfare is concentrated in the Southwest and Southern Plains, while the Northern Plains and the Northwest see welfare gains. The magnitude of the losses, however, outweighs the gains at the national scale.

Figure 19.1. Average Annual Welfare Losses

Results for 2050 (2040-2059) and 2090 (2080-2099) represent the five-GCM average and are aggregated to the four-digit HUC scale.



Through the end of the century, climate change is projected to result in $3.7 billion and $3.0 billion in national welfare loss under RCP8.5 and RCP4.5, respectively (2015-2099, $2015, five GCM average, discounted at 3%). The impacts vary by region; as shown in Table 19.2, the Southeast and Northwest regions are projected to see cumulative welfare gains under both RCPs. Welfare losses are largest in the Midwest, Southern Plains, and Southwest regions. As noted earlier, these results are consistent the precipitation projections for each of the five GCMs.

Table 19.2. Regional Cumulative Welfare Losses

Results are shown in millions of $2015 for the period 2015-2099 (discounted at 3%). Totals may not sum due to rounding.

Region	RCP8.5	RCP4.5
Northeast	$730	$510
Southeast	-$540	-$580
Midwest	$1,200	$980
Northern Plains	$37	$58
Southern Plains	$1,200	$860
Southwest	$1,200	$1,200
Northwest	-$12	-$17
National Total	**$3,700**	**$3,000**

19.5 DISCUSSION

The incremental effect of climate change on M&I water supply and demand averaged across the country may appear small in absolute terms, however communities with insufficient water to meet household demands will see large negative welfare impacts. It is important to note that climate change is one of several factors that affect water shortages, particularly in the municipal sector. Factors such as increased population also affect supplies. The estimates presented in this section reflect total unmet demands for the M&I sector of between 0.87 and 2.0 percent of total demand by 2090 depending on the GCM and scenario. The analysis projects that without climate change, there would be an unmet demand of 0.75 percent due to population increases. Climate change therefore acts as a threat multiplier, exacerbating existing trends toward increased water shortages.

This analysis also does not consider changes in M&I demand that may be associated with climate change. It is possible that in drier future climates, shortages would be even greater than estimated due to an increase in water demand, particularly for outdoor municipal uses due to reduced soil moisture levels associated with more arid climates, but also for some industrial uses where uncovered pond storage may be less efficient owing to higher evaporation rates.[351]

The national annual welfare losses projected in this study are consistent with estimated impacts in 2050 from another study estimating welfare impacts of water supply and demand.[352,353] By excluding areas with water systems not captured in the water supply model, this assessment is a lower-bound estimate of the total impacts of climate change on M&I water supply and demand. While city residents may not ultimately be faced with unmet demands and associated welfare losses because of back up water supply plans, there will be a cost to water utilities of implementing these designs.

In general, the analysis does not consider the effectiveness of adaptation. One form of adaptation would be on the supply side, in the form of infrastructure construction to provide more resiliency (e.g., enhanced options for interbasin transfers, enhanced emergency storage, more extensive use of groundwater sources, conservation initiatives, or even desalination plants). While these adaptive responses could reduce the damages reported in this section, implementing some of these options

[351] However, accelerated evaporation rates from larger reservoir infrastructure are reflected in the US Basins supply calculations.

[352] Henderson, J., C. Rodgers, R. Jones, J. Smith, K. Strzepek, and J. Martinich, 2015: Economic impacts of climate change on water resources in the coterminous United States. *Mitigation and Adaptation Strategies for Global Change*, **20**, 135-157.

[353] The estimates for other years in Henderson et al. 2015 diverge from the estimates found in this analysis, likely due to the water allocation optimization methods used in the earlier study.

would likely require large infrastructure investments and could interact with water right compacts in some areas of the country. A second form of adaptation would be on the demand side, in the form of behavioral changes to reduce demand, or changes in industrial processes to less water-intensive forms of industry. Some of these patterns of demand change represent existing trends in water demand that are reflected in the demand projections, but these trends could accelerate (or slow) over the long time periods considered here. Both supply- and demand-side adaptation could in turn reduce the vulnerability of the M&I sectors to future water shortages.

20. WINTER RECREATION

20.1 KEY FINDINGS

- Climate change is projected to shorten the season lengths for downhill skiing, cross-country skiing, and snowmobiling across the country, especially under RCP8.5. Under RCP8.5 projections for 2090, the median closing date of downhill ski resorts nationally is more than a month earlier compared to the reference period, moving from early April to the end of February. However, a large amount of regional variability is projected, with the most significant reductions in season length occurring in the upper Midwest and the Northeast, and the smallest reductions occurring in the central Rockies and Sierras.
- Shorter season lengths will lead to reduced winter recreational opportunities at a national level. Under RCP8.5, national downhill ski visits are projected to decrease considerably from approximately 56 million in 2013 to 31 million by 2090. Ski visits under RCP4.5 are projected to decrease slightly to 53 million by 2090.
- These reductions in downhill skiing visits result in an estimated $2.0 billion in annual damages (lost revenue) by 2090 under RCP8.5. Reductions in annual cross-country skiing and snowmobiling visits by 2090 result in $10 million and $5.5 million under RCP8.5, respectively.
- By 2090 under RCP4.5, the national monetized impact on downhill skiing is positive, totaling $130 million in benefits even though visits are modestly reduced compared to the reference period – reflecting both adverse impacts from climate change and increased visits due to population growth.

20.2 INTRODUCTION

Warmer temperatures and changes in precipitation are expected to decrease the duration and extent of natural snow cover across the northern hemisphere. If there are fewer days in the winter season with sufficient snow, key components of the winter recreation industry will face challenges. While improvements in snowmaking technology can offset declines in natural snowfall at many ski resorts, continued warming temperatures are likely to delay opening dates with resulting effects on recreation. In addition, adaptive responses, such as snowmaking, are less effective for cross-country skiing and snowmobiling than for downhill skiing. Climate change-related threats to winter recreation could affect tens of millions of visits annually, and is expected to have important implications in areas where these industries are a substantial part of the economic activity of the region.

20.3 APPROACH

This analysis estimates the impacts of climate change on three types of winter recreation in the contiguous U.S.: downhill skiing and snowboarding, cross-country skiing, and snowmobiling. The analysis uses the Utah Energy Balance (UEB) model, a water and energy balance model which tracks snow-water-equivalent (SWE), internal energy of the snowpack, and snow surface age in its simulation of snow accumulation and melt. The model simulates natural snow accumulation and snowmelt at 247 winter recreation sites across the contiguous U.S. using site-specific climatic and topographic characteristics of each site. At each of the 247 modeled locations, results include a simulation of natural snowpack for the 20-year reference period (1986-2005), and future simulations for the 20-year periods centered on the reporting years of 2050 and 2090 for each of five GCMs under RCP8.5 and RCP4.5. Snowpack was modeled at the bottom and top elevation of each location.

For downhill skiing and snowboarding, results from the natural snow model are combined with projections of the resorts' abilities to make artificial snow in the future. These calculations are based on a tabulation of cumulative hours with temperatures cold enough to make snow (approximately 28°F wet bulb temperature). Because ski resorts typically need between 400-500 hours of snowmaking conditions to open for the season, the date at which this number of hours is reached is calculated under reference and future climate conditions (30-year periods). Opening date for downhill skiing and snowboarding was calculated as the first date with 10 cm SWE from the UEB model, or the date to reach 450 hours of snowmaking conditions, whichever comes earlier. The closing date was estimated as the last day with 10 cm SWE. Changes in season length for each of the recreation types are used to estimate changes in visits, which are then monetized. For the reference period, recreational activity levels for downhill skiing, cross-country skiing, and snowmobiling, as well as average ticket prices at ski facilities and entry fees at national forests, are derived from a combination of National Ski Areas Association (NSAA) and U.S. Forest Service National Visitor Use Monitoring (NVUM) data. Future recreational activity levels are scaled into the future to account for population growth using state-level ICLUS population projections described in Modeling Framework section of this Technical Report. For more information regarding the approach used in this analysis to estimate climate change impacts on winter recreation, please refer to Wobus et al. (2017).[354]

20.4 RESULTS

Projected changes in the length of the winter season for downhill skiing reflect the combined influence of early season temperature changes, which modify resorts' ability to make snow, and the changes in precipitation and temperature throughout the ski season, which control the water and energy balance that drives the natural snowpack. Figure 20.1 shows that, in general, climate change is projected to substantially shorten average downhill skiing season lengths at the majority of sites across in the U.S. However, the results range from increases in a very limited number of areas (under RCP4.5, 10 sites in 2050 and 4 sites in 2090; under RCP8.5, 6 sites in 2050 and none in 2090, with a maximum value of 83% increase relative to the reference period), to declines of more than 80% under RCP8.5 in many locations. The projected changes in season length presented in Figure 20.1, which represent the average of the five GCMs, are most dramatic in the Northeast and upper Midwest, and less dramatic in higher-elevation areas of the Rockies and Sierras. The few locations with increases in season length in 2050 are located in the upper Midwest. These increases in season length are driven primarily by projected increases in precipitation, which offset projected increases in temperature by mid-century. However, these effects are not as significant by the end of the century.

For most downhill skiing locations, being open for the Christmas and New Year's holidays is critical to remaining profitable and staying in business given the disproportionate share of revenue and profit realized in this period (note that other critical periods are the Presidents Day to Martin Luther King Day period). Earlier closing dates could also impact skier visits during the Spring Break period, which typically falls in March. Figure 20.2 shows that climate change is projected to have a larger impact on closing dates than opening dates across the combinations of RCPs and the two future time-periods considered.

In the most extreme reductions, observed for the RCP8.5 projections for 2090, the median closing date is more than a month earlier compared to the reference period, moving from early April to the end of February. In contrast, the largest shift in the start date from the reference period, which also occurs under RCP8.5 in 2090, involves a shift of several weeks from the initial beginning of December to the

---

[354] Wobus, C., E.E. Small, H. Hosterman, D. Mills, J. Stein, M. Rissing, R. Jones, M. Duckworth, R. Hall, M. Kolian, J. Creason, and J. Martinich. 2017. Projected climate change impacts on skiing and snowmobiling: A case study of the United States. *Global Environmental Change*. doi: 10.1016/j.gloenvcha.2017.04.006.

end of the month. Figure 20.3 provides the detailed summary of the season length projections for Aspen Mountain in Colorado. As shown, projected season lengths shorten over the century and under RCP8.5, though considerable variability is observed across the different GCMs, especially under RCP8.5 in 2090.

Figure 20.1. Average Percent Change in Downhill Ski Season Length

Estimates are based on a combination of water balance modeling and snowmaking results. Projected values for 2050 (2040-2059) and 2090 (2080-2099) represent changes relative to the reference period (1986-2005) across the contiguous U.S.

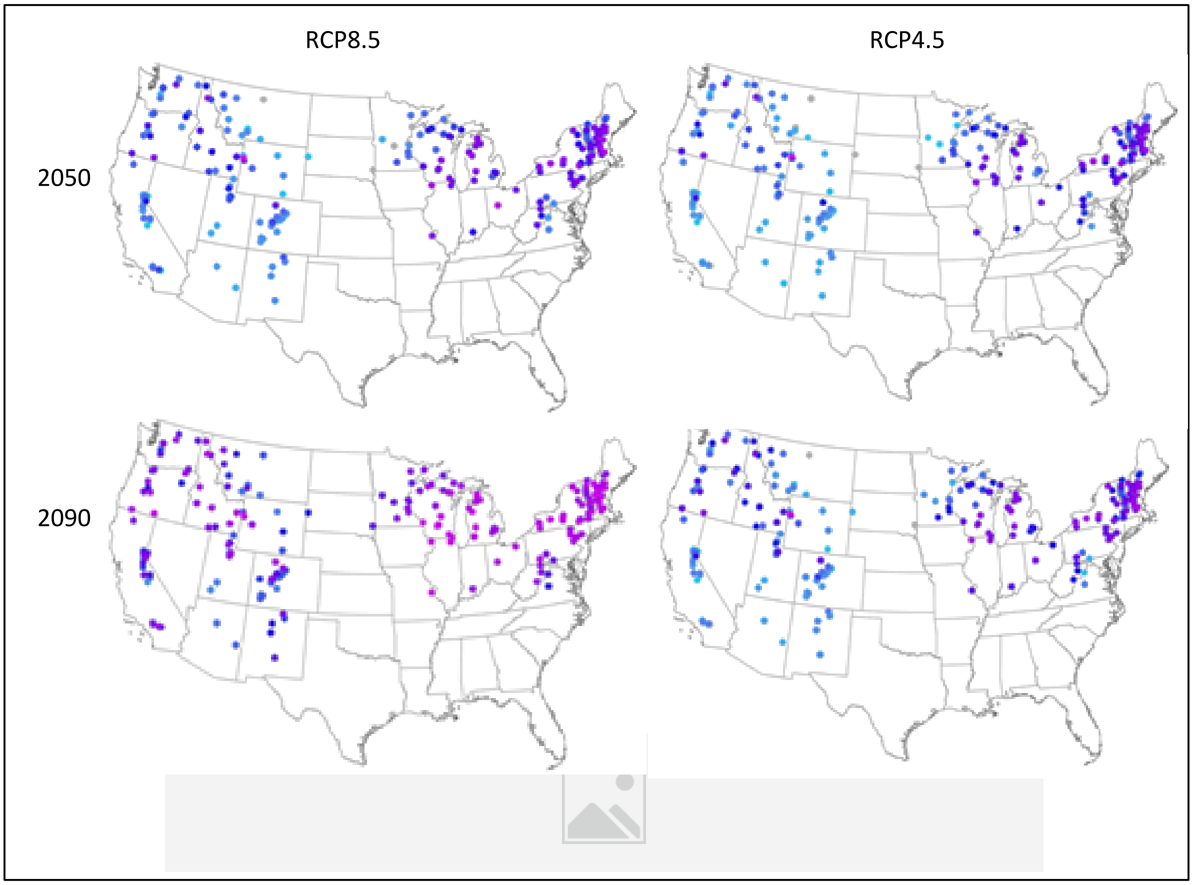
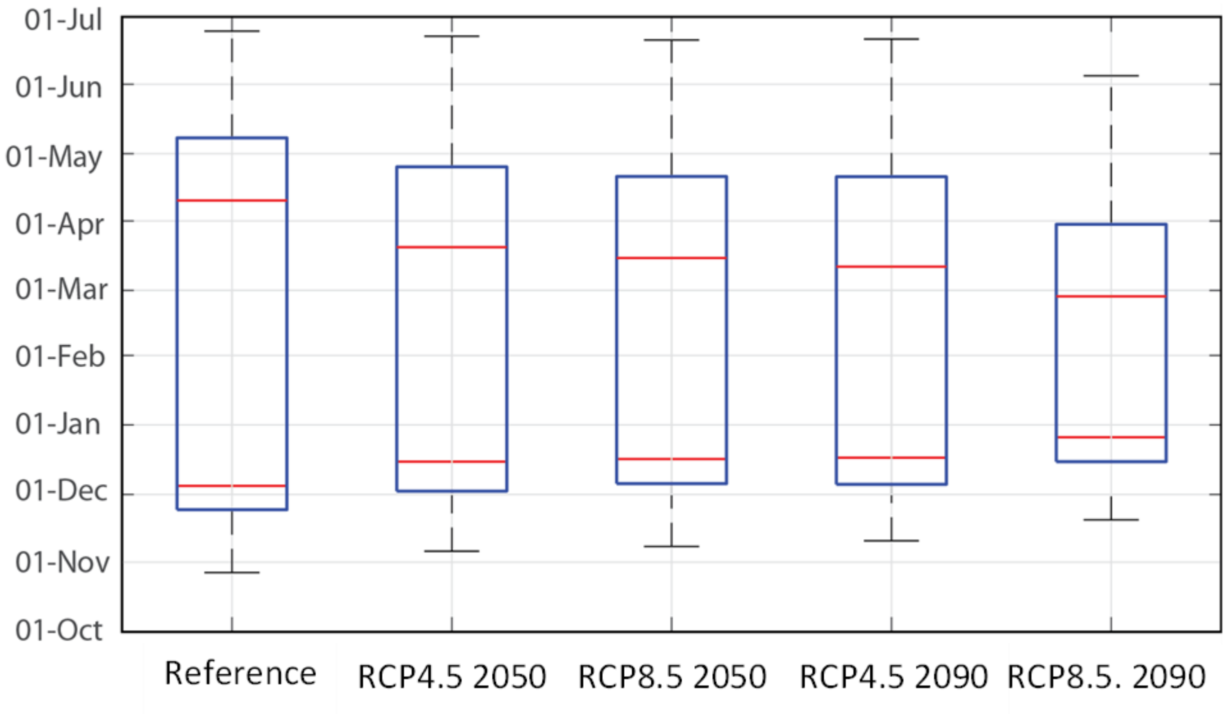


Figure 20.2. National Average Season Start and End Dates for the Downhill Ski Season

Results represent the five-GCM average for a given RCP for 2050 (2040-2059) and 2090 (2080-2099) relative to the reference period (1986-2005). The box and whiskers represent the distribution of results for the downhill ski season. Mean start dates are represented by red lines at bottom of the boxes and mean close dates are represented by the red lines at top of the box.



Across all modeled locations, average annual changes in cross-country skiing and snowmobiling season lengths across the GCMs range from small increases at some locations, to declines of more than 80% at others (Figure 20.4). In general, the most significant reductions in season length occur in the upper Midwest and the Northeast, and the smallest reductions occur at locations in the central Rockies and Sierras. Under RCP8.5, a substantially large fraction of the modeled locations is projected to experience average annual reductions from their reference period season length of > 80% compared to the RCP4.5 estimates.

Figure 20.3. Change in Season Length for Downhill Skiing at Aspen Mountain, CO
Results represent each GCM results for a given RCP for 2050 (2040-2059) and 2090 (2080-2099) relative to the reference period (1986-2005) for the Aspen Mountain, CO location. The box and whiskers represent the distribution of results for the downhill ski season length in number of days, with mean season lengths represented by the red line.

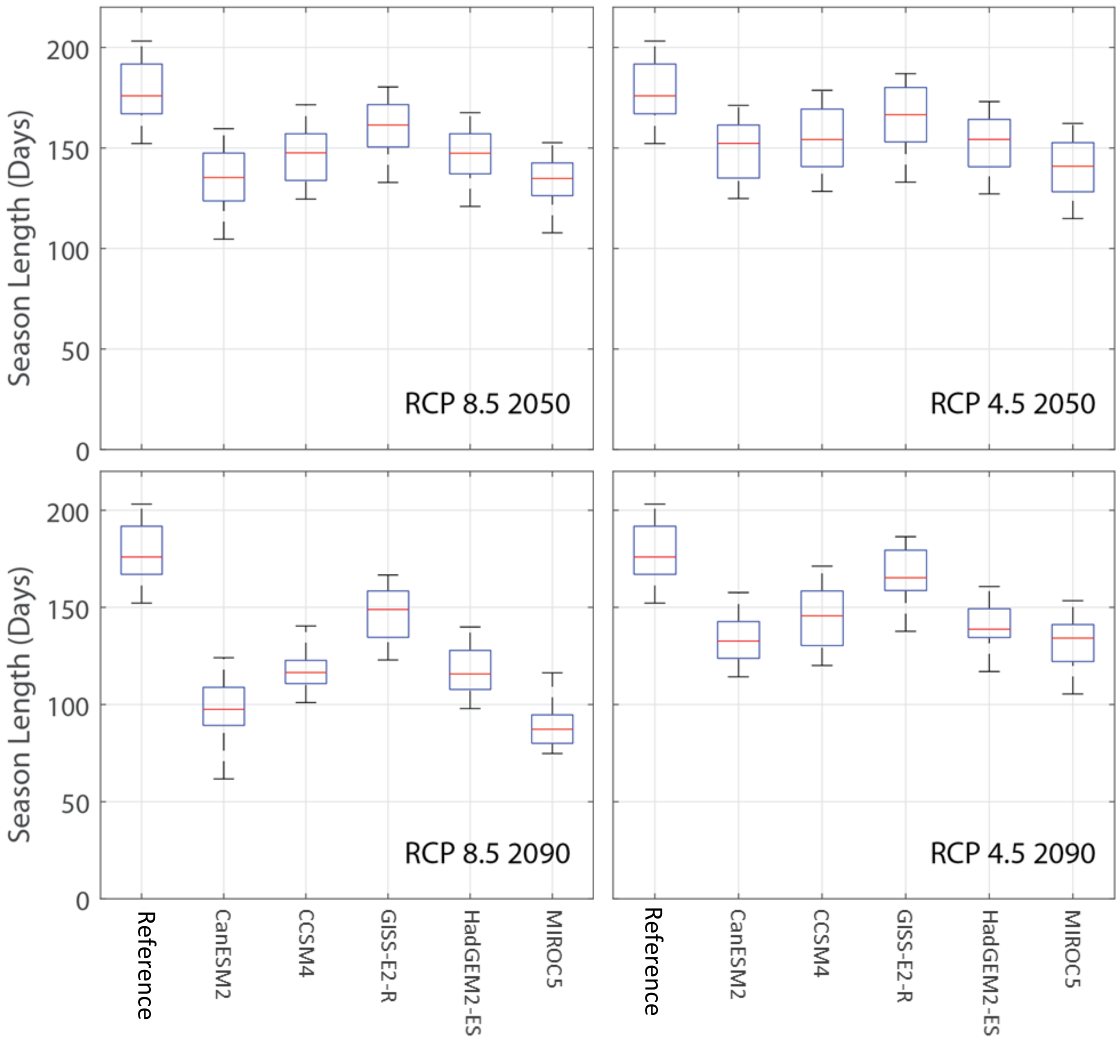
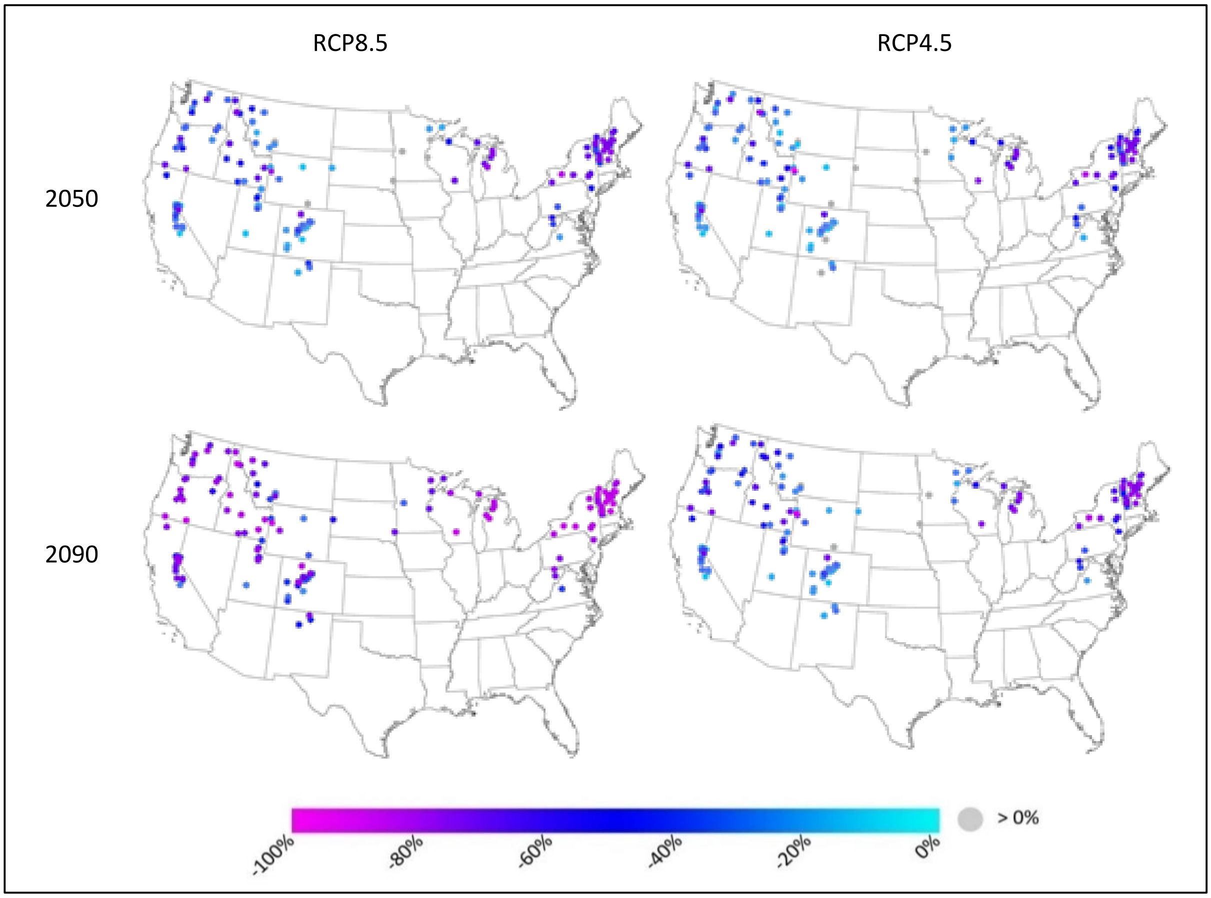


Figure 20.4. Average Percent Change in Annual Cross-Country Skiing and Snowmobiling Season Lengths

Results represent the five-GCM average for a given RCP for 2050 (2040-2059) and 2090 (2080-2099) relative to the reference period (1986-2005) across the contiguous U.S.



In this approach, future population growth increases the anticipated number of winter recreation participants and visits, which helps counteract adverse impacts of climate change. For all three recreation types, Table 20.1 shows the regional change in visits and dollars under RCP8.5 and RCP4.5, accounting for population growth and climate change. Under RCP8.5, national downhill ski visits decrease considerably after adjusting for changes in climate and population from approximately 56 million in 2013 to 31 million by 2090 (monetized impact equivalent to $2.0 billion in damages). Ski visits under RCP4.5 are projected to decrease slightly to 53 million by 2090, with an equivalent monetary impact of $130 million.[355]

For cross-country skiing and snowmobiling activity, projected recreational visits under RCP8.5 decrease in 2050 and 2090, even with increased participation due to population growth. Under RCP4.5, cross-

[355] By 2090 under RCP4.5, the national monetized impact on downhill skiing is positive, even though the change in visits is modestly negative. Although visits decrease at a national level under RCP4.5 in 2090, visits increased in the Southwest and Northern Plains regions where lift tickets are high, driving the monetized impacts slightly positive. Those regions include major ski areas states (for example, California, Colorado, and Utah are in the Southwest region and Montana and Wyoming are in the Northern Plains region) with high lift ticket prices of approximately $107-124 per visit, as opposed to approximately $60 to $80 per visit for the other regions.

country skiing visits increase slightly in 2050 and 2090, while snowmobiling visits decrease slightly in 2050 and increase slightly in 2090.

Table 20.1. Changes in Winter Recreational Visits and Economic Damages under Climate Change

Results represent the five-GCM average. Visits reported as millions of visits and monetized impacts are reported as millions of $2015, undiscounted. Totals may not sum due to rounding.

Winter Recreational Activities	Reference/2015		2050				2090			
			RCP8.5		RCP4.5		RCP8.5		RCP4.5	
	Visits (millions)	Dollars ($millions)	Change in visits	Monetized impact	Change in visits	Monetized impact	Change in visits	Monetized impact	Change in visits	Monetized impact
Downhill skiing	56	$5,400	-11	-$780	-6.8	-$350	-25	-$2,000	-3.2	$130
Cross-country skiing	3.6	$32	-0.09	-$1.1	0.22	$1.6	-1.1	-$10	0.63	$5.2
Snowmobiling	2.8	$13	-0.32	-$1.4	-0.11	-$0.53	-1.2	-$5.5	0.08	$0.35
Total	**62**	**$5,400**	**-12**	**-$780**	**-6.7**	**-$340**	**-28**	**-$2,000**	**-2.5**	**$130**

20.5 DISCUSSION

Physical models accounting for changes in the amount and duration of natural snow and ski resorts' ability to make snow demonstrate that the available time for winter recreation activities will decline at nearly all sites in the contiguous U.S. under climate change. Sites at higher elevations, such as the Rocky Mountains and Sierras, tend to be less affected by projected changes in temperature and precipitation, whereas sites at lower elevations, generally in the upper Midwest and New England, are more sensitive to climate change. These findings are consistent with a number of studies that have examined how climate change could influence seasonal snowpack in the western U.S.[356,357] These results also build on prior work related to winter recreation by combining the geographic breadth of previous studies,[358] with the detail that has historically been applied only to site- or regionally-specific studies.[359,360] However, the physical model was necessarily simplified in order to model nearly 250 specific sites across the U.S. More site-specific analyses could improve the model depiction of snowpack at any individual resort, but the computational demands of such an analysis would have been prohibitive at a national scale.

Several important caveats regarding the winter recreation analysis are summarized in this section. First, pressure on downhill ski resort operators from a sequence of short seasons or seasons with poor-quality conditions could possibly result in permanent closure. Since this analysis did not project potential ski area closures, the estimates of downhill skiing visits are conservative. Second, this analysis does not fully account for the different types of substitution that could arise with climate change (e.g., a switch from skiing to mountain biking), therefore conclusions about the net effects to recreational activity cannot be drawn. Finally, the industries supporting winter recreation are already experienced in addressing

[356] Mote, P.W., A.F. Hamlet, M.P. Clark, and D.P. Lettenmaier, 2005: Declining mountain snowpack in western North America. *Bulletin of the American Meteorological Society*, **86**, 39.

[357] Pierce, D.W. and D.R. Cayan, 2013: The uneven response of different snow measures to human-induced climate warming. *Journal of Climate*, **26**, 4148–4167.

[358] Burakowski, E. and M. Magnusson, 2012: Climate Impacts on the Winter Tourism Economy in the United States. Available online at https://www.nrdc.org/sites/default/files/climate-impacts-winter-tourism-report.pdf

[359] Lazar, B., and M. Williams, 2008: Climate change in western ski areas: Potential changes in the timing of wet avalanches and snow quality for the Aspen ski area in the years 2030 and 2100. *Cold Regions Science and Technology*, **51**, 219-228.

[360] Dawson, J. and D. Scott, 2013: Managing for climate change in the alpine ski sector. *Tourism Management*, **35**, 244–254.

variable winter conditions and could further implement innovative adaptive approaches that to provide greater resiliency than what is represented here.

AGRICULTURE

21. DOMESTIC YIELD AND WELFARE EFFECTS

21.1 KEY FINDINGS

- Climate change is projected to result in decreases in national yields for most major agricultural crops under both RCP8.5 and RCP4.5 through 2100. In general, larger declines are estimated under RCP8.5 than under RCP4.5. However, the direction and magnitude of crop yield response to climate change also varies by geographic region.
- As a result of declining yields, crop prices generally rise in the future under both RCPs compared to a no-climate change control scenario, with larger projected price increases under RCP8.5.
- Total cropland area increases to help meet demand in the face of falling yields, but national production and consumption of agricultural commodities are still projected to decline.
- Higher crop prices and lower production and consumption lead to generally negative effects on total economic welfare under both RCPs, with moderately larger losses under RCP8.5.

21.2 INTRODUCTION

The U.S. has a robust agriculture sector that produces nearly $330 billion per year in agricultural commodities.[361] The sector ensures a reliable food supply and supports job growth and economic development. In addition, as the U.S. is currently the world's leading exporter of agricultural products, the sector plays a critical role in the global economy.[362] Agricultural production is highly sensitive to climate conditions. Climate change will alter the spatial and temporal distribution of temperature and precipitation as well as the frequency and severity of extreme events, such as flooding and drought. These changes are likely to affect future agriculture productivity, and may lead to increased variability in yield. Changes in potential yields will shift land allocation, crop mix, and production practices throughout the U.S. These changes will affect commodity and production prices and the level of production and consumption of these goods.

---

[361] Hatfield, J., G. Takle, R. Grotjahn, P. Holden, R. C. Izaurralde, T. Mader, E. Marshall, and D. Liverman, 2014: Ch. 6: Agriculture. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 150-174. doi:10.7930/J02Z13FR.

[362] U.S. Congress, 2013: The Economic Contribution of America's Farmers and the Importance of Agricultural Exports. United States Congress, Joint Economic Committee, Vice Chair Amy Klobuchar. Available online at http://www.jec.senate.gov/public/_cache/files/266a0bf3-5142-4545-b806-ef9fd78b9c2f/jec-agriculture-report.pdf

21.3 APPROACH

This analysis estimates the effects of climate change on crop productivity in the contiguous U.S., and then simulates changes in market and economic welfare outcomes in the U.S. agriculture sector. To simulate the effects of climate change on crop productivity, the Environmental Policy Integrated Climate (EPIC) model[363,364] is used to simulate changes for eight crops: corn, soybean, wheat, alfalfa hay, sorghum, cotton, rice, and barley. Yield potential is simulated for each crop for both rainfed and irrigated production.[365] The EPIC model captures heterogeneous yield response to climate (including temperature, precipitation, relative humidity, wind speed, and solar radiation), which can vary depending on regional climate, soil type, irrigation status, and CO_2 levels. Because production regions may change over time in response to climate change, EPIC simulates potential cultivation and production in areas within 100 kilometers (62 miles) of historical production regions. EPIC is driven by changes in future climate projected by five GCMs under both RCP8.5 and RCP4.5, with comparisons to yields in the reference period of 1986-2005. The EPIC results presented in this section include the effect of CO_2 fertilization on crop yields; a sensitivity analysis of the effect of CO_2 fertilization on the crop yield results from EPIC are provided in the Appendix A.12. However, the yield projections presented in this Technical Report are based solely on one crop model. In addition, EPIC does not simulate the adverse effects from pests, disease, and ozone, and damage due to changes in the occurrence of storms, such as flooding, tornadoes, and hurricanes. Inclusion of these impacts on crop yields would likely result in larger adverse effects from climate change. For more information on the methods of EPIC modeling described in this section, please refer to Beach et al. (2015).[366]

The Forest and Agricultural Sector Optimization Model with Greenhouse Gases (FASOM-GHG)[367,368] was used to estimate changes in market and economic welfare outcomes in the U.S. agriculture sector. FASOM-GHG is driven by changes in potential yield from EPIC for each of the five GCMs under the two RCPs, and calculates changes in other crops based on the most relevant proxies. FASOM-GHG simulates future potential landowner decisions regarding crop mix and production practices, and projects the allocation of land over time to competing activities in the agricultural sector and the associated impacts on commodity markets.[369] Given the changes in potential yields projected by EPIC, FASOM-GHG uses an optimization approach (of the variables listed in the previous sentence) to maximize consumer and

---

363 Williams, J.R., 1995: The EPIC Model. In Computer Models in Watershed Hydrology, V.P. Singh (ed.), pp. 909-1000. Highlands Ranch, CO: Water Resources Publication.

364 Thomson, A.M., R.A. Brown, N.J. Rosenberg, R.C. Izaurralde, and V. Benson, 2005: Climate Change Impacts for the Conterminous USA: An Integrated Assessment. Part 3: Dryland production of grain and forage crops. Springer Netherlands, doi:10.1007/1-4020-3876-3.

365 The EPIC simulations assume that crops can be irrigated to a level that eliminates water stress. A particular concern for climate change is that in areas where the need for irrigation is greatest due to reduction in precipitation, the supply of water for irrigation will also be reduced. To fully consider this risk requires integration of crop modeling with hydrologic modeling for projections of future water supply, which was not modeled in this biophysical crop yield analysis.

366 Beach, R., Y. Cai, A. Thomson, X. Zhang, R. Jones, B. McCarl, A. Crimmins, J. Martinich, J. Cole, and B. Boehlert, 2015: Climate change impacts on US agriculture and forestry: benefits of global climate stabilization. *Environmental Research Letters*, **10**, doi: 10.1088/1748-9326/10/9/095004.

367 Beach, R., D. Adams, R. Alig, J. Baker, G. Latta, B. McCarl, B. Murray, S. Rose, and E. White, 2010: Model documentation for the Forest and Agricultural Sector Optimization Model with Greenhouse Gases (FASOMGHG): Draft Report. Prepared for U.S. Environmental Protection Agency. Available online at: http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers/1959FASOMGHG%20Model%20Documentation_DR_Aug2010.doc

368 Importantly, the agriculture-only version of FASOM-GHG was used in this analysis. As such, the interacting effects between agriculture and forestry, including the movement of land from forest to agriculture and vice versa, are not captured here. See Beach et al. (2015) for an example of a FASOM-GHG analysis looking at both the agriculture and forestry sectors.

369 FASOM-GHG is an intertemporal optimization model, which means decisions today are made with expectations of future potential conditions, including net returns and climate change effects, and thus can optimize near term land owner behavior. The model also simulates changes in agricultural commodities beyond those modeled in EPIC (eight crops).

producer surplus over time, which are the measures of economic welfare reported in the Results section.[370,371] The model is constrained such that total production is equal to total consumption, total U.S. land use remains constant, and non-climate drivers in the agriculture sector are consistent between the scenarios to isolate the effect of climate change.[372] Although the EPIC simulations assume that crops can be irrigated to a level that eliminates water stress, the FASOM-GHG simulations include shifts in water availability for irrigation based on data obtained from the water balance framework described in the Water Supply and Demand section of this report. Finally, this analysis does not reflect climate change impacts on international agriculture, which would also affect domestic relative returns to different uses of land and trade patterns and therefore affect land use decisions. These potential impacts are separately discussed in the following section of this report. For more information on the approach to using FASOM-GHG for estimating market and economic welfare impacts, please refer to Beach et al. (2015).[373]

21.4 RESULTS

Climate change is projected to have an overall adverse impact on the productivity of U.S. agriculture sector. Figure 21.1 presents the projected percent change in national crop yields through 2100 compared to reference yields under RCP8.5 and RCP4.5 (average results of the five climate models). For all major crops, with the exception of wheat,[374] unmitigated climate change under RCP8.5 is projected to result in lower yields by the end of the century compared to reference yield rates (though cotton yields are higher than the reference until just before the end of the century). Importantly, the projected magnitude of this effect increases with time, suggesting that higher levels of climate change increase the adverse effects to crop yields. Yields under RCP4.5 decline relative to the reference period for most crops, except for cotton, wheat, and sorghum. With the exception of hay and wheat, projected yields under RCP4.5 show smaller declines compared to those estimated for the higher forcing scenario. Compared to RCP8.5, RCP4.5 is projected to have a significantly smaller negative effect on the future yields of barley, corn, cotton, and rice. See Appendix A.12 for crop yield results comparing simulations with and without CO_2 fertilization.

---

[370] FASOM-GHG is optimized to maximize consumer and producer surplus in the base, but re-adjusts production and consumption patterns to re-optimize in response to changes in potential yields.

[371] Consumer and producer surplus are used to estimate impacts on total economic welfare. Consumer surplus is the monetary gain obtained by consumers because they are able to purchase a product for a price that is less than the highest price that they would be willing to pay. Producer surplus or producers' surplus is the amount that producers benefit by selling at a market price that is higher than the least that they would be willing to sell for.

[372] In addition, the analysis assumes no price incentives for avoiding GHG emissions or maintaining or increasing carbon sequestration in the agriculture sector (i.e., the sector does not participate in the global GHG mitigation assumed under RCP4.5).

[373] Beach, R., Y. Cai, A. Thomson, X. Zhang, R. Jones, B. McCarl, A. Crimmins, J. Martinich, J. Cole, and B. Boehlert, 2015: Climate change impacts on US agriculture and forestry: benefits of global climate stabilization. *Environmental Research Letters*, **10**, doi: 10.1088/1748-9326/10/9/095004.

[374] This finding is consistent with other recent reports (Marshall et al. 2015) which project an overall positive response of climate change on wheat yields in the contiguous U.S. However, estimated yields vary by region, based on the timing and magnitude of projected changes in temperature and precipitation. Importantly, crop model inter-comparisons have shown that projected changes in yield can vary considerably, and grow more variable over space and time. For example, Asseng et al. (2014) show a general trend towards decreasing wheat yields in the U.S. based on an ensemble mean of crop models. References: (1) Asseng, S., R. Ewert, P. Martre, R.P. Rötter, and D.B. Lobell, 2014: Rising temperatures reduce global wheat production. Nature Climate Change, 5, 143-147, doi: 10.1038/NCLIMATE2470, and (2) Marshall, E., M. Aillery, S. Malcolm, and R. Williams, 2015: Climate Change, Water Scarcity, and Adaptation in the U.S. Fieldcrop Sector. United States Department of Agriculture, Economic Research Service. Economic Research Report No. ERR-201. Available online at https://www.ers.usda.gov/publications/pub-details/?pubid=45496

Figure 21.1. Projected Percent Change in National Crop Yields

Results shown represent the average of the five GCMs under RCP8.5 and RCP4.5 compared to the reference period (1986-2005). Results are weighted averages of the individual irrigated and rainfed values from the EPIC model.

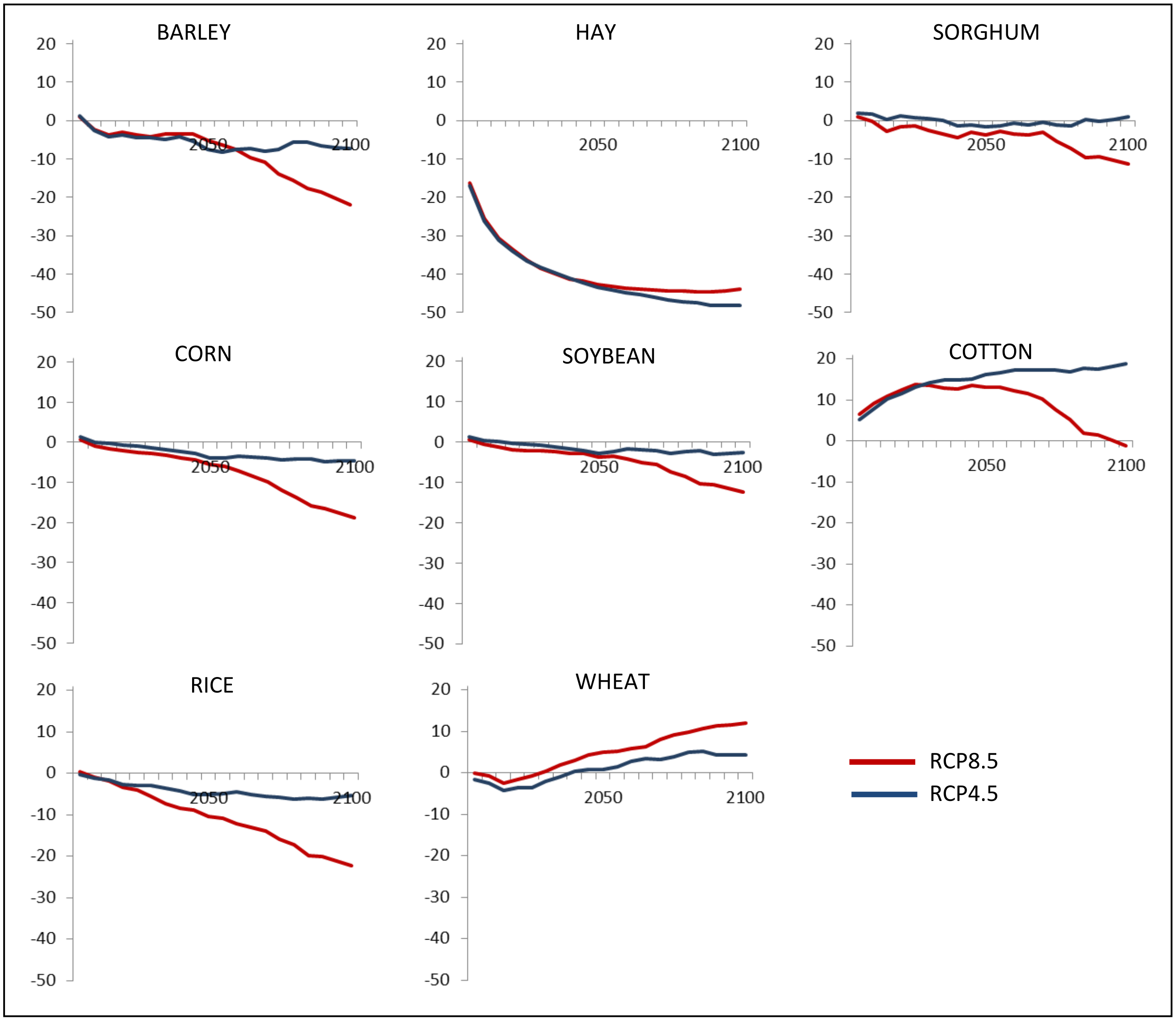
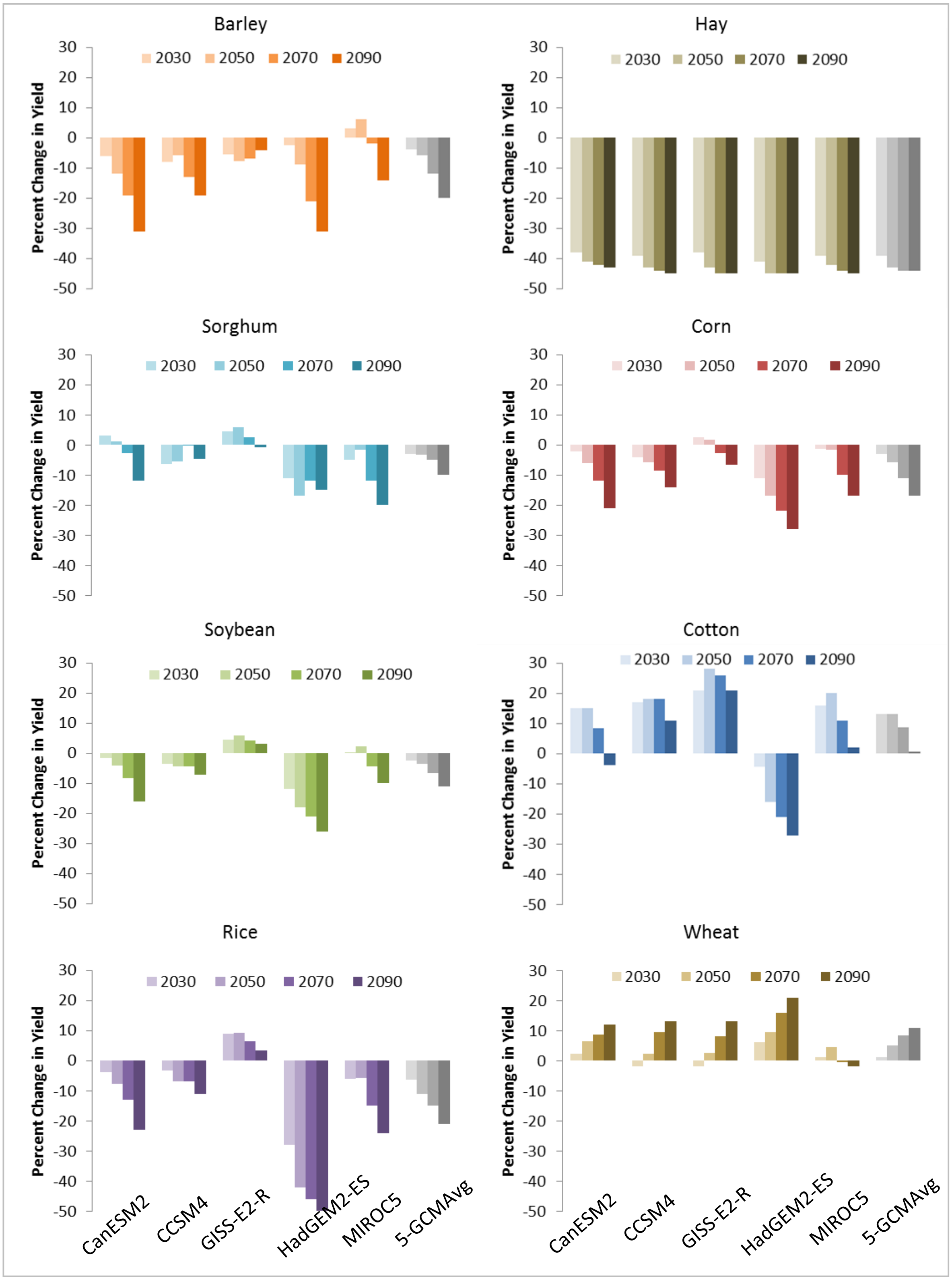


Figure 21.2 shows the projected change in national yield under RCP8.5 for the three largest U.S. crops (by area and production volume, not including hay) under the five different climate models, along with the ensemble average. In general, there is agreement in the direction of yield effects across the GCMs, although the magnitude of change varies by climate model and crop. In addition, the magnitude of change, whether positive or negative, increases over time in almost all cases. The largest change from reference yields is projected under the HadGEM2-ES model, which is the hottest model used in this analysis, with the exception of wheat where yield changes under this GCM are the most positive.

Figure 21.2. Projected Percent Change in Yield

Results shown represent projections by climate model and the average of the five GCMs under RCP8.5 compared to the reference period (1986-2005).



Spatial differences in projected climate change across the regions of the contiguous U.S. drive variability of crop yield response. Using the example of corn yields, Figure 21.3 shows the percent change by region under the two forcing scenarios, with uncertainty bands showing the range in response across climate models. As shown, yields under RCP8.5 are projected to decline considerably in the Midwest, Southeast, and Southern Plains. More modest losses are estimated for the Northeast, Northern Plains, and Southwest, with the Northwest showing moderate increases by mid-century and declines thereafter.

Figure 21.3. Percent Change in Projected Corn Yields by NCA Region

The graphs show the percent change in projected corn yields under RCP8.5 and RCP4.5 from 2006-2100 relative to the reference period (1986-2005). The bolded lines represent the five model average and the shaded cones reflect the minimum and maximum annual values from among the projected values across the five GCMs.

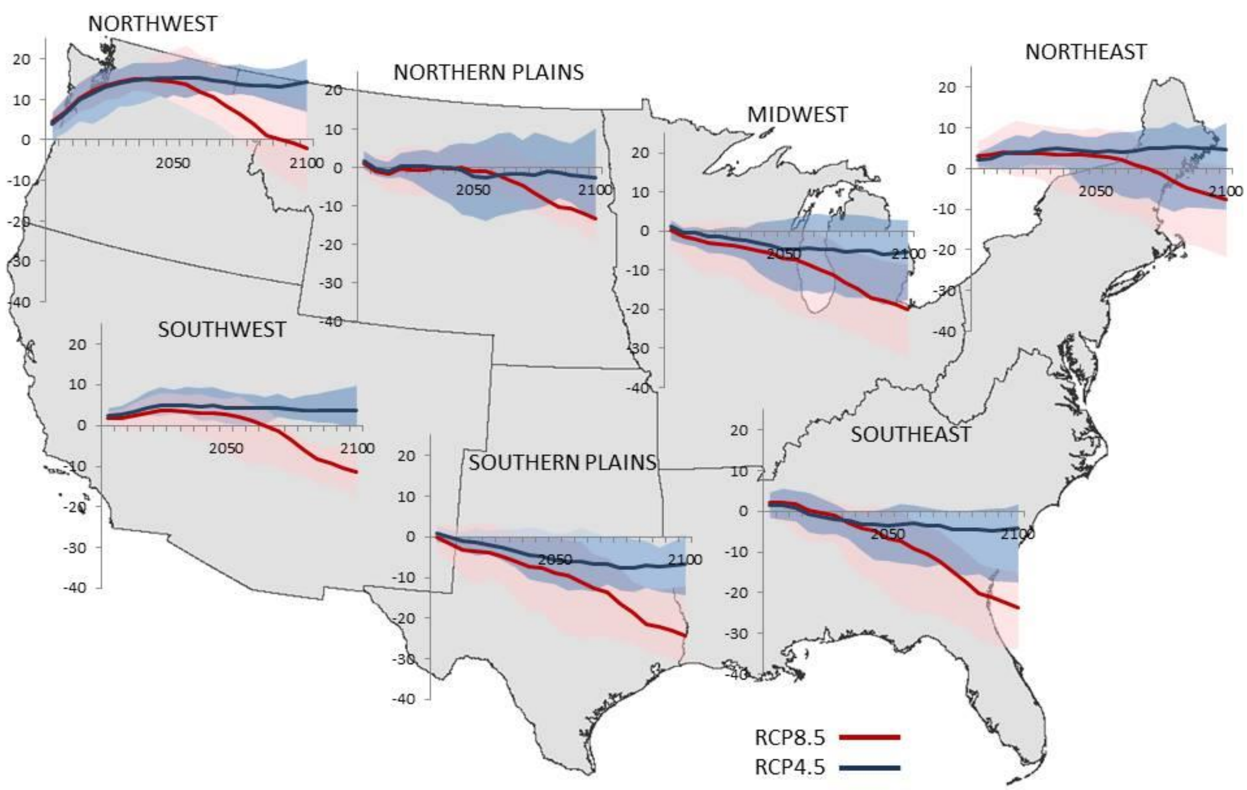


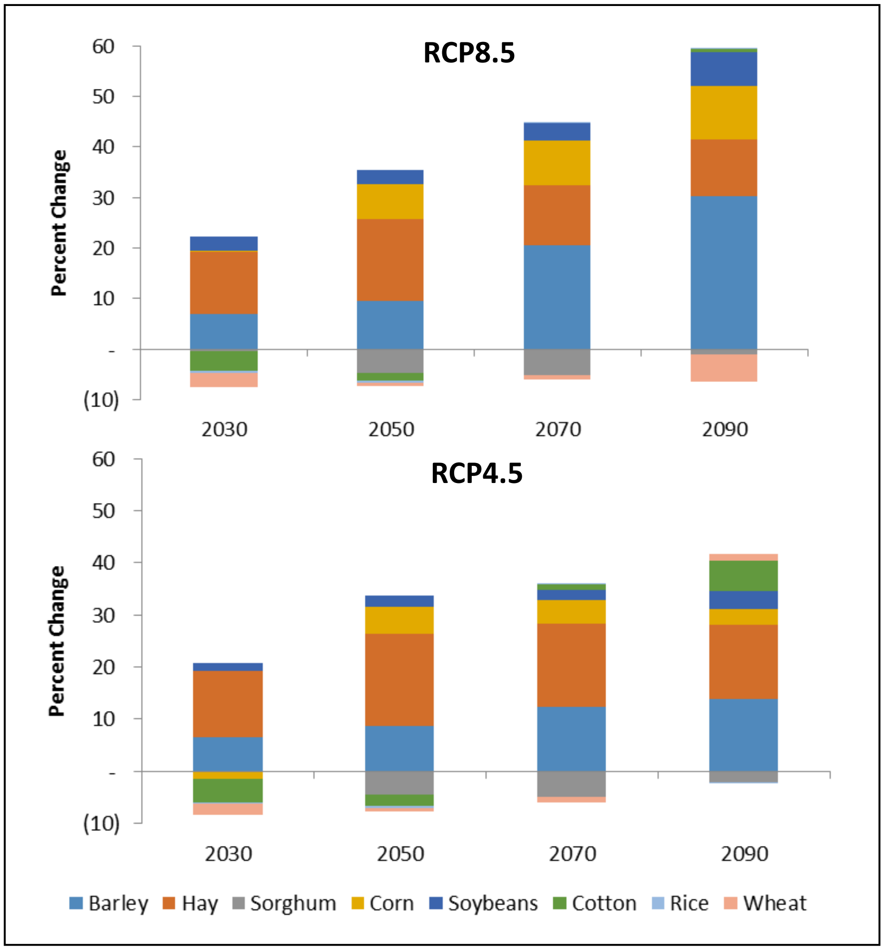
Figure 21.4 shows the projected change in total national acreage by crop under differing climate change scenarios.[375] In response to falling yields due to climate change, results show a general increase in total crop acreage relative to the no-climate change control scenario, as producers expand agricultural land to

[375] As an intertemporal model, FASOM-GHG makes land use decisions today are made with expectations of future potential conditions, including future climate change effects, and it therefore can optimize near term land owner behavior. The model also simulates changes in agricultural commodities beyond the eight crops modeled in EPIC and shown in Figure 21.4.

meet demands for these crop commodities.[376] Across crop varieties, acreage devoted to growing barley, hay, corn, and soybeans increase the most under RCP8.5, with small decreases in acreage for sorghum, wheat, and, through 2050, cotton. Similar patterns of change are observed under RCP4.5, though the magnitude of changes in acreage is generally smaller in the later parts of the century.

Figure 21.4. Average Percent Change in Total Acreage across the Eight Crop Types

Results, shown in millions of acres, are relative to a no-climate change control scenario.



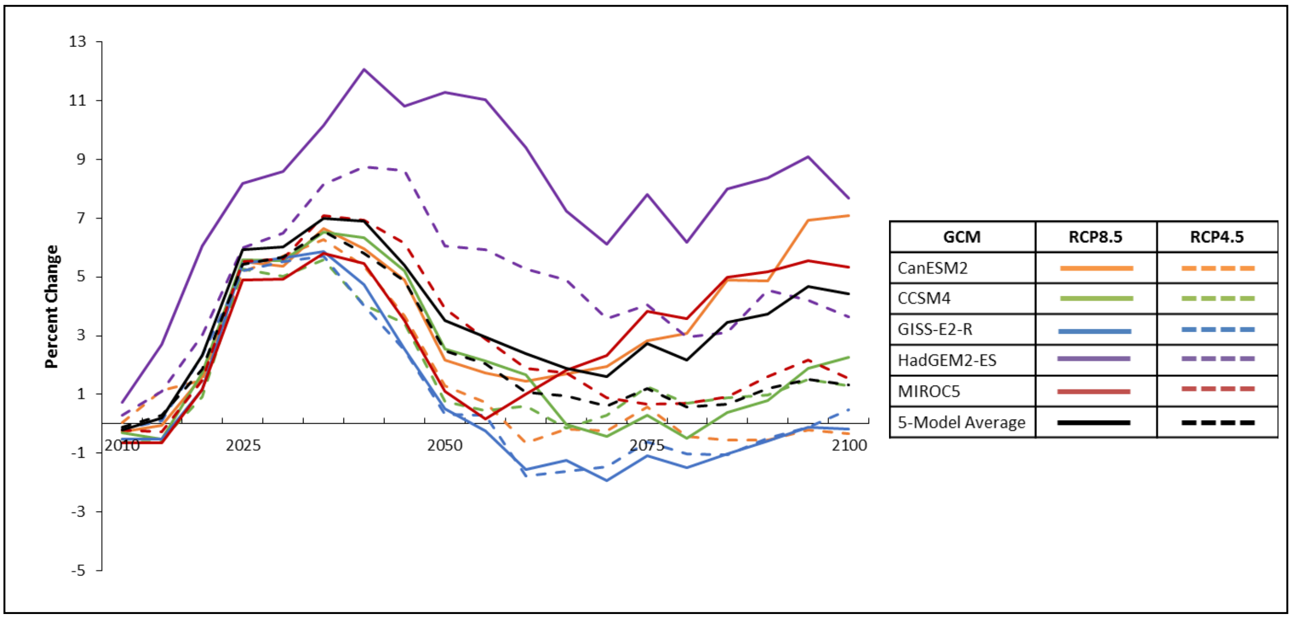
As described above, climate change, especially under RCP8.5, is projected in EPIC to result in generally lower crop yields in the U.S. Within the FASOM-GHG model, these yield effects create increased pressure on land resources (Figure 21.4) and increasing commodity prices. As shown in Figure 21.5, climate projections using the 10 GCM/RCP combinations generally show increases in crop prices of 1-11% by mid-century, and about 0-8% by 2100 (average prices across all crops modeled in FASOM-GHG). In almost all of the time periods, projected prices under each GCM are higher under RCP8.5 compared to RCP4.5. Price increases under RCP8.5 are largest under the hotter GCMs - HadGEM2-ES, CanESM2, and MIROC5. The smallest increases in prices are observed for the GISS-E2-R model, which even shows price declines for some years. One of the key drivers of the relatively larger price increases early in the

[376] The lower yields generally experienced under climate change tend to drive up market prices, leading producers to bring additional land into crop production. In these FASOM-GHG model scenarios, agricultural landowners are primarily converting cropland pasture (high-quality land currently being used as pasture) to crop production.

century (particularly 2020-2035) is the very large and rapid reduction in hay yields during this period. Not only does hay experience substantially more negative yield impacts than the other crops simulated using EPIC, but the majority of the yield reductions happen much earlier. As a result, land is being diverted from other crops to hay production, thus limiting the supply and driving up the price of wheat, potatoes, rice, barley, and other crops. As the yield reductions for hay begin to flatten out, the price impacts start to fall.[377] Prices then tend to increase again later in the century as the yield impacts for other major crops become more negative. Finally, these changes in land allocation, crop mix, and production practices in turn affect GHG emissions from agriculture. Figure A.12.2 in Appendix A.12 shows the estimated changes in cumulative GHG emissions from the agriculture sector.

Figure 21.5. Percent Change in Crop Price

*Values represent national changes in all crops aggregated into a single index***, r***elative to the no-climate change control scenario.*



The changes in crop prices and the level of production and consumption of agricultural products have important implications for the economic welfare of consumers and commodity producers. The FASOM-GHG model estimates these effects through changes in consumer and producer surplus, as summarized in Table 21.1. As shown in Table 21.1, climate change under both RCPs is projected to result in substantial decreases in total economic welfare (well-being) in the agriculture sector through 2100, with greater losses under RCP8.5. The cumulative, discounted (3%) decrease in total welfare is estimated at $190 ($160-260) billion through 2100 under RCP8.5, and $180 ($160-230) billion under RCP4.5. However, decreases in crop yield and the resulting price increases result in cumulative gains in producer surplus through the end of the century.[378] But as indicated by the total welfare estimates, the declines in

[377] FASOM-GHG incorporates assumptions about yield improvements taking place over time. All climate change yield impacts are implemented as relative changes in yields compared with these projections. Because yields are improving in the control scenario, there is a general trend towards reduced pressure on land resources over time. There is also more flexibility to reallocate land and change production practices farther into the future. Other things being equal, climate change impacts of a given magnitude that occur earlier in the century will be more difficult for the agricultural sector to adjust to and will result in larger price increases.

[378] Falling crop yields and resulting rising crop prices also drive up livestock prices and reduce production and consumption of livestock products, which is part of the overall decline in economic welfare from the agriculture sector as modeled in FASOM-GHG.

projected consumer surplus are larger than the increases in producer surplus, resulting in negative welfare effects overall.

Table 21.1. Cumulative Change in Welfare

Values represent the cumulative change in welfare across the 2010-2100 period relative to the reference period (1986-2005), and are discounted at 3% using billions of $2015. Totals may not sum due to rounding.

	Consumer Surplus		Producer Surplus		Total	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
CanESM2	-$290	-$260	$120	$86	-$180	-$170
CCSM4	-$280	-$260	$92	$99	-$180	-$170
GISS_E2_R	-$230	-$240	$68	$89	-$160	-$160
HadGEM2_ES	-$440	-$350	$190	$120	-$260	-$230
MIROC5	-$270	-$280	$97	$93	-$180	-$190
5-GCM Average	**-$300**	**-$280**	**$110**	**$97**	**-$190**	**-$180**

21.5 DISCUSSION

The results of this sectoral analysis are consistent with published studies focused on agricultural impacts. Projections of adverse yields resulting from unmitigated climate change, large regional differences in crop response, increasing vulnerability of water supplies for irrigation, and the ability of adaptation (via crop mix and land use management changes) to reduce adverse effects are consistent with the findings of the major climate science assessments.[379] In addition, the yield projections are generally consistent with findings of other recent analyses.[380,381]

Several important limitations of this analysis should be noted. First, the methodology does not reflect climate change impacts on international agriculture and related price and trade effects, which would also affect relative estimated returns to different uses of land and trade patterns and therefore affect land use decisions.[382] For example, incorporating negative impacts from climate change on yields in the rest of the world would tend to drive up global prices and make U.S. exports more competitive. Implications of international effects on U.S. agriculture are explored in the following section of this Technical Report. Second, the use of just one crop process model and one market model, both of which contain their own structural uncertainties, should be noted given the importance of these general uncertainties raised in recent model inter-comparisons.[383] Third, as mentioned above, this analysis does not consider interactions with and resulting market or GHG emissions effects from the forestry sector, which could impact net results. Fourth, several uncertainties in the FASOM-GHG analysis remain regarding issues such as future potential changes in crop technology, energy and land use policies, and other interactions that could affect market outcomes. Finally, this analysis omits important aspects of

---

[379] Hatfield, J., G. Takle, R. Grotjahn, P. Holden, R. C. Izaurralde, T. Mader, E. Marshall, and D. Liverman, 2014: Ch. 6: Agriculture. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 150-174. doi:10.7930/J02Z13FR.

[380] Marshall, E., M. Aillery, S. Malcolm, and R. Williams, 2015: Climate Change, Water Scarcity, and Adaptation in the U.S. Fieldcrop Sector. U.S. Department of Agriculture, Economic Research Service, ERR-201.

[381] EPA, 2015: Climate Change in the United States: Benefits of Global Action. United States Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-15-001.

[382] Leclère, D., P. Havlik, S. Fuss, E. Schmid, A. Mosnier, B. Walsh, H. Valin, M. Herrero, N. Khabarov, and M. Obersteiner, 2014: Climate change induced transformations of agricultural systems: insights from a global model. *Environmental Research Letters*, **9**, 124018, doi: 10.1088/1748-9326/9/12/124018.

[383] Rosenzweig, C., J. Elliot, D. Deryng, A.C. Ruane, C. Müller, A. Arneth, K.J. Boote, C. Folberth, M. Glotter, N. Khabarov, K. Neumann, F. Piontek, T.A. Pugh, E. Schmid, E. Stehfest, H. Yang, and J.W. Jones, 2013: Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proceedings of the National Academy of Sciences*, **111**, 3268–73, doi: 10.1073/pnas.1222463110.

climate change impacts to agriculture, including damages from extreme weather events, wildfire, and changes in weeds, pests, disease, and ozone damage. Collectively, these effects would likely result in larger yield losses than those estimated in this section.

22. U.S. AND GLOBAL AGRICULTURE INTERACTIONS

22.1 KEY FINDINGS

- Climate change impacts are projected to result in increased prices and decreased production and consumption for corn, soy, and wheat under all scenarios when compared with the control. Under RCP8.5, projected U.S. yields are lower, production declines are steeper, and prices rise more sharply than under RCP4.5 by 2050.
- Climate-driven changes to global agriculture will affect the U.S. agriculture market. The net difference in impacts between the U.S.-only and global scenarios is relatively small for corn and soybeans, but U.S. wheat output under the global scenarios results in a significantly smaller net change in crop area and total production, and higher net price impacts due to the relatively smaller global market share the U.S. commands for wheat than for corn or soybeans.

22.2 INTRODUCTION

This assessment offers a secondary climate impacts analysis for the U.S. agricultural sector, building upon the primary analysis described in the previous section using the FASOM-GHG modeling framework. While FASOM-GHG provides substantial detail on U.S. production systems and has endogenous trade flows, it does not have detailed global components and instead, holds agricultural supply functions fixed in the rest of the world. By assuming fixed global supply, a domestic market model like FASOM-GHG can respond to future domestic productivity changes by adjusting imports and exports of key commodities. This model component can act as a buffer to reduce the net welfare impacts of the exogenous domestic productivity changes. However, this approach does not recognize the impacts of climate change on agricultural productivity in the rest of the world, nor the resulting effects on competitiveness, international trade, and global markets. Thus, a more comprehensive summary of climate change impacts on the U.S. agriculture sector necessitates an understanding of global interactions.

22.3 APPROACH

This analysis evaluates climate impacts on U.S. agriculture with and without accounting for climate change impacts to agriculture in the rest of the world. This evaluation is accomplished through a scenario design that first isolates several climate change scenarios and crop yield impacts to the U.S. only, followed by scenarios that extend the climate impacts to the rest of the world using the Global Biosphere Management Model (GLOBIOM), a detailed partial equilibrium model of the global agriculture, forestry, and bioenergy sectors. GLOBIOM partitions the world into 30 economic regions, in which a representative regional consumer optimizes consumption depending on income, preferences, and product prices. On the production side, producers maximize their margins and the model solves for a market equilibrium corresponding to overall welfare maximization.

GLOBIOM is combined with a global version of the Environmental Policy Integrated Climate (EPIC) crop model to calculate the impact of climate change on the agricultural sector. EPIC is used to simulate yields for each global location, management practice, and climatic scenario. For this study, EPIC was applied to estimate the biophysical and environmental parameters of 18 crops for three different types of management systems (low input rainfed, high input rainfed, and irrigated systems). In this analysis, EPIC results are driven by global climate projections under RCP8.5 and RCP4.5 in the HadGEM2-ES

GCM,[384] and with full CO_2 fertilization effects.[385] The EPIC simulations include some adjustments in crop management intensity in response to climate, such as marginal changes to fertilizer and irrigation water use, as well as shifts in annual planting and harvesting dates. Other larger scale adjustments (e.g., management intensification from high input rainfed to high input, irrigated) are determined by GLOBIOM.

For additional information on the model structure, parameters, and the approach to analyzing interactions between U.S. and global agriculture markets in response to climate change, please see Havlík et al. (2011);[386] Havlík et al. (2014);[387] and Leclère et al. (2014).[388]

22.4 RESULTS

This analysis focuses on three primary crop groups that account for more than 50% of the current U.S. cropland base: corn, soybeans, and wheat. Figure 22.1 shows changes in the output (yield, crop area, production, consumption, and prices) of these three crops in 2050 relative to a no climate change control scenario. In general, projected yields are lower, production declines are steeper, and prices rise more sharply under RCP8.5 compared to RCP4.5.

As shown in Figure 22.1, projected corn yields under RCP8.5 decline more than 20% from the control, even when accounting for CO_2 fertilization and allowing land management responses to buffer against the climate-induced yield change. As yields decrease, more land area shifts to corn production, resulting in corn area increases of 11%-12% under RCP8.5, but total production still falls by approximately 12% and corn prices increase more than 70%. Under RCP4.5, net impacts are smaller, with total production and corn area declining less than 5% relative to the control, and a corresponding net price increase ranging approximately 15%-17%. While the impact on net yield for corn is close to zero under RCP4.5, corn area declines relative to the control, a result partially driven by improved productivity and utilization of grasslands for livestock feeding as a substitute to traditional feed grains (note that the proportionate change in consumption of corn for feed is higher than consumption for food).

Under RCP8.5, projected impacts on U.S. soybean systems are similar in direction, though slightly larger in total magnitude relative to corn. Under this scenario, projected soybean yields decline more than 25% and prices rise more than 75%. Impacts on U.S. soybeans under RCP4.5 are more notable than for corn, with yields declining approximately 13%-15% relative to the control. Similar to corn, crop area, total

[384] Globally-downscaled datasets using CMIP5 GCMs with the full suite of climate variables needed to run EPIC are limited. Of the available data from the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP: www.isimip.org), the HadGEM2-ES model matches one of the five GCMs used throughout the sectors of this Technical Report, and was thus selected for this GLOBIOM analysis. As shown in the domestic FASOM-GHG results, the HadGEM2-ES projections for the contiguous U.S. resulted in the largest changes in yields for major crops, the largest increase in crop price index, and the most negative welfare impacts. At a global level, the HadGEM2-ES model shows one of the warmest responses to changes in radiative forcing among the CMIP5 models. Thus, by choosing to focus on this GCM, this analysis ensures a relatively strong global climate signal to help identify the relative impacts of accounting for impacts in the rest of the world on U.S. agriculture.

[385] The effect of net CO_2 fertilization on crop yields is still debated in the literature (Tubiello et al., 2007), so EPIC simulations were run to produce crop yield impact estimates assuming both “no” and “full” CO_2 fertilization. Scenarios applied to this study assume full fertilization. Source: Tubiello, F.N., J.S. Amthor, K.J. Boote, M. Donatelli, W. Easterling, G. Fischer, R.M. Gifford, M. Howden, J. Reilly, and C. Rosenzweig, 2007: Crop response to elevated CO_2 and world food supply - A comment on "Food for Thought..." by Long et al., Science 312: 1918-1921, 2006. *European Journal of Agronomy*, **26**, 215-223.

[386] Havlík, P., U.A. Schneider, E. Schmid, H. Böttcher, S. Fritz, R. Skalsky, K. Aoki, S. De Cara, G. Kindermann, F. Kraxner, S. Leduc, I. McCallum, A. Mosnier, T. Sauer, and M. Obersteiner, 2011: Global land-use implications of first and second generation biofuel targets. *Energy Policy*, **39**, 5690-5702.

[387] Havlík, P., H. Valin, M. Herrero, M. Obersteiner, E. Schmid, M.C. Rufino, A. Mosnier, P.K. Thornton, H. Bottcher, R.T. Conant, S. Frank, S. Fritz, S. Fuss, F. Kraxner, and A. Notenbaert, 2014: Climate change mitigation through livestock system transitions. *Proceedings of the National Academy of Sciences*, **111**, 3709-3714.

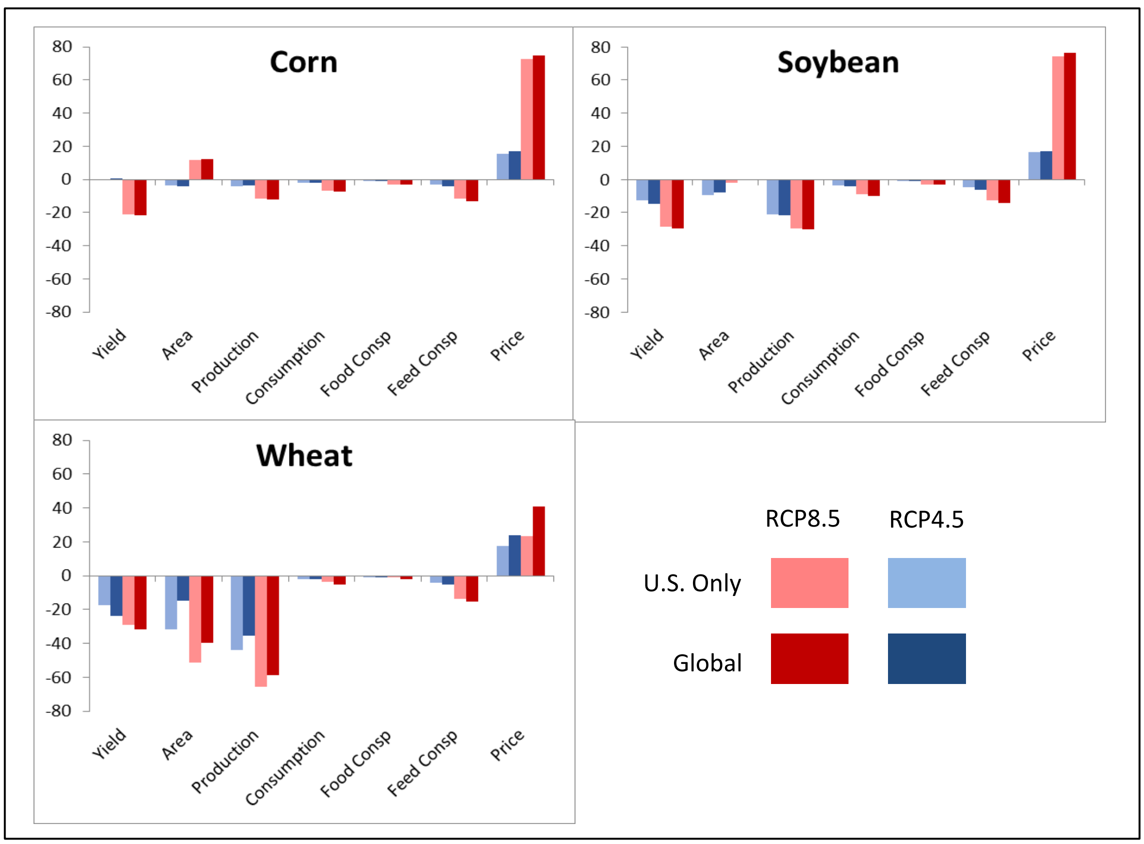
[388] Leclère, D., P. Havlík, S. Fuss, E. Schmid, A. Mosnier, B. Walsh, H. Valin, M. Herrero, N. Khabarov, and M. Obersteiner, 2014: Climate change induced transformations of agricultural systems: insights from a global model. *Environmental Research Letters*, **9**, 1748-9326.

production, and consumption all decline for soybeans under RCP4.5, with prices increasing approximately 16%-17%.

U.S. wheat production systems see the largest projected yield impact in the scenarios that included impacts of global agriculture. Wheat yields decline up to 32% under RCP8.5 and approximately 18%-24% under RCP4.5 relative to the control. Production and total area decline substantially (more than 35% under RCP4.5 and more than 58% for RCP8.5 for production; more than 15% under RCP4.5 and more than 39% under RCP8.5 for total area), especially when compared to corn and soybeans. However, consumption and price impacts are relatively less severe than price impacts seen for corn and soybeans. Prices rise less than 41% for both RCP8.5 and RCP4.5. This is due in part to supply-side adjustments and shifting trade patterns in the rest of the world that buffer against productivity losses from the U.S. wheat system. As the U.S. share of global corn and soybean production and exports is much larger than the share for wheat, corn and soybean prices are more significantly impacted by the climate change scenarios as the rest of the world is less able to respond to changes in U.S. output.

Figure 22.1. Percent Change in U.S. Crop Output

GLOBIOM results are presented (from left to right) as climate change impacts in 2050 on: yield, crop area, production, consumption, consumption for food, consumption for feed, and prices. All values are relative to a no climate change control. Lighter colors represent impacts for the U.S.-only climate change scenarios; darker bars represent global impacts.



The net difference in impacts is relatively small for corn and soybeans when comparing the U.S.-only and global scenarios. Projected domestic price impacts for corn and soybeans do increase when global agriculture effects are accounted for, but this shift results in a net increase of less than 10% for both crops relative to the U.S.-only scenarios. For wheat, however, this relative difference between global and domestic estimated impacts is much greater. Unlike corn and soybeans, the net change in crop area and total production of wheat is significantly smaller for the global scenarios than when only U.S. impacts are considered, as U.S. wheat production reacts to climate-induced productivity changes in the rest of the world more than it does for corn and soy. When global climate change effects on agriculture are accounted for, net price impacts for U.S. wheat is approximately 35% higher than the projected price impact under the U.S.-only scenario for RCP4.5, and 70% higher for RCP8.5.

22.5 DISCUSSION

Results of this analysis provide global perspective as a complement to the domestic FASOM-GHG modeling presented in the previous section by directly evaluating the importance of including global agricultural impacts of climate change on U.S. agricultural outputs relative to a scenario in which U.S. impacts are evaluated in isolation (i.e. holding climate in the rest of the world to reference levels). While the estimated net impact of moving from national to global impact scenarios is fairly small for some crop groups like corn and soybean, the changes could be substantial for crops like wheat.

The primary reason from this difference among crop types is that U.S. wheat production commands a smaller global market share than corn or soybeans. U.S-produced corn and soybeans account for roughly 37% and 33% of global production and 46% and 44% of total global exports from all regions, respectively.[389] Conversely, U.S. wheat production only accounts for approximately 10% of global production and 17% of global exports. Any given crop with a higher total share of production and exports would see greater net effects on prices given local climate change impacts, regardless of production shifts in the rest of the world. Thus, any significant change to U.S. corn and soybean production systems would have important implications for global market effects, leading to higher overall price impacts and less difference between the U.S.-only and global agriculture scenarios.

The global wheat market is less reliant on U.S. wheat production overall, so even a large shift in U.S. production under the U.S.-only scenarios does not result in similarly scaled price impacts. Commanding a smaller market share globally offers greater flexibility for U.S. wheat producers and consumers to adapt to lower yields induced by climate change by shifting production and export patterns.

These results demonstrate that future climate impacts analyses on U.S. agriculture could benefit from additional consideration of global impacts and trade adjustments, as global and domestic-only results may differ according to different crop types and relative country production and export volumes. This specific type of comparison between U.S. and global agriculture impacts is unique, as it has not been addressed in the literature using a detailed global model like GLOBIOM. Nonetheless, these estimated impacts are generally in line with previously published estimates that considered global scenarios (but not U.S. impacts only).[390]

There are a few important caveats to note regarding this analysis. First, exogenous crop yield impacts were produced using a single biophysical model (global EPIC), an approach that does not capture the potential structural uncertainties that have been highlighted in the literature.[391] Second, the scenario

---

[389] Food and Agriculture Organization of the United Nations, cited 2016: FAOSTAT statistics database. Available online at http://www.fao.org/faostat/en/

[390] Brown, M.E., J.M. Antle, P. Backlund, E.R. Carr, W.E. Easterling, M.K. Walsh, C. Ammann, W. Attavanich, C.B. Barrett, M.F. Bellemare, V. Dancheck, C. Funk, K. Grace, J.S.I. Ingram, H. Jiang, H. Maletta, T. Mata, A. Murray, M. Ngugi, D. Ojima, B. O'Neill, and C. Tebaldi. 2015. Climate Change, Global Food Security, and the U.S. Food System. 146 pages. Available online at http://www.usda.gov/oce/climate_change/FoodSecurity2015Assessment/FullAssessment.pdf

[391] Rosenzweig, C., J. W. Jones, J. L. Hatfield, Alex Ruane, K. J. Thornburn, J. M. Antle, G. C. Nelson, C. Porter, S. Janssen, B. Basso, F. Ewert, D. Wallach, G. Baigorria, and J. M. Winter, 2013: The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies. *Papers in Natural Resources*. University of Nebraska – Lincoln, School of Natural Resources. Available online at http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1448&context=natrespapers

design was developed using underlying climate data from one GCM (HadGEM2-ES), and thus does not capture the uncertainty in regional climate projection across climate models. It is also important to caveat that there are key structural differences between GLOBIOM and FASOM-GHG that can influence the magnitude of net agricultural sector impacts, specifically with each model's treatment of time dynamics. FASOM-GHG is an intertemporal optimization model, and land management changes in a given period can be made in anticipation of future climate and productivity changes. GLOBIOM is a recursive dynamic framework, so management changes reflect a contemporaneous response to the exogenous yield shock and do not reflect expectations of the future. Finally, scenarios included in this analysis assume international trade consistent with current patterns.

ECOSYSTEMS

23. CORAL REEFS

23.1 KEY FINDINGS

- Coral reefs are already disappearing due to climate change and other non-climate stressors. Temperature increases, including the increasing frequency and intensity of high-temperature bleaching events, and ocean acidification are projected to further reduce coral cover in the future.
- Extensive loss of shallow corals is projected by 2050 for major U.S. reef locations. Modest delays in Hawaiian coral reef loss are projected under RCP4.5 compared to RCP8.5, but the lower emissions scenario provides little benefit to coral cover in South Florida and Puerto Rico, as these reefs have already passed critical thresholds of ecosystem change.
- Coral reef recreation is projected to decline considerably under both scenarios, though slightly less under RCP4.5.

23.2 BACKGROUND

Coral reefs, including those found in Hawai'i and the Caribbean, are unique ecosystems that are home to large numbers of marine plant and animal species. They also provide vital fish spawning habitat, protect shorelines, and are valuable for recreation and tourism. However, shallow-water coral reefs are highly vulnerable to climate change.[392] High water temperatures can cause coral to expel the symbiotic algae that provide nourishment and vibrant color for their hosts. This coral bleaching can cause the coral to die, especially when bleaching events occur consecutively. In addition, ocean acidification (ocean chemistry changes due to elevated emissions of CO_2) can reduce the availability of calcium carbonate in seawater that is needed to build and maintain coral skeletons.

23.3 APPROACH

This analysis examines the physical and economic impacts of climate change (temperature effects) and ocean acidification on shallow-water coral reefs in Hawai'i, South Florida, and Puerto Rico. Using the COMBO (Coral Mortality and Bleaching Output) model,[393,394] the analysis first estimates declines in coral reef cover (a measure of coral reef health and density) using projections of future sea surface

---

[392] Melillo, Jerry M., Terese (T.C.) Richmond, and Gary W. Yohe, Eds., 2014: Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program, 841 pp. doi:10.7930/J0Z31WJ2.

[393] Buddemeier, R.W., P.L. Jokiel, K.M. Zimmerman, D.R. Lane, J.M. Carey, G.C. Bohling, and J.A. Martinich, 2008: A modeling tool to evaluate regional coral reef responses to changes in climate and ocean chemistry. *Limn Oceanogr Methods*, **6**, 395–411, doi: 10.4319/lom.2008.6.395.

[394] Buddemeier, R.W., D.R. Lane, and J.A. Martinich, 2011: Modeling regional coral reef responses to global warming and changes in ocean chemistry: Caribbean case study. *Climatic Change*, **109**, 375–397, doi:10.1007/s10584-011-0022-z.

temperature (from the five GCMs) and ocean acidification (i.e., carbonite saturation state with respect to aragonite) under RCP8.5 and RCP4.5. The effects of future bleaching events, driven by projected changes from the climate models, are also estimated. Next, the analysis quantifies the economic impacts associated with coral reef cover loss based on declines in reef-based recreation. The analysis estimates these impacts using a benefit-transfer approach; that is, it draws on reef-related recreation benefits measured in previously published studies conducted at a range of coral reef sites to estimate the value of reef-related recreation benefits in the areas considered in this study.[395] As shown in Appendix A.13, COMBO was also simulated using explicit modeling of three types of coral that have different responses to bleaching: feeders, switchers, and optimizers. Each coral type has its own bleaching threshold, mortality, and growth parameters, which together help account for variability in biological response to future bleaching events. For more information on the approach for the coral reef sector, please refer to Lane et al. (2013)[396] and Lane et al. (2014).[397]

23.4 RESULTS

For major U.S. reefs, projections under RCP8.5 (average of five GCMs) show extensive bleaching and dramatic loss of shallow coral cover by 2050, and near complete loss by 2100. In Hawai'i, coral cover is projected to decline from 38% in 2010 to approximately 11% by 2050, with further declines thereafter (Figure 23.1). In South Florida and Puerto Rico, where present-day sea surface temperatures are already close to bleaching thresholds and where these reefs have historically been affected by non-climate stressors, coral is projected to disappear even faster.

Some of the projected biological and economic impacts of climate change on coral reefs in the U.S. are delayed, but not avoided, under RCP4.5. Figure 23.1 shows projected change in percent coral reef cover from 2010 to 2100 in Hawai'i, South Florida, and Puerto Rico under RCP8.5 and RCP4.5. These results represent the average results across the five GCMs, and are displayed using a consistent y-axis scale to show differences in initial coral cover. In Hawai'i, the decline in reef cover slows modestly under RCP4.5 compared to RCP8.5, but both scenarios suggest substantial reductions. In South Florida and Puerto Rico, the RCP4.5 scenario is likely insufficient to avoid multiple bleaching and mortality events by 2020, and coral cover declines thereafter nearly as fast as under RCP8.5.

---

[395] Lane, D.R., R.C. Ready, R.W. Buddemeier, J.A. Martinich, K.C. Shouse, and C.W. Wobus, 2013: Quantifying and valuing potential climate change impacts on coral reefs in the United States: Comparison of two scenarios. *PLoS ONE*, **8**, e82579, doi:10.1371/journal.pone.0082579.

[396] Ibid.

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

Figure 23.1. Average Change in Percent Coral Reef Cover

Results show change in percent coral cover under RCP8.5 and RCP4.5 for the five-model average

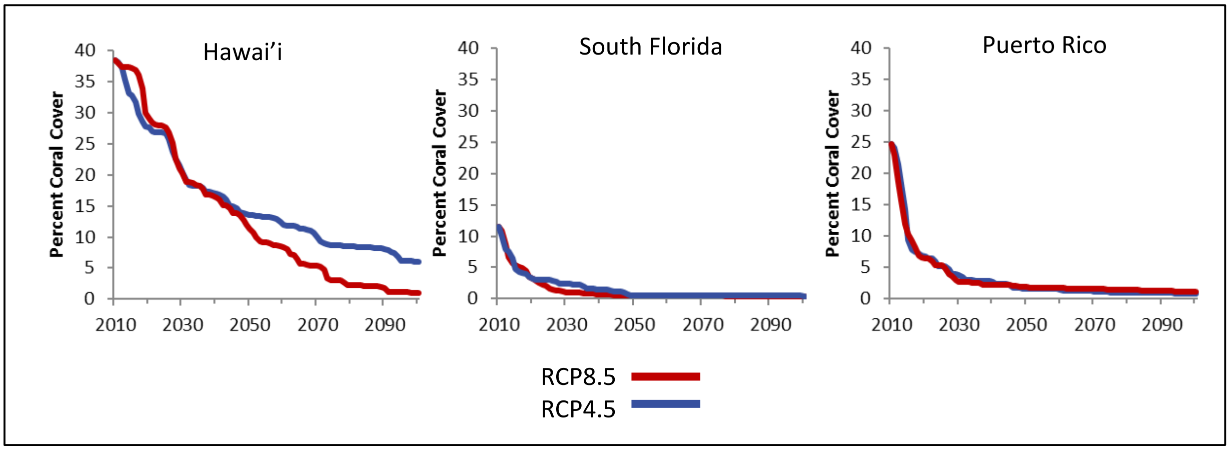


Figure 23.2. Change in Percent Coral Reef Cover by GCM

Results show change in percent coral cover under RCP8.5 and RCP4.5 for each GCM

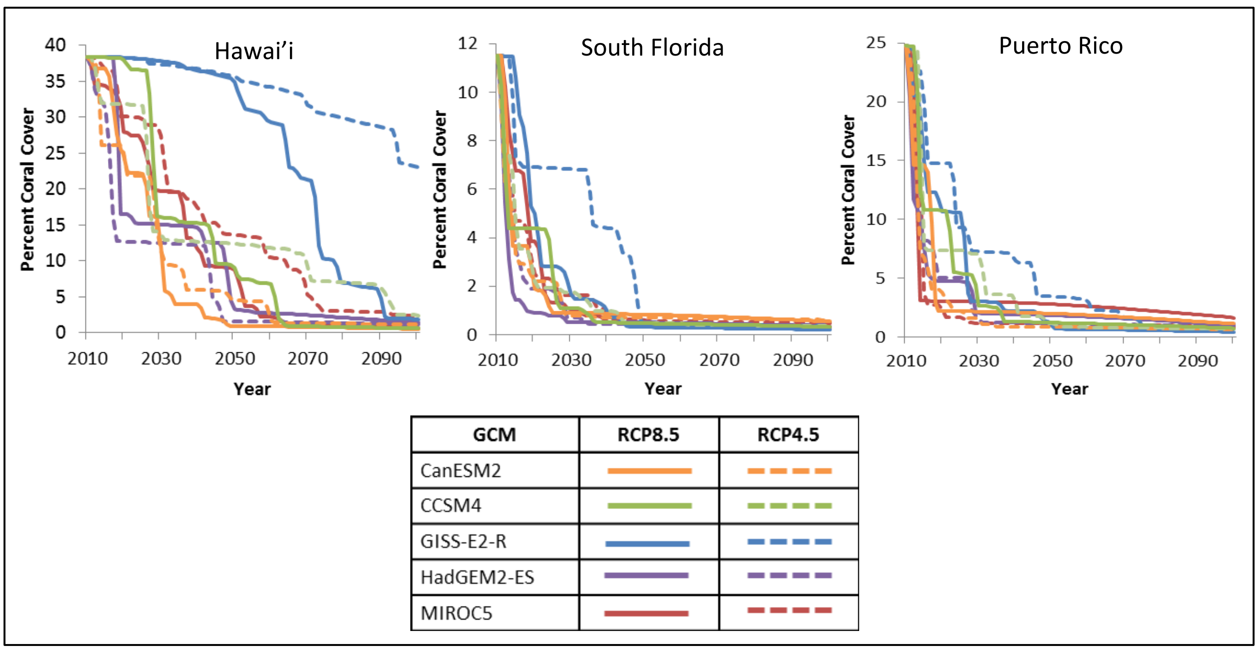


Figure 23.2 shows projected changes in coral cover from 2010 to 2100 under each GCM/RCP combination for the three regions (note differences in scaling of y-axis). Four of the five GCMs show similar results over time. The GISS-E2-R model, which projects comparatively smaller increases in sea surface temperatures over time under both RCPs compared to the other GCMs, estimates a delay in the timing of coral loss. This effect is most notable in projected changes in Hawaiian coral cover.

The projected loss of coral reef cover will have substantial effects on reef-based recreation (Table 23.1). Under most RCP/GCM combinations, more than 90% of the value of recreation in the reference period is lost by the end of the century. Across all three regions, an estimated $140 billion (discounted 3%) in reef-based recreation is projected to be lost through 2100 under RCP8.5, and $130 billion under RCP4.5. More than half of these losses are projected for South Florida, which has larger levels of tourism for reef-based recreation. Table 23.2 provides cumulative estimates for the differences between the RCPs. Including the economic value of other services provided by coral reefs, such as shoreline protection and fish-rearing habitat, would provide a more comprehensive understanding of the total economic value of these declines in habitat.

Table 23.1. Cumulative Value of Lost Reef-Based Recreation

Results are presented through 2100 in 2015$, discounted at 3%.[398] *Estimates for Puerto Rico only represent recreational effects for permanent residents, and therefore are both smaller (listed in millions) and not directly comparable to the results for the other locations which include visits from nonresident tourists. Totals may not sum due to rounding.*

GCM	HAWAI'I (Billions $)		SOUTH FLORIDA (Billions $)		PUERTO RICO (Millions $)		TOTAL (Billions $)	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5
CanESM2	$57	$55	$96	$97	$9.1	$9.6	$150	$150
CCSM4	$41	$43	$95	$95	$8.5	$8.4	$140	$140
GISS-E2-R	$14	$6.0	$86	$70	$8.3	$7.1	$99	$76
HadGEM2-ES	$51	$60	$100	$99	$9.3	$9.2	$150	$160
MIROC5	$47	$38	$93	$94	$9.2	$9.6	$140	$130
5-GCM Average	**$42**	**$40**	**$95**	**$91**	**$8.9**	**$8.8**	**$140**	**$130**

Table 23.2. Cumulative Difference in Value of Reef-Based Recreation

Results are presented as the difference between RCP8.5 and RCP4.5 at major U.S. coral reefs through 2100 in millions of 2015$, discounted at 3%. Due to rounding, values may not equate to differences between RCP-specific results shown in Table 23.1.

GCM	HAWAI'I	SOUTH FLORIDA	PUERTO RICO	TOTAL
CanESM2	$1,400	$1,200	-$0.47	$2,600
CCSM4	-$2,200	-$290	$0.11	-$2,500
GISS-E2-R	$8,000	$15,000	$1.2	$23,000
HadGEM2-ES	-$8,700	$4,800	$0.051	-$3,900
MIROC5	$9,200	-$1,700	-$0.36	$7,500
5-GCM Average	**$1,500**	**$3,900**	**$0.11**	**$5,400**

23.5 DISCUSSION

The findings described above suggest very substantial impacts to U.S. coral reefs within the coming decades. Drastic decline in coral reef cover, indicating the exceedance of an ecosystem threshold, is likely to have significant ecological and economic consequences at regional levels. The projections of

[398] Values calculated by comparing recreation provided by available coral cover in each year to a no-climate change control scenario which assumes constant coral cover (based on reference period values) but includes changes in population and the effects of economic discounting.

shallow coral loss for major U.S. reefs are consistent with the findings of the assessment literature,[399,400] with other studies,[401,402] and, most importantly, with what has been observed in reefs across the U.S. over the past 15 years. Unlike other sectors of this Technical Report where the climate change signal emerges from natural variability over the course of the next 25 years, the most severe impacts to coral reefs are occurring now.[403]

Importantly, the impacts modeled in COMBO do not include non-climate stressors, such as overfishing or water pollution, which have significantly affected U.S. reef ecosystems over the past 40 years. In addition, the COMBO analysis does not account for the ability of large-scale reefs to contain important refugia for resilient corals that could potentially be used in coral restoration efforts. Together, these factors can adjust the estimates presented in this report downwards or upwards.[404] See Lane et al. (2013)[405] for additional information regarding caveats to the modeling of coral reefs using the COMBO model.

---

[399] Doney, S., A. A. Rosenberg, M. Alexander, F. Chavez, C. D. Harvell, G. Hofmann, M. Orbach, and M. Ruckelshaus, 2014: Ch. 24: Oceans and Marine Resources. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 557-578, doi:10.7930/J0RF5RZW.

[400] Romero-Lankao, P., J.B. Smith, D.J. Davidson, N.S. Diffenbaugh, P.L. Kinney, P. Kirshen, P. Kovacs, and L. Villers Ruiz, 2014: North America. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability*. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, 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. 1439-1498.

[401] Donner, S.D., 2009: Coping with commitment: Projected thermal stress on coral reefs under different future scenarios. *PLOS ONE,* doi:10.1371/journal.pone.0005712.

[402] Veron, J.E.N., O. Hoegh-Guldberg, T.M. Lenton, J.M. Lough, D.O. Obura, P. Pearce-Kelly, C.R. Sheppard, M. Spalding, M.G. Stafford-Smith, and A.D. Rogers, 2009: The coral reef crisis: The critical importance of <350 ppm CO_2. *Marine Pollution Bulletin*, **58**, doi: 10.1016/j.marpolbul.2009.09.009.

[403] National Oceanographic and Atmospheric Administration, cited 2016: Coral Health and Monitoring Program. Available online at: http://www.coral.noaa.gov/

[404] Recent research suggests that reefs experiencing smaller levels of non-climate stressors (e.g., water pollution and overfishing) are equally vulnerable to bleaching events. See Hughes, T.P., et al., 2017: Global warming and recurrent mass bleaching of corals. Nature, 543, doi:10.1038/nature21707.

[405] Lane, D.R., R.C. Ready, R.W. Buddemeier, J.A. Martinich, K.C. Shouse, and C.W. Wobus, 2013: Quantifying and valuing potential climate change impacts on coral reefs in the United States: Comparison of two scenarios. *PLoS ONE*, **8**, e82579, doi:10.1371/journal.pone.0082579.

24. SHELLFISH

24.1 KEY FINDINGS

- Harvests of five types of U.S. shellfish are projected to decline substantially by the end of the century due to ocean acidification. Declines in supply are substantially higher under RCP8.5 as compared to RCP4.5.
- Decreases in supply are projected to result in price increases for six types of shellfish by the end of the century, ranging from 24% to 230% depending on the species and region from which they are harvested. Under RCP8.5, percent change in the price of oysters is projected to increase by 33% in the Northeast, 140% in the Southeast, and 150% in the Northwest by 2090.
- Cumulative discounted losses in consumer welfare are $230 million under RCP8.5 and $140 million under RCP4.5.

24.2 INTRODUCTION

The ocean absorbs about one quarter of the CO_2 released into the atmosphere by human activities. Although the ocean's ability to absorb CO_2 prevents atmospheric levels from climbing even higher, measurements made over the last few decades have demonstrated that marine CO_2 levels have risen, leading to an increase in acidity.[406] Ocean acidification is projected to adversely affect a number of valuable marine ecosystem services by making it more difficult for many organisms to form shells and skeletons.[407] Some shellfish are highly vulnerable to ocean acidification[408] and impacts to these species are expected to negatively affect consumers, the fishing industry, and the broader economy. Certain species have high commercial value; for example, oysters, clams, and scallops supplied approximately 170 million pounds of U.S. seafood each year between 1990-2010 valued at $400 million.[409]

24.3 APPROACH

This analysis models biophysical and economic impacts of ocean acidification on several shellfish species of the contiguous U.S. under RCP8.5 and RCP4.5. The biophysical impacts are estimated using CO_2 and sea surface temperature projections from five GCMs to simulate seawater chemistry conditions through the 21st century. These conditions are then used to estimate how the growth rates of oysters, scallops, geoducks, quahogs, clams, and mussels[410] will change over time along the contiguous U.S. coastline. The economic analysis uses the projected growth rates of these species to estimate changes to the U.S. supply of shellfish in three U.S. regions: the Northeast, the Southeast (which includes the Gulf of

---

[406] EPA, 2016: Climate change indicators in the United States, 2016. Fourth Edition. United States Environmental Protection Agency, EPA 430-R-16-004. Available online at www.epa.gov/climate-indicators

[407] Doney, S., A. A. Rosenberg, M. Alexander, F. Chavez, C. D. Harvell, G. Hofmann, M. Orbach, and M. Ruckelshaus, 2014: Ch. 24: Oceans and Marine Resources. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 557-578. doi:10.7930/J0RF5RZW.

[408] In early life stages, some species will have higher mortality rates and more developmental abnormalities under acidification conditions expected over the next several decades. In addition, adult shellfish tend to grow more slowly and have thinner, more fragile shells under these conditions.

[409] NOAA, cited 2017: Annual Commercial Landing Statistics (1990-2010). National Oceanic and Atmospheric Administration, Office of Science and Technology. Available online at http://www.st.nmfs.noaa.gov/commercial-fisheries/commercial-landings/annual-landings/index

[410] The consumer demand model described in Moore (in press) includes mussels, however, the supply of mussels is held constant in this analysis. This is because mussels did not exhibit a statistically significant reaction to increasing CO_2 concentrations (and falling aragonite saturation state) in the biophysical experiments underlying the methodology.

Mexico), and the Northwest. Not all species are present in each region. A two-stage consumer demand model of the shellfish market, described in Moore and Griffiths (2017)[411] but expanded to capture regional differences (e.g. Richards et al. 1997),[412] projects changes in prices and consumer behavior under the ten RCP/GCM combinations, and estimates changes in consumer welfare. By considering impacts to five of these species (excluding mussels), this approach estimates just a fraction of the potential economic damages from ocean acidification. For more information on the approach to estimating the economic impacts of ocean acidification in the shellfish market, see Moore and Griffiths (2017) and Moore (2015).[413]

24.4 RESULTS

Continued ocean acidification is estimated to reduce the supply of oysters, scallops, geoducks, quahogs, and clams (Figure 24.1). Under RCP8.5, supplies decrease by the following amounts by the end of the century (average of 2080-2099): 50% of oysters, 55% of scallops, 54% of geoducks, 45% of quahogs, and 35% of clams. Under RCP4.5, national supplies decrease by the following amounts by the end of the century: 24% of oysters, 27% of scallops, 11% of geoducks, 9.0% of quahogs, and 6.1% of clams.

These decreases in supply are projected to result in price increases in all species and in all regions (Table 24.1). The largest increases in price by the end of the century compared to the reference period (2010) are projected to occur under RCP8.5 in quahogs in the Northeast (a 230% increase) and Southeast (a 180% increase), geoducks in the Northwest (a 220% increase), oysters in the Northwest and Southeast (150% and 140% increase, respectively), and scallops in the Northeast and Southeast (increases of 130%). Figure 24.2 shows the regional percent change in the price of oysters, where there is projected catches for all three regions.

---

411 Moore, C. and C. Griffiths, 2017: Welfare Analysis in a Two-Stage Inverse Demand Model: An Application to Harvest Changes in the Chesapeake Bay. *Empirical Economics*. 181:1-26. DOI 10.1007/s00181-017-1309-3.

412 Richards, T.J., Van Ispelen, P. and Kagan, A., 1997: A two-stage analysis of the effectiveness of promotion programs for US apples. American Journal of Agricultural Economics, 79(3), pp.825-837. The Richards et al. 1997 study uses two-stage budgeting to examine consumer demand for apples from three different countries. This analysis takes the same approach to examine the demand for shellfish harvested in different regions within the contiguous U.S.

413 Moore, C., 2015: Welfare estimates of avoided ocean acidification in the US mollusk market. *Journal of Agricultural and Resource Economics*, **40**, 50-62.

Table 24.1. Percent Increase in U.S. Shellfish Price

The table presents the estimated percent change in shellfish price from 2010 to 2090 (2080-2099). Note that not all species are commercially harvested in each region.

	RCP8.5	RCP4.5
Northeast		
Clam	89%	39%
Mussel	74%	30%
Oyster	33%	24%
Quahog	230%	59%
Scallop	130%	51%
Southeast		
Oyster	140%	48%
Quahog	180%	51%
Scallop	130%	52%
Northwest		
Geoduck	220%	48%
Oyster	150%	54%

Figure 24.1. Percent Change in U.S. Shellfish Supplies

The graphs present the estimated percent change in national shellfish supply from 2011 to 2099 under RCP8.5 and RCP4.5 for the five-GCM average.

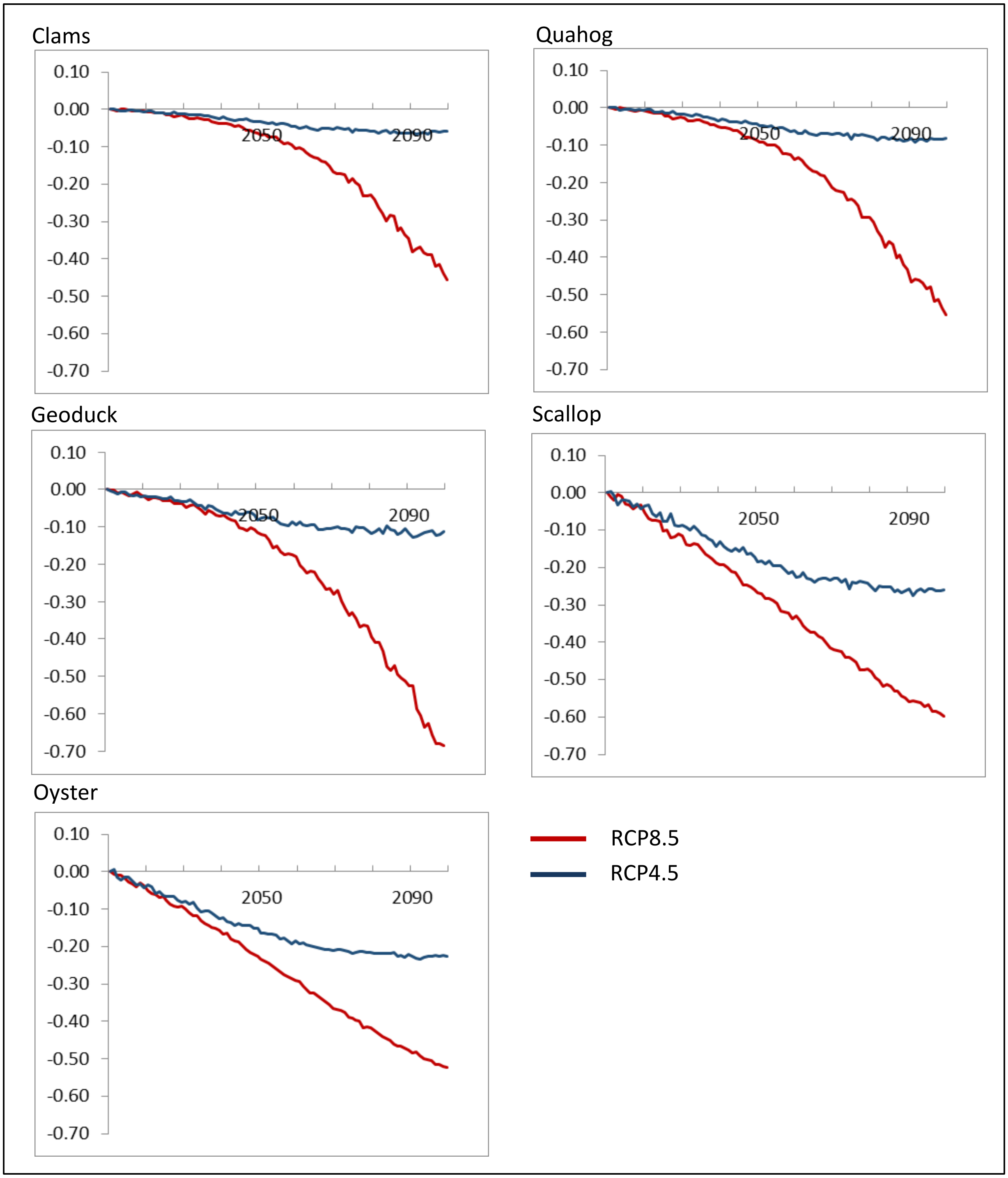
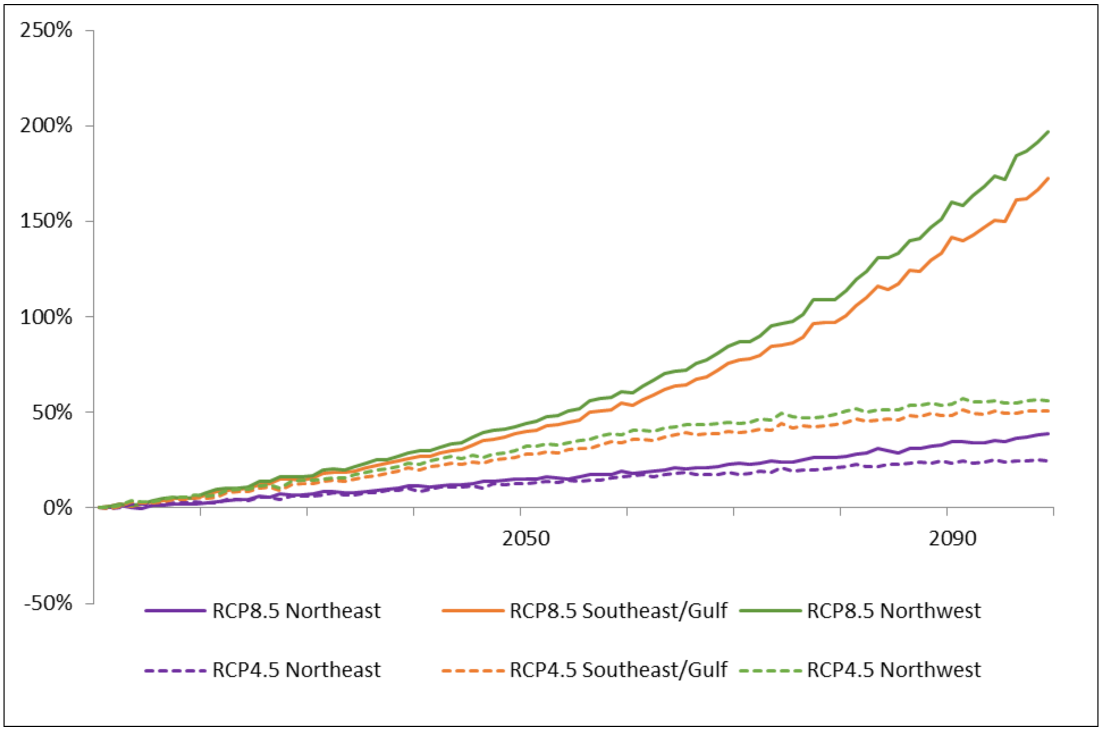


Figure 24.2. Percent Change in the Price of Oysters

The graph presents the estimated percent change in the price of oysters by region under RCP8.5 and RCP4.5 from 2011 to 2099



Changes in consumer welfare are reported as compensating surplus lost (Table 24.2). Cumulative losses in consumer welfare in response to decreasing supplies of these five shellfish are estimated at $140 million under RCP4.5 (ranging from $46 to $220 million) and $230 million under RCP8.5 (ranging from $95 to $360 million).

Table 24.2. Cumulative Losses in Consumer Welfare

The table presents the cumulative losses from 2010 to 2099 on the five species analyzed (millions 2015$, discounted at 3% to 2015) under RCP8.5 and RCP4.5 for each GCM and the five-GCM average.

Model	RCP8.5	RCP4.5
CanESM2	$95	$46
CCSM4	$97	$66
GISS-E2-R	$360	$200
HadGEM2-ES	$300	$180
MIROC5	$310	$220
5-GCM Average	**$230**	**$140**

24.5 DISCUSSION

Warming waters and more acidic conditions due to climate change are projected to decrease shellfish supply in the U.S., increasing prices and decreasing consumer welfare, particularly under RCP8.5. These projections are consistent with the findings of the assessment literature, which describe reduced growth and survival of U.S. shellfish stocks due to continued ocean acidification.[414] Demand for shellfish is projected to increase through the end of the century with a growing population and rising incomes, exacerbating the economic impacts in this sector. As prices rise in response to the contracting supply, consumers will substitute away from the affected species toward other less-preferred commodities.

Climate change will also influence losses in shellfish catch through mechanisms beyond just loss in supply. For instance, as ocean temperatures have increased, the average center of biomass for 105 marine fish and invertebrate species has already shifted northward by about 10 miles and moved an average of 20 feet deeper between 1982 and 2015.[415] This approach isolates impacts due to acidification, but does not evaluate the impacts of other stressors on shellfish supply over time, including overfishing pressures, losses due to nutrient and eutrophication issues (including coastal acidification), disease or contamination. Furthermore, the monetized shellfish losses reported here do not include impacts on the fishing industry, nor on local economies that rely on these activities.

---

[414] Doney, S., A. A. Rosenberg, M. Alexander, F. Chavez, C. D. Harvell, G. Hofmann, M. Orbach, and M. Ruckelshaus, 2014: Ch. 24: Oceans and Marine Resources. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 557-578. doi:10.7930/J0RF5RZW.

[415] EPA, 2016: Climate change indicators in the United States, 2016. Fourth Edition. United States Environmental Protection Agency, EPA 430-R-16-004. [Available online at www.epa.gov/climate-indicators]

25. FRESHWATER FISH

25.1 KEY FINDINGS

- Under RCP8.5, coldwater fisheries are projected to be lost in many areas of the U.S. over the course of the 21st century, especially in the mountain regions of the Northwest, Southwest, and the Northeast through Appalachia. By 2090, coldwater recreational fishing days are estimated to decline nationally by more than 90 million days per year under RCP8.5 and almost 67 million days per year under RCP4.5.
- Large losses of suitable stream habitat are projected for warmwater species, such as small and large mouth bass, across the Southern Plains, Northern Plains, and Midwest by the end of the century. Habitats suitable for rough water species, such as catfish and carp, are projected to increase in these regions.
- Lost recreational fishing values (for all fishing guilds) in 2090 compared to the reference period are approximately $3.1 billion annually under RCP8.5 and $1.7 billion annually under RCP4.5. Cumulative discounted losses are $45 billion under RCP8.5 and $38 billion under RCP4.5.

25.2 INTRODUCTION

Freshwater fishing is an important recreational activity that contributes significantly to local economies in many parts of the country. In 2011 alone, more than 27 million people in the U.S. spent a total of $25 billion on over 365 million freshwater recreational fishing trips.[416] Most fish species thrive only in certain ranges of water temperature and stream flow conditions. For example, trout and salmon can only tolerate coldwater streams, while shad and largemouth bass thrive in warmwater habitats. Climate change threatens to disrupt these habitats and affect certain fish populations through higher stream temperatures and changes in river flow.[417]

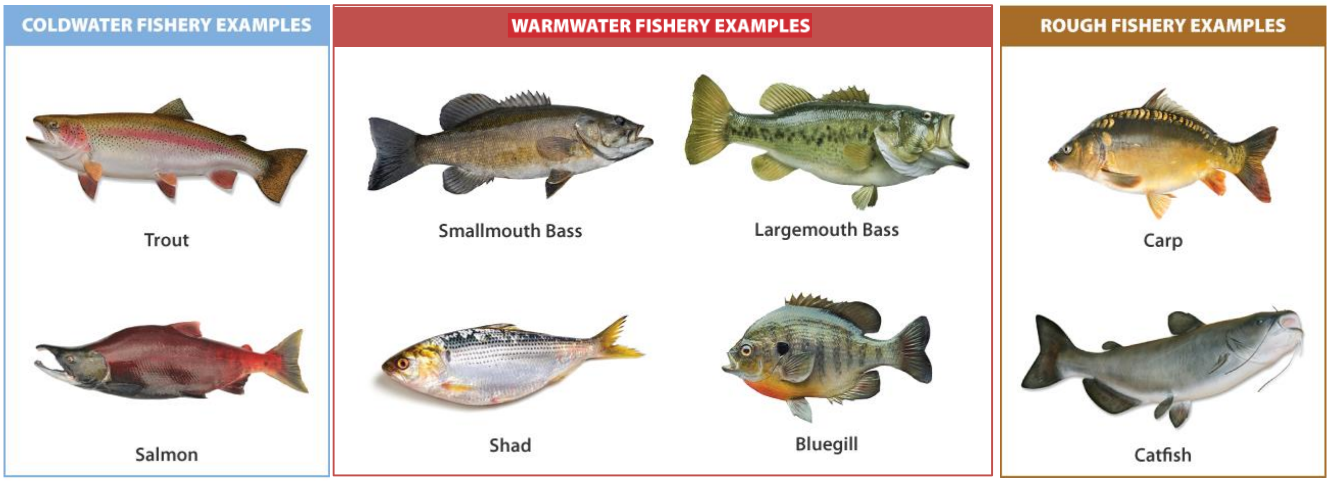
25.3 APPROACH

This analysis projects the impacts of climate change on the distribution of habitat suitable for freshwater fish across the U.S. and estimates the economic implications of these changes. Water temperature and streamflow changes are simulated for the two RCPs using five GCMs to estimate changes in suitable habitat for three types of freshwater fishery guilds: coldwater, warmwater, and rough (species tolerant to the warmest stream temperatures). Each fishery type represents a categorization of individual species based on their tolerance for different river and stream water temperatures, which directly affects dissolved oxygen concentrations and other parameters that affect suitability. The coldwater fish guild contains species that are the least tolerant to increasing stream temperatures, and are therefore the most vulnerable to climate change.

---

[416] U.S. Department of the Interior, U.S. Fish and Wildlife Service, and U.S. Department of Commerce,
U.S. Census Bureau, 2014: 2011 National Survey of Fishing, Hunting, and Wildlife-Associated Recreation. Available online at http://www.census.gov/prod/2012pubs/fhw11-nat.pdf

[417] Groffman, P. M., P. Kareiva, S. Carter, N. B. Grimm, J. Lawler, M. Mack, V. Matzek, and H. Tallis, 2014: Ch. 8: Ecosystems, Biodiversity, and Ecosystem Services. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 195-219. doi:10.7930/J0TD9V7H.



Results from habitat modeling considering projected changes in both water temperature and streamflow serve as input to an economic model to analyze the impacts of habitat change on number of fishing days and the value of recreational fishing.[418] Accounting for population growth, the model estimates fishing behavior as the likelihood that an adult in a particular state is an angler and the likelihood that an angler fishes for species in each fishery type. The fishing value for each fishery type is derived by multiplying the number of fishing days by the value of a fishing trip.[419] Reported values of the change in the number of annual fishing days represent the change in "supply of fishing days," or the impact on availability of freshwater fish to support fishing trips, not any change in "demand for fishing days," or impact on recreational behavior. For more information on the approach for the freshwater fish sector, please refer to Lane et al. (2014)[420] and Jones et al. (2012).[421]

25.4 RESULTS

Increasing stream temperatures and changes in stream flow are likely to transform many habitats that are currently suitable for coldwater fish into areas that are only suitable for warm or rough water species that are less recreationally valuable. Figure 25.1 shows the projected changes in potential freshwater fish habitat from the reference period to 2090. Under RCP8.5, coldwater fisheries are estimated to be limited almost exclusively to the Mountainous West by 2090, nearly disappearing from the Northeast through Appalachia in all five of the GCMs. In addition, substantial portions of Florida and central states, including Texas, Oklahoma, and Kansas, shift from warmwater to rough habitat. The losses of coldwater and warmwater habit are largest under the HadGEM2-ES climate model, while the smallest shifts are projected under the GISS-E2-R GCM. Importantly, projected shifts from coldwater and warmwater habitat are reduced under RCP4.5 compared to RCP8.5.

[418] The approach used in this Technical Report slightly modifies the approach described in Jones et al. (2012) by using a ratio of change in suitable habitat at the 8-digit hydrologic unit code level to drive the recreational fishing behavior model.

[419] Jones, R., C. Travers, C. Rodgers, B. Lazar, E. English, J. Lipton, J. Vogel, K. Strzepek, and J. Martinich, 2012: Climate Change Impacts on Freshwater Recreational Fishing in the United States. *Mitigation and Adaptation Strategies for Global Change*, **18**, 731, doi: 10.1007/s11027-012-9385-3.

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

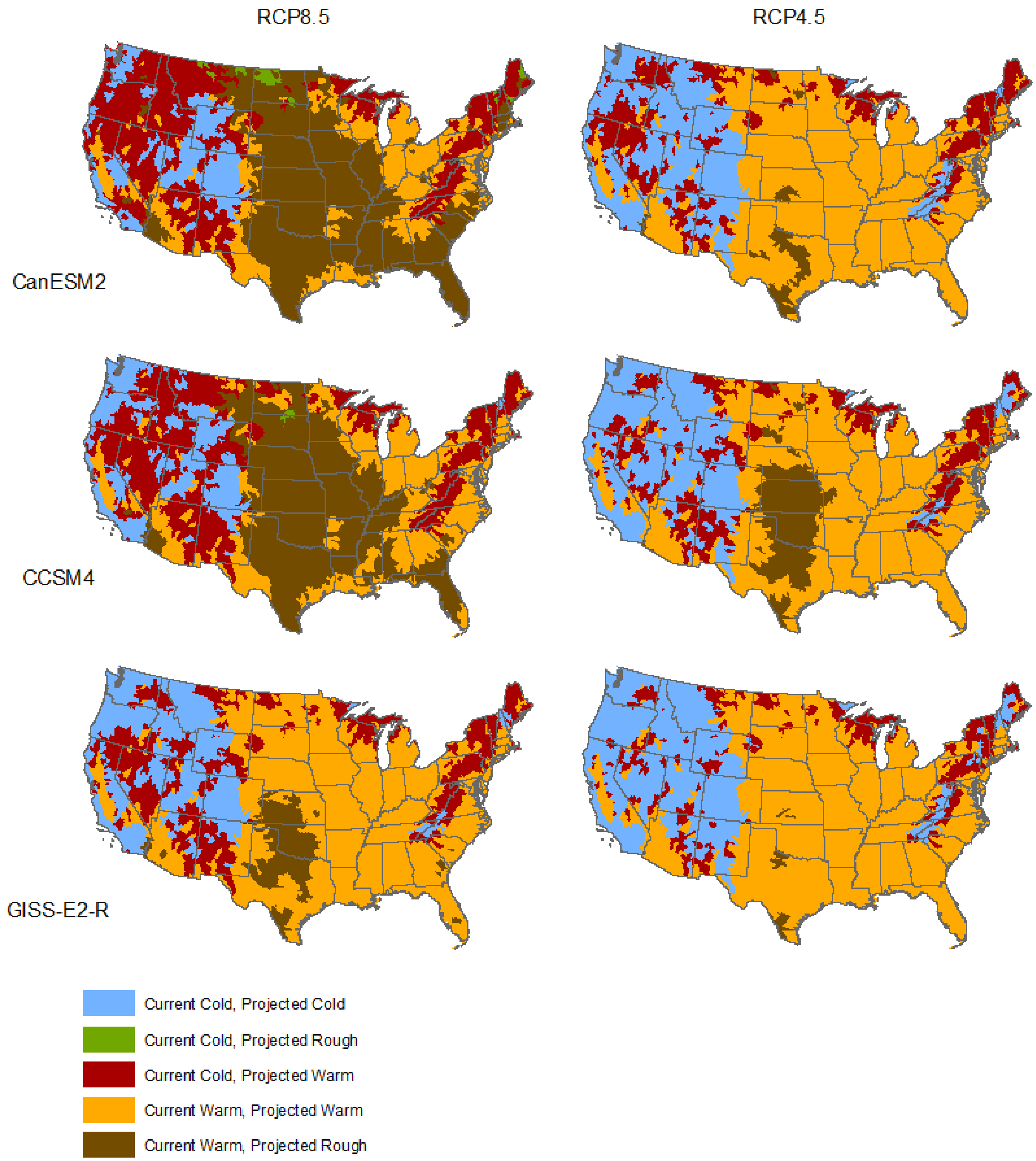
[421] Jones, R., C. Travers, C. Rodgers, B. Lazar, E. English, J. Lipton, J. Vogel, K. Strzepek, and J. Martinich, 2012: Climate Change Impacts on Freshwater Recreational Fishing in the United States. *Mitigation and Adaptation Strategies for Global Change*, **18**, 731, doi: 10.1007/s11027-012-9385-3.

Climate change is projected to have a significant impact on freshwater recreational fishing in the contiguous U.S. Between 2011 and 2050, coldwater fishing days are estimated to decline nationally by 67 million days per year (five-model average, with a range of 54-80 million days per year across the GCMs) under RCP8.5 and 62 million days per year (47-75 million days per year) under RCP4.5. Lost fishing days under RCP8.5 becomes significantly larger by 2090, when coldwater fishing days are estimated to decline nationally by 90 million days per year (73-104 million days per year) under RCP8.5. Coldwater fishing days decline by almost 67 million days per year under RCP4.5 in 2090. A high number of lost coldwater fishing days occur in mountainous regions by 2090 under both RCPs, including the Northeast, the Northwest, and the Southwest.

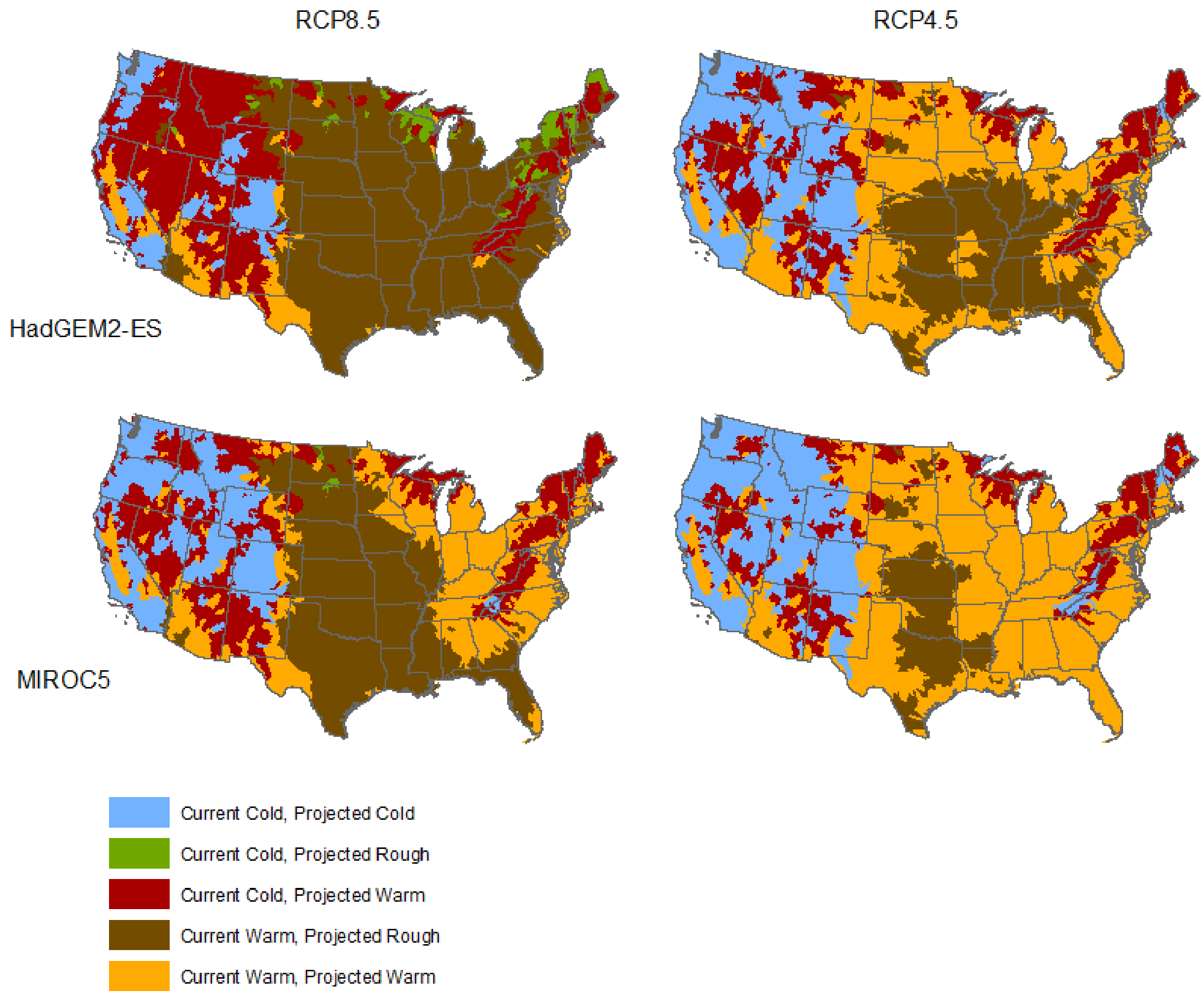
Figure 25.1. Projected Impact of Climate Change on Potential Freshwater Fish Habitat

The maps show the projected changes in habitat from the reference period centered on 2011 (labeled "Current") to 2090 (labeled "Projected") under RCP8.5 and RCP4.5.

(a) Projected changes for CanESM2, CCSM4, and GISS-E2-R



(b) Projected changes for HadGEM2-ES and MIROC5



Lost recreational fishing values (for all fishing guilds) in 2090 compared to 2011 are $3.1 billion annually under RCP8.5 and $1.7 billion annually under RCP4.5 (undiscounted). Cumulative losses through 2100 to national recreational value are estimated at $45 billion under RCP8.5 and $38 billion under RCP4.5, respectively (discounted at 3%). Cumulative losses for coldwater fishing only are estimated at $100 billion under RCP8.5 and $93 billion under RCP4.5 (discounted at 3%). These results (Table 25.1) reflect tradeoffs in economic losses from coldwater fishing, spatially-varied gains and losses in warmwater fishing, and gains in rough fishing.

Table 25.1. Change in National Value of Recreational Fishing

Results are presented in millions of $2015, discounted at 3% for 2011-2100. Values may not sum due to rounding.

	All Fishing		Coldwater Fishing	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5
CanESM2	-$42,000	-$28,000	-$110,000	-$93,000
CCSM4	-$49,000	-$35,000	-$110,000	-$95,000
GISS-E2-R	$680	-$9,400	-$85,000	-$75,000
HadGEM2-ES	-$85,000	-$64,000	-$120,000	-$110,000
MIROC5	-$50,000	-$51,000	-$96,000	-$88,000
5-GCM Average	**-$45,000**	**-$38,000**	**-$100,000**	**-$93,000**

25.5 DISCUSSION

Warming waters and changes in stream flows due to climate change are projected to alter the distribution of freshwater fisheries across the country. The projected loss of coldwater fish habitat and expansion of rough fisheries are consistent with the conclusions of the assessment literature, which find that as temperatures rise and precipitation patterns change, many fish species (such as salmon, trout, and char) will be lost from lower-elevation streams.[422] Modeling altered stream flows as well as increased temperature, Wenger et al. (2011)[423] projects an overall loss of 47% of habitat for four trout species in the western U.S. by 2080 under a moderate GHG emissions scenario (SRES A1B). A recent review of 31 peer-reviewed studies found that observed changes in climate are already altering the abundance, growth, recruitment, and habitat ranges of some North American inland fish populations, particularly coldwater species.[424] Varying degrees of physiological impacts of climate change on fish, such as decreased cardiorespiratory performance, compromised immune function, and altered reproductive behaviors, have also been observed.[425]

As the implications of changes to the distribution of freshwater fisheries extend beyond recreational use by humans, including effects on food chains and ecosystem services, this analysis underestimates the avoided economic impacts projected under RCP4.5. Climate change will also influence losses in freshwater fishing through mechanisms beyond just loss of habitat. For instance, changing temperatures can affect the timing of when stream and lake waters freeze or thaw, which can affect the length of open water fishing season, potentially extending fishing efforts in northern regions.[426] This analysis does

---

[422] Groffman, P. M., P. Kareiva, S. Carter, N. B. Grimm, J. Lawler, M. Mack, V. Matzek, and H. Tallis, 2014: Ch. 8: Ecosystems, Biodiversity, and Ecosystem Services. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 195-219. doi:10.7930/J0TD9V7H.

[423] Wenger, S.J., D.J. Isaak, C.H. Luce, H.M. Neville, K.D. Fausch, J.B. Dunham, D.C. Dauwalter, M.K. Young, M.M. Elsner, B.E. Rieman, A.F. Hamlet, and J.E. Williams, 2011: Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. *PNAS*, **108**, 14175-14180, doi: 10.1073/pnas.1103097108.

[424] Lynch, A.J., B.J.E. Myers, C. Chu, L.A. Eby, J.A. Falke, R.P. Kovach, T.J. Krabbenhoft, T.J. Kwak, J.L. Lyons, C.P. Paukert, and J.E. Whitney, 2016: Climate Change Effects on North American Inland Fish Populations and Assesmblages. *Fisheries*, **41**, 346-361, doi: 10.1080/03632415.2016.1186016.

[425] Whitney, J.E., R. Al-Chokhachy, D.B. Bunnell, C.A. Caldwell, S.J. Cooke, E.J. Eliason, M. Rogers, A.J. Lunch, and C.P. Paukert, 2016: Physiological Basis of Climate Change Impacts on North American Inland Fishes. *Fisheries*, **41**, 332-345, doi: 10.1080/03632415.2016.1186656.

[426] Paukert, C.P., A.J. Lynch, and J.E. Whitney, 2016: Effects of Climate Change on North American Inland Fishes: Introduction to the Special Issue. *Fisheries*, **41**, doi: 10.1080/03632415.2016.1187011.

not evaluate impacts to fisheries in lakes and reservoirs, which have different vulnerabilities to climate change, can be thermally stratified or provide other climate refugia for fish, and are also oftentimes heavily managed (i.e., water level and fish stocking). Changes in land use, water demands for irrigation or commercial uses, water quality, and diseases, parasites or invasive species will also interact with climate impacts to affect aquatic ecosystems and freshwater fishing.

26. WILDFIRE

26.1 KEY FINDINGS

- Under RCP8.5, wildfire acres burned in the contiguous U.S. are projected to remain consistent with rates observed over the past several decades, but moderately decrease under RCP4.5, with changes under both scenarios driven by shifts in vegetation over time. In Alaska, burned acreage is projected to increase under both RCPs, especially under RCP8.5.
- Under both RCPs, the largest levels of future wildfire activity are projected to occur in the southwestern parts of both the contiguous U.S. and Alaska.
- Through 2100, the cumulative, discounted wildfire response costs in the contiguous U.S. and Alaska under RCP8.5 are estimated at $24 billion. Other impacts, such as property damage or health effects from decreased air quality, are not estimated, but would significantly increase economic damages.
- Compared to the more severe climate change scenario, RCP4.5 is projected to reduce the cumulative area burned by wildfires in the contiguous U.S. and Alaska over the course of the 21st century by approximately 60 million acres. The corresponding avoided response costs are estimated at $75 million (cumulative, discounted).

26.2 INTRODUCTION

Terrestrial ecosystems in the U.S. provide a wealth of goods and services such as timber, wildlife habitat, erosion management, water filtration, recreation, and aesthetic value. Climate change threatens these ecosystems as heat, drought, and other disturbances have already led to an increased frequency of large wildfires, as well as longer durations of individual wildfires and longer wildfire seasons in the western U.S.[427] Wildfires can damage property, disrupt ecosystem services, destroy timber stocks, impair air quality, and result in loss of life.[428] In the last decade (2006-2015), approximately 7 million acres of forest have burned each year due to wildfires in the contiguous U.S. and Alaska, and the federal government has spent approximately $1.5 billion per year on wildfire suppression.[429] Additionally, wildfires release carbon stored in terrestrial ecosystems, potentially further accelerating climate change.[430,431]

---

[427] Fann, N., T. Brennan, P. Dolwick, J.L. Gamble, V. Ilacqua, L. Kolb, C.G. Nolte, T.L. Spero, and L. Ziska, 2016: Ch. 3: Air Quality Impacts. The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment. U.S. Global Change Research Program, Washington, DC, 69–98, doi: 10.7930/J0GQ6VP6.

[428] Groffman, P. M., P. Kareiva, S. Carter, N. B. Grimm, J. Lawler, M. Mack, V. Matzek, and H. Tallis, 2014: Ch. 8: Ecosystems, Biodiversity, and Ecosystem Services. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 195-219. doi:10.7930/J0TD9V7H.

[429] National Interagency Fire Center, 2016: Federal Firefighting Costs (Suppression Only). Available online at https://www.nifc.gov/fireInfo/fireInfo_documents/SuppCosts.pdf

[430] Groffman, P. M., P. Kareiva, S. Carter, N. B. Grimm, J. Lawler, M. Mack, V. Matzek, and H. Tallis, 2014: Ch. 8: Ecosystems, Biodiversity, and Ecosystem Services. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 195-219. doi:10.7930/J0TD9V7H.

[431] Joyce, L. A., S. W. Running, D. D. Breshears, V. H. Dale, R. W. Malmsheimer, R. N. Sampson, B. Sohngen, and C. W. Woodall, 2014: Ch. 7: Forests. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 175-194. doi:10.7930/J0Z60KZC.

26.3 APPROACH

This analysis projects wildfire activity and future response costs in the contiguous U.S. and Alaska using models developed and calibrated for each geographic area. To simulate the effects of climate change on areas burned by wildfires in the contiguous U.S., the analysis uses the MC2 dynamic global vegetation model (DGVM) developed and run by the U.S. Forest Service's (USFS) Pacific Northwest Research Station. The model simulates changes in future terrestrial ecosystem vegetative cover, including shifts in vegetation types over time, and burned area across the contiguous U.S. in the 21st century, excluding consideration of the proportion of a cell assumed to be in developed or in agricultural land use types.[432] The MC2 model is driven by changes in future climate (e.g., temperature, precipitation, humidity) based on the climate projections of five GCMs under two RCP scenarios.

The projected impacts of wildfires are summarized by scenario and geographic area,[433] and then monetized using average wildfire response costs for each region based on data from the National Wildfire Coordinating Group.[434] These costs include expenditures associated with labor (e.g., fire crews) and equipment (e.g., helicopters, bulldozers) that are used for fire-fighting. Importantly, the analysis adjusts projected changes in fire regime over time to account for fire suppression tactics. However, the economic costs associated with the endogenous fire suppression tactics within MC2 are not accounted for in the valuation results presented in this section (i.e., only wildfires that occur in spite of the endogenous suppression are quantified and valued, therefore resulting in an underestimate of total suppression costs). For more information on the MC2 model, including the wildfire module, and calibration used in this analysis, please refer to Drapek et al. (2015)[435] and Conklin et al. (2016).[436] For information on the approach to estimating wildfire response costs in the contiguous U.S., please refer to Mills et al. (2014).[437]

The Alaska Frame-Based Ecosystem Code (ALFRESCO) model[438] projects changes in wildfire activity in Alaska. ALFRESCO is a spatially explicit model that simulates spatial processes of fire and recruitment across the circumpolar arctic/boreal zone. The model combines disturbance events, seed dispersal, and succession on a landscape at a spatio-temporal scale appropriate for investigating effects of climatic change. In Alaska, wildfire suppression activities are prioritized based on spatially-delineated zones called fire management option (FMO) regions. Table 26.1 provides a brief summary of characteristics of

---

[432] A static layer of current agricultural lands based on the National Land Cover Dataset is removed from the vegetative mapping, along with a dynamic layer of developed (urban and suburban) lands based on the ICLUSv2 projections described in the Modeling Framework section of this Technical Report. For more information on the National Land Cover Dataset, see: Homer, C., J. Dewitz, L. Yang, S. Jin, P. Danielson, G. Xian, J. Coulston, N. Herold, J. Wickham, and K. Megown, 2015: Completion of the 2011 National Land Cover Database for the conterminous United States - Representing a decade of land cover change information. *Photogrammetric Engineering and Remote Sensing*, **81**, 345-354.

[433] Over the century-long modeled period, the same area can potentially burn in the future if the vegetation has recovered sufficiently to build combustible fuel, and if appropriate conditions are met to cause ignition.

[434] National Wildfire Coordinating Group, 2011: Historical incident ICS-209 reports. Available online at http://fam.nwcg.gov/fam-web/hist_209/report_list_209

[435] Drapek, R.J., J.B. Kim, and R.P Neilson, 2015: Continent-wide Simulations of a Dynamic Global Vegetation Model over the United States and Canada under Nine AR4 Future Scenarios. Global Vegetation Dynamics: Concepts and Applications in the MC1 Model, 73-90.

[436] Conklin, D.R., J.M. Lenihan, D. Bachelet, R.P. Neilson, and J.B. Kim, 2016: MCFire model technical description. Gen. Tech. Rep. PNW-GTR-926. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. See also: Kim, J.B., Monier, E., Sohngen, B., Pitts, G., et al., 2017: Assessing climate change impacts, benefits of mitigation, and uncertainties on major global forest regions under multiple socioeconomic and emissions scenarios. Environmental Research Letters, doi: 10.1088/1748-9326/aa63fc.

[437] Mills, D., R. Jones, K. Carney, A. St Juliana, R. Ready, A. Crimmins, J. Martinich, K. Shouse, B. DeAngelo, and E. Monier, 2014: Quantifying and Monetizing Potential Climate Change Policy Impacts on Terrestrial Ecosystem Carbon Storage and Wildfires in the United States. *Climatic Change*. doi:10.1007/s10584-014-1118-z.

[438] Rupp, T.S., A.M. Starfield, and F.S. Chapin III, 2000: A frame-based spatially explicit model of subarctic vegetation response to climatic change: comparison with a point model. *Landscape Ecology*, **15**, 383-400, doi: 10.1023/A:1008168418778.

the four FMOs. The analysis relies on a configuration of ALFRESCO that considers the spatial distribution of FMOs and adjusts the probability of fire spread between cells (for example, fire is less likely to spread in FMOs with higher suppression priority).[439] Projected annual area burned under RCP8.5 and RCP4.5 in two GCMs (CCSM4 and GISS-E2-R)[440] is aggregated by FMO to calculate response costs using historical (2002-2013) data from the Alaska Interagency Coordination Center and the National Fire and Aviation Management web application. For more information on the approach and results to estimating wildfire response costs in Alaska, please refer to Melvin et al. (2017).[441]

Table 26.1. Characteristics of the Four Fire Management Option Regions in Alaska

FMO	Characteristics	Area (millions of acres)
Critical	Highest priority areas where the risks to human life, residences, and community-dependent infrastructure are greatest. Immediate action is taken to suppress all wildfires.	3.2
Full	High-valued areas, but where risks to human life or inhabited property are low. Fires are usually suppressed.	53
Modified	Areas where risks to humans and infrastructure are relatively low and management decisions are designed to balance area burned with suppression costs. Suppression occurs if there is high fire danger.	42
Limited	Remote areas with a low density of valuable property, allowing for natural fire dynamics and associated ecological processes. In general, no actions are taken to suppress these fires.	264

26.4 RESULTS

Contiguous U.S.

Figure 26.1 shows the annual acres burned by wildfires in the contiguous U.S. through 2100 driven by climate projections from five GCMs under two RCPs, as well as for an average across the climate models. The large inter-annual variability reflects simulated periods of fuel accumulation followed by seasons of large wildfire activity – a trend similar to the variability observed over the past several decades.[442] In general, projected annual acres burned across the contiguous U.S. under RCP8.5 remain consistent with

[439] Two hundred replicate simulations for the 1901-2100 time period are simulated for each of the ten GCM x RCP combinations. Because ALFRESCO is a stochastic model, each replicate simulation produced a different spatial and temporal pattern of wildfire occurrence. The median values across the two hundred simulations are presented in this Technical Report, which allows for greater statistical certainty in projected outcomes for each FMO.

[440] As described in the Modeling Framework section of this Technical Report, the SNAP downscaled climate projections only contained two GCMs (two of five available) which overlapped with the climate models being used for the contiguous U.S. Therefore, this section presents wildfire modeling results using these two GCMs. See Melvin et al. (2017) for results using all five of the SNAP GCMs.

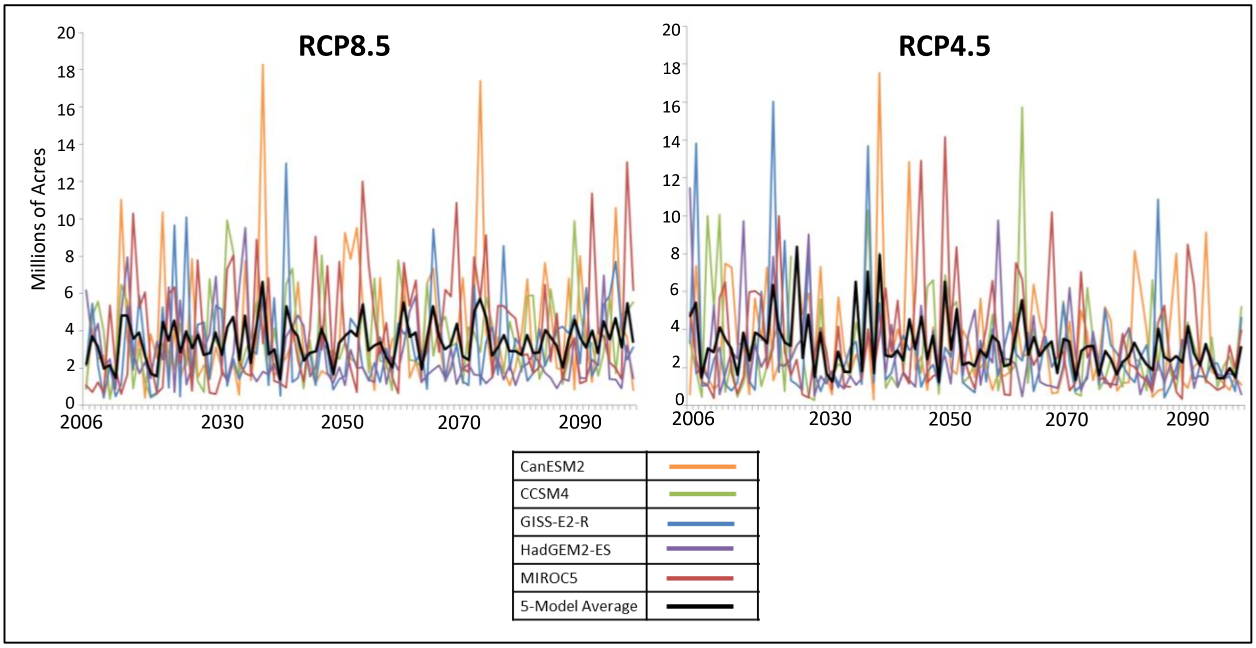
[441] Melvin, A.M., J. Murray, B. Boehlert, J.A. Martinich, L. Rennels, and T.S. Rupp, 2017: Estimating wildfire response costs in Alaska's changing climate. *Climatic Change Letters*, doi: 10.1007/s10584-017-1923-2. Available online at http://link.springer.com/article/10.1007%2Fs10584-017-1923-2

[442] National Interagency Fire Center, 2016: Federal Firefighting Costs (Suppression Only). Available online at https://www.nifc.gov/fireInfo/fireInfo_documents/SuppCosts.pdf

levels observed over the past several decades, but decrease slightly under RCP4.5. MC2 output based on the MIROC5 climate projections show the largest level of wildfire activity (a projected 320 million acres through 2100), while activity is smallest under the HadGEM2-ES GCM (250 million acres through 2100).

Figure 26.1. Projected Wildfire Activity

Estimated annual acres burned (millions) by wildfire in the contiguous U.S. over the course of the 21st century under RCP8.5 and RCP4.5 in the five GCMs, with the five-GCM average shown in black.[443]



The projections of future wildfire activity vary considerably by region. Figure 26.2 shows the projected change in average annual acres burned in 2050 and 2090 compared to the reference period (1986-2005). As shown, parts of the Southwest (e.g., Colorado and Nevada) and New England are projected to experience the highest levels of wildfire activity by the end of the century, though the spatial patterns of change vary by GCM (see Figure A14.1 of the Appendix for GCM-specific maps). In some regions that experience large levels of wildfire activity today, such as California, the MC2 model projects a shift toward fewer acres burned, due to vegetation converting to types that burn less frequently. These modeling results may indicate the exceedance of an ecosystem threshold, whereby historically-dominant plant species are replaced with those having less-frequent fire return intervals. These shifts result in lower levels of future burning than would be anticipated in an analysis that does not include these dynamic changes.

[443] To enable the reader to more clearly see differences amongst the lines for each GCM, the following two values were excluded from the graphic: the CCSM4 estimate for 2024 under RCP4.5 (27 million acres) and the MIROC5 estimate for 2034 under RCP4.5 (21 million acres). These values are included in all other cumulative impact and economic results in this section.

Figure 26.2. Projected Change in Wildfire Activity

Projected change in average annual acres burned across the contiguous U.S. under RCP8.5 and RCP4.5 by mid-century (2040-2059) and end of century (2080-2099) compared to the reference period (1986-2005). Results shown represent the average of the five GCMs. Acres burned include all vegetation types and are calculated at a cell resolution of 1/16th of a degree, and aggregated to ½ degree for mapping purposes. Agricultural and developed lands are removed.

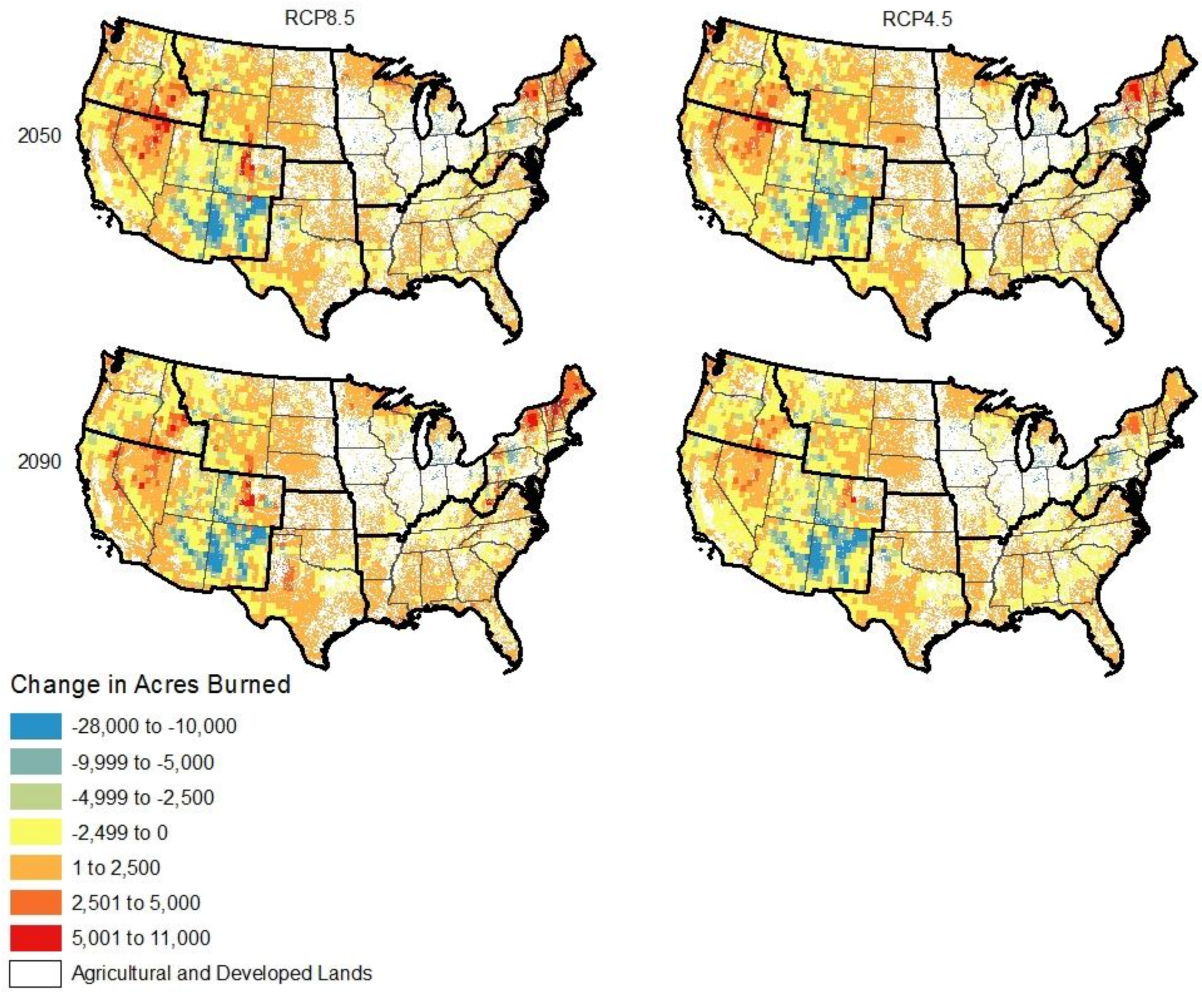


Table 26.2 shows the cumulative acres burned and discounted wildfire response costs by region and for the contiguous U.S. Cumulatively through the end of the century, approximately 330 million acres are projected to burn under RCP8.5 and 290 million under RCP4.5 (average of the five GCMs). The difference between the RCP8.5 and RCP4.5 estimates represents a 12% reduction in cumulative wildfire acreage in the contiguous U.S. due to reduced levels of climate change. In terms of economic effects, the cumulative wildfire response costs are estimated at $23 billion through 2099 under RCP8.5 and $23 billion under RCP4.5 (2015$, discounted at 3%), with the difference between the RCPs equaling $55 million. At a regional level, the Southwest is projected to experience the largest amount of wildfire activity and incur the highest response costs through 2099. Conversely, the Southeast is projected to have the smallest level of wildfire activity and subsequent response costs.

Table 26.2. Projected Acres Burned and Response Costs

Cumulative values represent the average of the five GCMs over the 2006-2099 period by region and the national (contiguous U.S.) total. Totals may not sum due to rounding.

Region	Cumulative Acres Burned (millions of acres)		Cumulative Response Costs (millions of $2015, discounted at 3%)	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Northeast	36	28	$640	$600
Southeast	15	13	$230	$300
Midwest	26	21	$480	$440
Northern Plains	36	33	$3,300	$3,700
Southern Plains	14	11	$380	$640
Southwest	150	150	$13,000	$13,000
Northwest	47	40	$5,400	$4,800
National Total	**330**	**290**	**$23,000**	**$23,000**

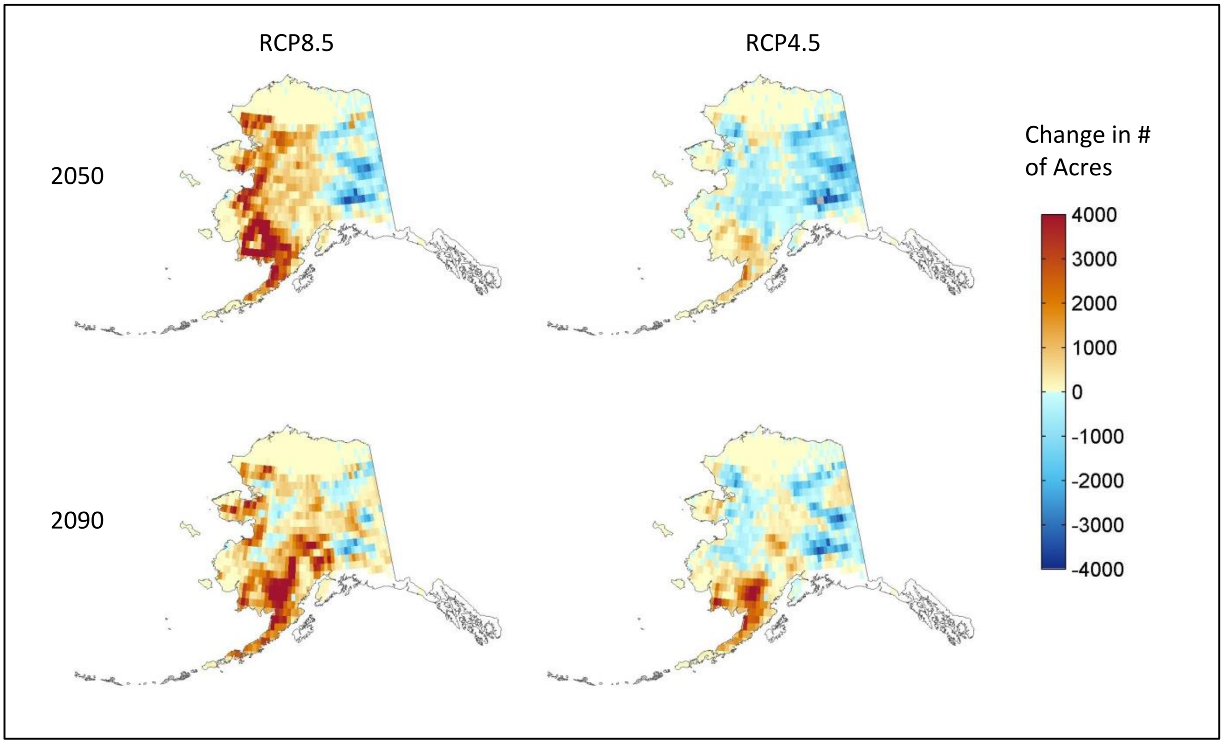
Alaska

Climate change is one of several factors that will affect the distribution, extent, and cost of wildfires in Alaska throughout this century. Figure 26.3 shows the projected change in average annual acres burned in Alaska under RCP8.5 and RCP4.5 based on outputs of the ALFRESCO model. The relative change in mean annual acres burned between the reference period (1970-2005) and 2050 and 2090 indicates an increase in area burned under RCP8.5 across much of the state. The largest increase in area burned under RCP8.5 is projected in the Southwest and western parts of the Far North, while results under RCP4.5 project a smaller increase in the Southwest and a decline in acres burned across much of rest of the State. Under all scenarios and timeframes, the eastern parts of the State show a decrease in wildfire activity, and the North Slope is generally projected to experience a slight increase in burned area. The projected shifts in burning over time are influenced by changes in vegetation composition, where forests historically dominated by black spruce are replaced with deciduous forest. This transition can influence the flammability of forested areas, including the modeled fire return intervals within ALFRESCO. [444]

[444] See Melvin et al. (2017) for more detail.

Figure 26.3. Projected Impact of Climate Change on Alaska Wildfire Activity

Change in average annual acres burned under RCP8.5 and RCP4.5 (mean of two GCMs) by mid-century (2040-2059) and end of century (2080-2099) compared to the reference period (1970-2005). Results are presented at a ½ degree cell resolution.



As shown in Table 26.3, the analysis projects approximately 120 million burned acres through the end of the century under RCP8.5, and 98 million burned acres under RCP4.5 (average of the five GCMs). The difference in area burned across Alaska between the two RCPs averages approximately 22 million acres through 2100. Projected cumulative, discounted wildfire suppression costs are estimated at $1.1 billion (2015$) under both RCP8.5 and RCP4.5. The difference in projected costs between the two RCPs averages approximately $20 million through 2100, with RCP4.5 providing modest benefits. An important limitation of the valuation approach used in this analysis is that per-acre response costs only represent federal costs, which are a subset of total suppression costs.[445]

Differences in response costs across the FMOs are influenced by the size of each FMO, the projected area burned, and the response cost per unit area. While the Limited FMO covers the largest area and contained over half the projected cumulative acres burned, this FMO accounted for only about 18% of the projected incurred costs due to the low response cost per acre. In contrast, the Full FMO, whose wildfires have larger response costs per acre, accounted for only 17% of the cumulative area burned, but about 65% of incurred costs. Southwest Alaska contains a large area designated as Full and showed the largest projected relative increase in burning (Figure 26.3), likely driving this finding.

[445] For instance, between 2009-2015, an average of 68% of annual costs were incurred by the state. This indicates that the cost per acre values used are likely an underestimate of what will be realized in the future.

Table 26.3. Projected Cumulative Area Burned and Wildfire Response Costs in Alaska

Results represent values for the 2006-2100 period, and are shown for each FMO, along with the State total. Totals may not sum due to rounding.

Cumulative Acres Burned by FMO (in millions)						
GCM	**RCP**	**Critical**	**Full**	**Modified**	**Limited**	**State Total**
CCSM4	RCP8.5	0.72	23	20	89	**130**
	RCP4.5	0.66	19	17	77	**110**
GISS-E2-R	RCP8.5	0.57	18	16	71	**110**
	RCP4.5	0.47	15	13	58	**86**
Average	RCP8.5	0.65	21	18	80	**120**
	RCP4.5	0.57	17	15	68	**98**
Cumulative Response Costs by FMO (in millions of $2015, discounted at 3%)						
CCSM4	RCP8.5	$53	$840	$180	$230	**$1,300**
	RCP4.5	$57	$900	$200	$250	**$1,400**
GISS-E2-R	RCP8.5	$36	$570	$130	$160	**$890**
	RCP4.5	$32	$490	$100	$130	**$750**
Average	RCP8.5	$45	$710	$160	$200	**$1,100**
	RCP4.5	$45	$700	$150	$190	**$1,100**

Contiguous U.S. and Alaska Combined

Table 26.4 provides the combined cumulative acres burned and wildfire response costs in the contiguous U.S. and Alaska through the end of the century.

Table 26.4. Projected Cumulative Area Burned and Wildfire Response Costs

Cumulative values for the contiguous U.S. and Alaska represent the average of the five GCMs over the 2006-2099 period. Totals may not sum due to rounding.

	Cumulative Acres Burned (in millions)	Cumulative Response Costs (in millions of $2015, discounted at 3%)
RCP8.5	450	$24,000
RCP4.5	390	$24,000
Difference	60	$75

26.5 DISCUSSION

To place the estimates of this Technical Report in context with observations with recent history, approximately 7 million acres of forest burned each year between 2006-2015 due to wildfires in the contiguous U.S. and Alaska, and the federal government spent about $1.5 billion per year on suppression.[446] During this same period, the MC2 and ALFRESCO models project 3.9 million burned acres and the economic valuation methods estimate $510 million in response costs each year.[447] As such, these modeling approaches appear to underestimate burning in the historic period by a factor of approximately two, and response costs by a factor of three.[448] Therefore, the values reported in this section should be treated as conservative estimates. Reasons for this discrepancy include the fact that endogenous fire suppression tactics within MC2 are not captured in the valuation methodology used for estimating response costs in the contiguous U.S., and that the valuation approach used to estimate response costs in Alaska is based on data of federal expenditures that does not include state costs, which can equal 50% or more of total expenditures.

Few empirical studies have sought to quantify future wildfire response costs at these large geographic scales, but some recent studies provide a basis for general comparison. Econometric modeling based on observed wildfire trends[449] found that federal wildfire suppression costs in the contiguous U.S. under a high GHG emissions scenario will increase by 46% (31%-69%) by mid-century compared to reference expenditures and 39% (15%-77%) by late-century. The vegetation modeling-based approach used in the analysis of this Technical Report estimates a 12% decrease (36% decrease to 7% increase) in annual average wildfire suppression costs for the contiguous U.S. under RCP8.5 in 2050 (compared to the reference), and a 18% decrease (1%-53%) in 2090. Differences in results are likely attributed to the methods for simulating future wildfire (i.e., statistically versus dynamically in a vegetation model) and the use of different GCMs. Recent research has investigated the differences between statistical and dynamic vegetation modeling approaches, and found that including changes in vegetation and the drought-fire dynamics are important, and may challenge the assumption that warming climates will result in increased burned area.[450] However, additional research is needed to fully understand the structural differences between modeling approaches and their subsequent effects on results.

As a comparison for the Alaska results, a recent study on Canadian wildfire response costs under climate change estimated average annual costs to increase by 119% (compared to the reference period) under RCP8.5 by the end of the century and 60% under RCP4.5.[451] The results presented in this Technical Report indicate that response costs in Alaska will increase by approximately 68% in 2090 under RCP8.5 (compared to the reference period) and 14% under RCP4.5. Differences in results between the two studies are likely attributed to the different geographic regions analyzed, different underlying wildfire methods, and the use of different GCMs.

Several caveats to the results presented in this section are important to consider. First, the wildfire valuation analyses do not quantify human health impacts associated with worsened air quality, property

---

[446] National Interagency Fire Center, 2016: Federal Firefighting Costs (Suppression Only). Available online at https://www.nifc.gov/fireInfo/fireInfo_documents/SuppCosts.pdf

[447] These results are for RCP8.5, though values under RCP8.5 and RCP4.5 do not differ much in these early years.

[448] Dynamic vegetation and wildfire models simulate vegetation and fire interactions on a spatially broad, long-term basis. The interaction between fire and vegetation is non-linear, and dynamic over time. Fire can have threshold effects on vegetation, and vice-versa. Wildfires are highly complex and stochastic processes. For example, a) wildfire ignitions are not only stochastic, but in many parts of the country, the patterns are highly correlated with anthropogenic activities; b) wildfire spread and severity is highly dynamic and dependent on fine spatial scale patterns of fuels, topography and weather, and c) fire suppression is an active policy in many parts of the country, although particular suppression activities are not consistent across the country. For these reasons, a model simulating general patterns of wildfire occurrence and effects on a continental scale is unlikely to perfectly replicate historical observations.

[449] Office of Management and Budget, 2016: Climate Change: Fiscal Risks Facing the Federal Government. Executive Office of the President.

[450] McKenzie, D., J.S. Littell, 2016: Climate change and the eco- hydrology of fire: Will area burned increase in a warming western USA? Ecological Applications: 27(1):26-36.

[451] Hope, E.S., D.W. McKenney, J.H. Pedlar, B.J. Stocks, and S. Gauthier, 2016: Wildfire Suppression Costs for Canada under a Changing Climate. *PLoS ONE*, **11**, e0157425, doi:10.1371/journal.pone.0157425

damage and loss, and loss of recreation, all of which could have large economic implications. Second, continued expansion of development into the wildland-urban interface could increase the number of human-ignited fires and the size of the area designated for higher suppressive action. The wildfire modeling conducted does not account for these interactions. Third, the MC2 and ALFRESCO models do not account for the effects of pest infestations (e.g., pine bark beetles) and tree disease, which can make trees susceptible to burning and affect wildfire activity. Fourth, the analyses do not assume any shifts in the general approach to wildland fire management, such as changes in suppression technologies or fuels management, which could affect future burned acreage and response costs. Finally, new evolving research indicates that climate warming may increase lightning strikes,[452] which could influence the frequency of lightning-caused fires in the future if increases in precipitation do not serve to counteract these effects.

[452] Romps, D.M., J.T. Seeley, D. Vollaro, and J. Molinari, 2014: Projected increase in lightning strikes in the United States due to global warming. *Science*, **346**, 851-854, doi: 10.1126/science.1259100.

27. CARBON STORAGE

27.1 KEY FINDINGS

- Carbon flow projections in the contiguous U.S. demonstrate high inter-annual variability, with the magnitude and even directionality (from sinks to sources) of impacts varying over time under both RCP8.5 and RCP4.5.
- Though carbon flows show substantial regional variation, overall national terrestrial ecosystem carbon storage is projected to increase by 3.0 billion metric tons under RCP8.5 and 0.36 billion metric tons under RCP4.5 through the end of the century. The Northwest is projected to experience the largest increase in stored carbon through 2100, while the Northeast and Midwest experience losses under both RCPs.

27.2 INTRODUCTION

Terrestrial ecosystems influence and are influenced by climate change through their important role in the global carbon cycle. These ecosystems capture and store carbon from the atmosphere, with different systems and plant species storing carbon over various timeframes, which can reduce atmospheric concentrations of carbon dioxide and related climate impacts. However, they can also act as a source, releasing carbon through decomposition, wildfires, and other forms of combustion (e.g., bioenergy, open burning). Terrestrial ecosystems in the U.S., which include forests, grasslands, and shrublands, are currently a net carbon sink.[453] Forest carbon storage has increased over the past several decades due to net increases in forest area and improved forest management, as well as higher productivity rates and longer growing seasons driven by climate change.[454]

While warming temperatures and rising carbon dioxide levels can increase grassland productivity and carbon sequestration, grassland carbon is also sensitive to precipitation and may shift from sinks to sources in some regions in response to drought.[455] Climate-driven changes in the distribution of vegetation types, wildfire, pests, and disease are affecting, and will continue to affect, U.S. terrestrial ecosystem carbon storage.[456]

27.3 APPROACH

This analysis simulates climate change effects on terrestrial vegetative carbon storage in the contiguous U.S. Changes in carbon storage and annual flows are calculated using the MC2 dynamic global

---

[453] Land use, land-use change, and forestry (LULUCF) activities in 2014 resulted in a net increase in C stocks (i.e., net CO_2 removals) of 787.0 MMT CO_2 Eq. (214.6 MMT C). This represents an offset of approximately 11.5 percent of total (i.e., gross) greenhouse gas emissions in 2014. Emissions from land use, land-use change, and forestry activities in 2014 are 24.6 MMT CO_2 Eq. and represent 0.4 percent of total greenhouse gas emissions. Total C sequestration in the LULUCF sector increased by approximately 4.5 percent between 1990 and 2014. Source: EPA, 2016: Forest sections of the Land Use, Land Use change, and Forestry chapter, and Annex. In: U.S. Environmental Protection Agency, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2013. EPA 430-R-15-004.

[454] Galloway, J. N., W. H. Schlesinger, C. M. Clark, N. B. Grimm, R. B. Jackson, B. E. Law, P. E. Thornton, A. R. Townsend, and R. Martin, 2014: Ch. 15: Biogeochemical Cycles. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 350-368. doi:10.7930/J0X63JT0.

[455] Scott, R. L., J. A. Biederman, E. P. Hamerlynck, and G. A. Barron-Gafford, 2015: The carbon balance pivot point of southwestern U.S. semiarid ecosystems: Insights from the 21st century drought. *Journal of Geophysical Research-Biogeosciences,* **120**, 2612-2624.

[456] Joyce, L. A., S. W. Running, D. D. Breshears, V. H. Dale, R. W. Malmsheimer, R. N. Sampson, B. Sohngen, and C. W. Wood, 2014: Ch. 7: Forests. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program. doi:10.7930/J0Z60KZC.

vegetation model developed and run by the USFS' Pacific Northwest Research Station.[457] The model simulates changes in future terrestrial vegetative growth and cover (e.g., grasses, shrubs, hard and softwood forests), including shifts in vegetation types over time, and burned area across the contiguous U.S. from 2015 to the end of the century,[458] excluding consideration of the proportion of a cell assumed to be in developed or in agricultural land use types.[459] MC2 is driven by changes in future climate (e.g., temperature, precipitation, humidity) based on climate projections of five GCMs under two RCP scenarios for four future periods using a 20-year averaging window around the representative year: 2030 (2020-2039), 2050 (2040-2059), 2070 (2060-2079), and 2090 (2080-2099). Projected vegetative cover estimates and the resulting carbon flux from year to year represent changes in climate, biogeography, biogeochemistry, and wildfire dynamics. Projected annual changes in terrestrial carbon flow for non-agricultural, non-developed lands across the contiguous U.S. are summarized by scenario and geographic area in this Section of the Technical Report.

Projected changes in carbon storage have been monetized previously using the social cost of carbon dioxide.[460,461,462] This analysis did not consider the effects of future changes in ozone, pests, and disease, which could influence the ability of U.S. terrestrial ecosystems to store carbon. For more information on the MC2 model and calibration used in this analysis, please refer to Drapek et al. (2015)[463] and Conklin et al. (2016).[464] For information on the approach to valuing changes in carbon storage, please refer to Mills et al. (2014).[465]

27.4 RESULTS

Carbon flow (or flux) projections in the contiguous U.S. fluctuate and are highly variable by GCM, with the magnitude and even directionality (from sinks to sources) of impacts varying over time under both RCPs (Figure 27.1). The large inter-annual variability in carbon flow likely reflects similarly high inter-annual variability in annual acres burned by wildfires under both RCPs (see Figure 27.1 in Wildfire section), for which MC2 simulates periods of fuel accumulation (carbon storage) followed by seasons of

---

[457] Drapek, R.J., J.B. Kim, and R.P Neilson, 2015: Continent-wide Simulations of a Dynamic Global Vegetation Model over the United States and Canada under Nine AR4 Future Scenarios. Global Vegetation Dynamics: Concepts and Applications in the MC1 Model, 73-90.

[458] Although the MC2 simulations under each RCP/GCM combination start in the year 2006, results in this section begin in 2015 due to the fact that values are discounted back to 2015 (consistent with the approach across this Technical Report), and because the application of the dynamic developed lands layer begins in 2010.

[459] A static layer of current agricultural lands based on the National Land Cover Dataset is removed from the vegetative mapping, along with a dynamic layer of developed (urban and suburban) lands based on the ICLUSv2 projections described in the Modeling Framework section of this Technical Report. For more information on the National Land Cover Dataset, see: Homer, C., J. Dewitz, L. Yang, S. Jin, P. Danielson, G. Xian, J. Coulston, N. Herold, J. Wickham, and K. Megown, 2015: Completion of the 2011 National Land Cover Database for the conterminous United States - Representing a decade of land cover change information. *Photogrammetric Engineering and Remote Sensing*, **81**, 345-354.

[460] Mills, D., R. Jones, K. Carney, A. St Juliana, R. Ready, A. Crimmins, J. Martinich, K. Shouse, B. DeAngelo, and E. Monier,. 2014: Quantifying and Monetizing Potential Climate Change Policy Impacts on Terrestrial Ecosystem Carbon Storage and Wildfires in the United States. *Climatic Change*, **131**, 163-178, doi:10.1007/s10584-014-1118-z.

[461] Economic estimates of carbon storage changes are not reported in this Technical Report in response to the March 28, 2017 Executive Order on *Promoting Energy Independence and Economic Growth*, which withdrew the U.S. Government's social cost of carbon dioxide estimates.

[462] For a review of the latest science and recommendations related to estimating the social cost of carbon dioxide, see the January 2017 report of the National Academies of Sciences: http://sites.nationalacademies.org/dbasse/becs/valuing-climate-damages/

[463] Drapek, R.J., J.B. Kim, and R.P Neilson, 2015: Continent-wide Simulations of a Dynamic Global Vegetation Model over the United States and Canada under Nine AR4 Future Scenarios. Global Vegetation Dynamics: Concepts and Applications in the MC1 Model, 73-90.

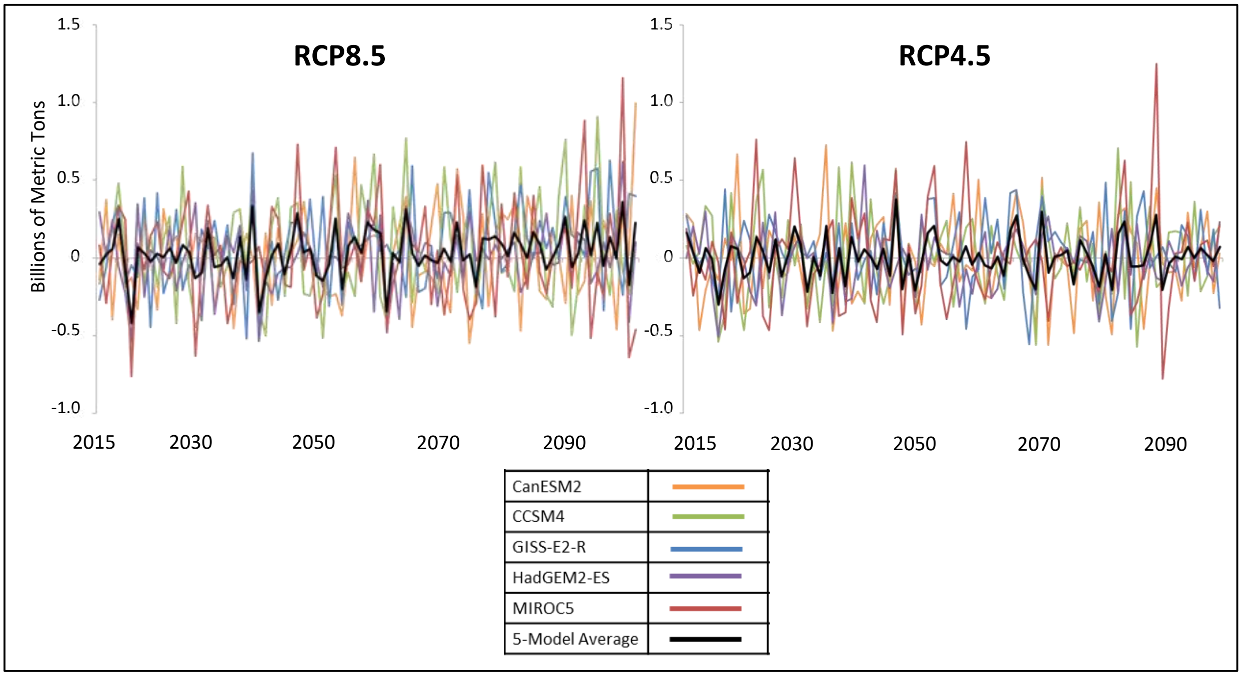
[464] Conklin, DR, JM Lenihan, D Bachelet, RP Neilson, and JB Kim, 2016: MCFire model technical description. Gen. Tech. Rep. PNW-GTR-926. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

[465] Mills, D., R. Jones, K. Carney, A. St Juliana, R. Ready, A. Crimmins, J. Martinich, K. Shouse, B. DeAngelo, and E. Monier,. 2014: Quantifying and Monetizing Potential Climate Change Policy Impacts on Terrestrial Ecosystem Carbon Storage and Wildfires in the United States. *Climatic Change*, **131**, 163-178, doi:10.1007/s10584-014-1118-z.

large wildfire activity (carbon loss) – a trend similar to the variability observed over the past several decades.[466,467]

Figure 27.1. Projected Annual Carbon Flow

Estimated annual carbon flow (billions of metric tons) in the contiguous U.S. over the course of the 21st century under RCP8.5 and RCP4.5 in the five GCMs, with the five-GCM average shown in black.[468]



There is also substantial regional variation in vegetative carbon. Figure 27.2 shows changes in annual average carbon stored in the 20-year eras around 2050 and 2090 across the contiguous U.S. compared to the reference period (see Figure A15.1 of the Appendix for GCM-specific maps). At a national level, carbon flows from vegetation is positive in 2050, with an increase in average carbon storage of 28 million metric tons under RCP8.5 and 9.8 million metric tons under RCP4.5. These values increase by 2090 to 88 million metric tons under RCP8.5 and 11 million metric tons under RCP4.5 in 2090. The amount of carbon stored by vegetation in Southeast, Southwest, Northwest, and Northern Plains increases under both RCPs, particularly later in the century, while carbon storage is projected to generally decrease under both RCPs in the Midwest and Northeast. The amount of carbon stored by vegetation in the Southern Plains increases under RCP8.5, but decreases for RCP4.5.

---

[466] National Interagency Fire Center, 2016: Federal Firefighting Costs (Suppression Only). Available online at https://www.nifc.gov/fireInfo/fireInfo_documents/SuppCosts.pdf

[467] EPA, 2016: Forest sections of the Land Use, Land Use change, and Forestry chapter, and Annex. In: U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2013*. EPA 430-R-15-004.

[468] Carbon flow losses appearing every decade (e.g., in 2020, 2030) across all scenarios are driven by the re-estimation of developed lands and the application of this mask layer to the vegetation modeling.

Figure 27.2. Projected Percent Change in Carbon Stored

Projected percent change in the five-GCM average annual carbon stock across the contiguous U.S. under RCP8.5 and RCP4.5 by mid-century (2040-2059) and end of century (2080-2099) compared to the reference period (1986-2005). Changes in carbon stock calculated at a cell resolution of 1/16th of a degree and converted to ½ degree for mapping purposes. Agricultural and developed lands are omitted (shown in gray).

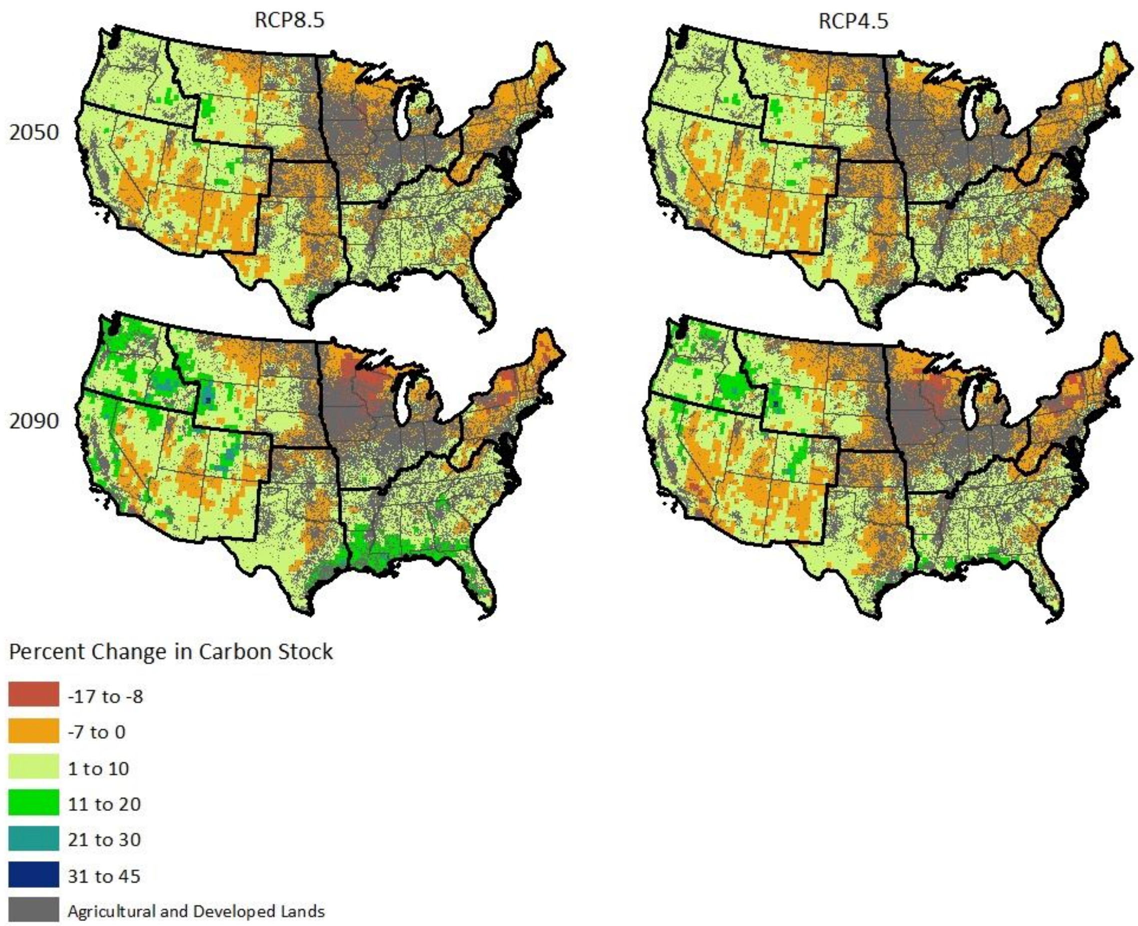


Table 27.1 shows the cumulative changes in carbon storage from 2015-2099 at regional and national levels, along with the monetized value of these changes. Through the end of the century, national terrestrial ecosystem carbon storage is projected to increase by 3.0 billion metric tons under RCP8.5 and 0.36 billion metric tons under RCP4.5. Moderate losses of carbon storage are projected for the Northeast and Midwest under both RCPs (approximately 0.6 billion metric tons) and also in the Southern Plains under RCP4.5 (Figure 27.2 and Table 27.1). The Northwest is projected to have the largest cumulative increase in vegetative carbon of 1.3 billion metric tons under RCP8.5 by the end of the century.

Table 27.1. Projected National and Regional Carbon Storage

Values represent the average of the five GCMs over the 2015-2099 period. Totals may not sum due to rounding.

Region	Change in Carbon Storage (billions of metric tons)	
	RCP8.5	RCP4.5
Northeast	-0.56	-0.60
Southeast	0.94	0.17
Midwest	-0.60	-0.59
Northern Plains	0.55	0.28
Southern Plains	0.32	-0.12
Southwest	1.00	0.37
Northwest	1.30	0.85
National Total	**3.0**	**0.36**

27.5 DISCUSSION

The observed rise in global atmospheric carbon dioxide concentration is lower than would be expected given anthropogenic greenhouse gas emissions, demonstrating continued uptake of carbon by the ocean and terrestrial vegetation over the last 50 years.[469] The findings of this analysis are consistent with recent literature[470], which projects increases in forest and grassland carbon stocks across North America in the future, a trend that also follows observations over the last few decades.[471] However, uncertainty remains regarding the magnitude of carbon storage changes across the contiguous U.S., with projections in the literature depending upon the modeling approaches used, climate drivers, and assumptions regarding future changes in landuse and land cover.

This analysis omits carbon storage changes on agricultural lands, urban landscapes, and in non-terrestrial ecosystems, such as tidal marshes and seagrass beds. In addition, many factors beyond rising carbon dioxide will have an influence on carbon storage in the U.S., including changes in land use, management practices (e.g. changes in wildfire suppression and fuel management actions), and other environmental factors that may limit or enhance plant growth or result in shifts in vegetation type. As forests make up approximately 80% of the aggregate North American carbon sink for atmospheric carbon, deforestation could have large impacts on U.S. carbon storage.[472] Please refer to Mills et al. (2014) for complete discussion about the limitations and uncertainty associated with the analysis.[473]

Many of the caveats described in the Wildfire section also apply to the carbon storage results presented in this section. For instance, continued expansion of development into the wildland-urban interface

[469] Ballentyne, A.P., C.B. Alden, J.B. Miller, P.P. Tans, and J.W.C. White, 2012: Increase in observed net carbon dioxide uptake by land and oceans during the past 50 years. *Nature*, **488**, 70-72.

[470] Raczka, B.M., K.J. Davis, D. Huntzinger, R.P. Neilson, B. Poulter, A.D. Richardson, J. Xiao, I. Baker, P. Ciais, T. F. Keenan, B. Law, W.M. Post, D. Ricciuto, K. Schaefer, H. Tian, E. Tomelleri, H. Verbeeck, and N. Viovy, 2013: Evaluation of continental carbon cycle simulations with North American flux tower observations. *Ecological Monographs*, **83**, 531-556.

[471] EPA, 2016: Forest sections of the Land Use, Land Use change, and Forestry chapter, and Annex. In: U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2103*. EPA 430-R-15-004.

[472] Ibid.

[473] Mills, D., R. Jones, K. Carney, A. St Juliana, R. Ready, A. Crimmins, J. Martinich, K. Shouse, B. DeAngelo, and E. Monier, 2014: Quantifying and Monetizing Potential Climate Change Policy Impacts on Terrestrial Ecosystem Carbon Storage and Wildfires in the United States. *Climatic Change*, **131**, 163-178, doi:10.1007/s10584-014-1118-z.

could increase the number of human-ignited fires and the size of the area designated for higher suppressive action. Climate change may also impact vegetative diseases or pest infestations (e.g., pine bark beetles). These impacts are not included in the modeling. See the Wildfire section for additional limitations of the modeling approach.

SYNTHESIS OF RESULTS

28. NATIONAL SUMMARY

Figure 28.1 and tables 28.1 and 28.2 provide an overview of the national-scale results presented throughout this Technical Report. Focusing on physical effects (Table 28.1) and economic impacts (Figure 28.1 and Table 28.2), these summaries present the estimated annual effects of climate change in the U.S. under RCP8.5 and RCP4.5 in the years 2050 and 2090 for the impact sectors considered in this Technical Report. Although not available for all sectors, cumulative impacts for the entire 21st century would likely be much larger than the annual estimates presented. In addition, the individual monetized estimates are not aggregated, as only a subset of climate change impacts is quantified in this report. Importantly, many of the reported values do not estimate and monetize the full extent of potential impacts from climate change on that sector, and as such, the results should be treated as conservative. For example, the air quality analysis only estimates economic damages from mortality caused by changes in ozone, omitting effects from changes in other air pollutants and morbidity effects, while the extreme temperature mortality analysis only includes 49 major cities, covering about one third of the population. In addition, interactive effects across sectors are only modeled in several instances (e.g., irrigation for agriculture informed by water supply/demand model), therefore omitting potentially important compounding impacts. Please refer to the sectoral sections of this report describing the individual modeling efforts for detailed information on the results, a summary of the methodologies used, and references to the supporting peer-reviewed literature.

As shown in Figure 28.1 and Tables 28.1 and 28.2, annual impacts and damages are projected to increase over time and are generally larger under RCP8.5 compared to RCP4.5. Projected impacts on extreme temperature mortality, outdoor labor, and coastal property are the most economically significant under both time periods and RCPs. Estimated impacts on air quality and road infrastructure are also large. For the wildfire sector, climate change, on average, is projected to result in a decrease in economic impacts in the future. It is important to note that while the magnitude of estimated economic impacts for some of the sectors is relatively small, many of the physical impacts have significant societal or iconic values.

28.1. Annual Damages from Climate Change

Mean estimates of annual climate change damages are shown in $millions for RCP8.5 and RCP4.5 in 2050 and 2090. The three graphs are on different scales to capture the range of impacts. Note that graph (c) includes negative damages (benefits). The data underlying this graphic can be found in Table 28.2.

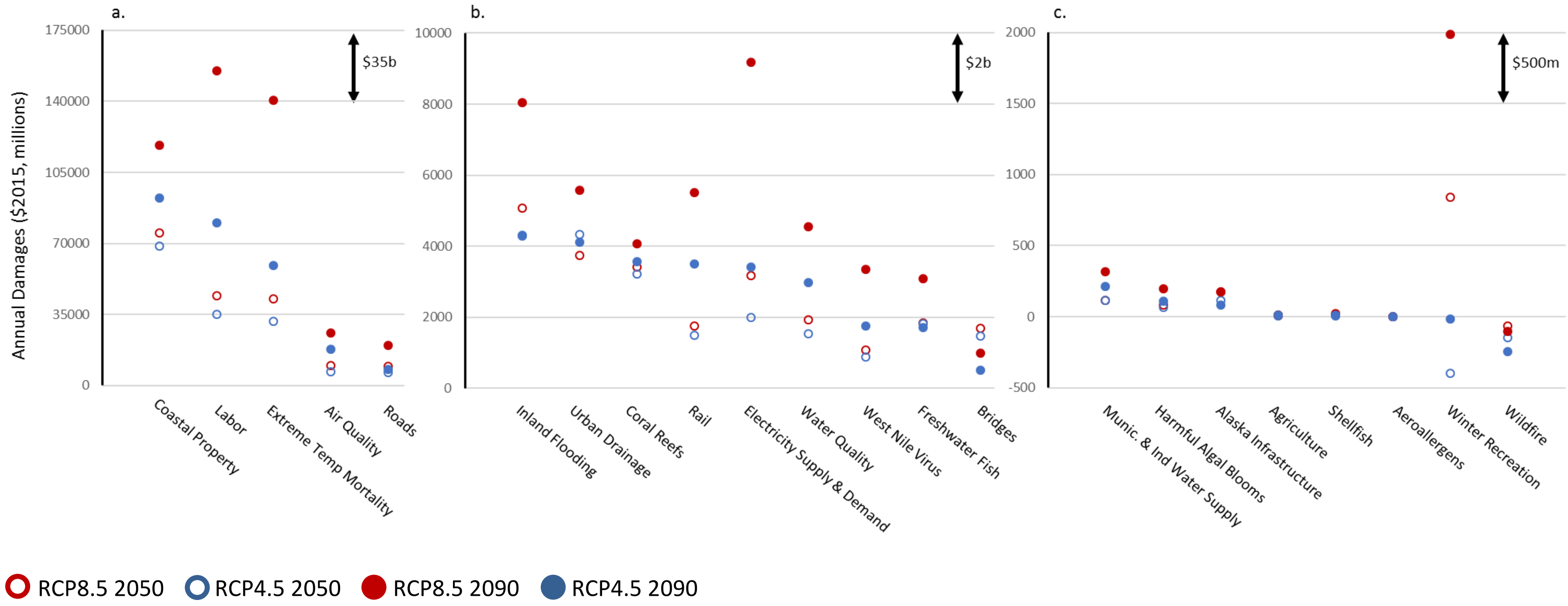


Table 28.1. Projected Annual Physical Impacts of Climate Change across U.S. Sectors Analyzed

Only some of the sectoral analyses produced discrete physical metric estimates, in contrast to Table 28.2 that provides economic impacts across all sectors of this report. Positive numbers represent damages due to climate change, while negative numbers represent a reduction in damages compared to the reference period. Unless noted at the bottom of Table 28.2, upper and lower bounds are based on values across the GCMs. See notes at the bottom of Table 28.2 for additional sector-specific information.

	2050			2090		
	RCP8.5	**RCP4.5**	**Benefit**	**RCP8.5**	**RCP4.5**	**Benefit**
HEALTH						
Air Quality: # Deaths	790 (420 to 1,200)	550 (300 to 810)	240 (NA)	1,700 (920 to 2,500)	1,200 (630 to 1,700)	500 (NA)
Extreme Temperature Mortality: # Deaths (thousands)	3.4 (2.3 to 5.9)	2.6 (1.7 to 3.9)	0.88 (0.17 to 2.0)	9.3 (5.4 to 13)	3.9 (2.4 to 7.4)	5.4 (2.8 to 8.1)
Labor: Lost Labor Hours (millions)	880 (500 to 1,400)	700 (380 to 1,100)	180 (-24 to 290)	1,900 (1,000 to 2,700)	970 (620 to 1,500)	910 (420 to 1,300)
Aeroallergens: ED visits (thousands)	1.2 (0.068 to 1.8)	0.90 (0.19 to 1.6)	0.30 (-0.12 to 0.83)	2.5 (0.87 to 3.5)	1.1 (-0.081 to 1.9)	1.4 (0.95 to 1.9)
Harmful Algal Blooms: # Days above 100k cells/mL	9.2 (5.4 to 15)	8.4 (6.8 to 13)	0.71 (-0.88 to 2.3)	15 (6.5 to 24)	9 (2.7 to 15)	5.7 (2.2 to 11)
West Nile Virus: # Cases (thousands)	1.3 (0.92 to 1.8)	1.0 (0.72 to 1.4)	0.23 (0.19 to 0.33)	3.3 (2.0 to 4.6)	1.7 (1.2 to 2.4)	1.6 (0.81 to 2.2)
INFRASTRUCTURE						
Bridges: # Vulnerable Bridges (thousands)	4.6 (3.3 to 6.1)	2.5 (1.6 to 3.5)	2.1 (0.88 to 4.1)	6.0 (2.4 to 8.8)	5.0 (3.1 to 6.3)	0.99 (-0.67 to 3.2)
WATER RESOURCES						
Winter Recreation: Lost Visits (millions)	12 (-3.3 to 20)	-4.5 (-10 to -1.1)	16 (-2.2 to 30)	28 (4.7 to 38)	2.5 (-18 to 14)	25 (23 to 30)
AGRICULTURE						
Agriculture: % Decrease in Corn Yields (example crop)	5.8% (-1.6% to 17%)	3.6% (-3.8% to 12%)	2.2% (-6.3% to 6.6%)	17% (6.7% to 28%)	4.5% (-3.1% to 15%)	13% (8.0% to 22%)

	2050			2090		
	RCP8.5	RCP4.5	Benefit	RCP8.5	RCP4.5	Benefit
ECOSYSTEMS						
Coral Reefs, HI: % Lost Cover	70% (11% to 97%)	64% (7.3% to 94%)	5.6% (-11% to 17%)	96% (88% to 98%)	79% (26% to 97%)	16% (-1.2% to 63%)
Coral Reefs, FL: % Lost Cover	95% (93% to 97%)	94% (89% to 96%)	1.6% (-1.1% to 8.5%)	97% (95% to 98%)	96% (95% to 97%)	0.57% (0.10% to 1.3%)
Coral Reefs, PR: % Lost Cover	93% (89% to 95%)	93% (85% to 96%)	-0.80% (-6.7% to 9.7%)	95% (92% to 98%)	97% (96% to 97%)	-1.4% (-3.9% to 0.88%)
Freshwater Fish: Lost Coldwater Fishing Days (millions)	67 (54 to 80)	62 (47 to 75)	5.4 (3.3 to 6.8)	90 (73 to 100)	67 (55 to 80)	23 (18 to 29)
Shellfish: %Decrease in Oyster Supply (example species)	23% (22% to 24%)	16% (14% to 17%)	7.1% (5.2% to 8.1%)	48% (46% to 50%)	22% (20% to 24%)	25% (24% to 26%)
Wildfire: Acres Burned (millions)	-0.55 (-1.9 to 0.50)	-1.8 (-2.6 to -0.69)	1.2 (0.093 to 2.1)	-0.36 (-1.9 to 0.38)	-2.1 (-2.8 to -1.5)	1.7 (0.49 to 2.3)
Carbon Storage: Metric Tons Lost (millions)	-28 (-110 to 25)	-10 (-42 to 24)	-18 (-71 to 19)	-88 (-200 to -33)	-11 (-34 to 36)	-77 (-180 to -22)

Note: "NA" indicates analyses where GCM-specific results are not available.

Table 28.2. Projected Annual Economic Impacts of Climate Change across U.S. Sectors Analyzed
Positive numbers represent damages due to climate change, while negative numbers represent a reduction in damages compared to the reference period. Unless noted, upper and lower bounds are based on values across the GCMs. Values shown in millions of undiscounted $2015.

	2050			2090		
	RCP8.5	RCP4.5	Benefit	RCP8.5	RCP4.5	Benefit
HEALTH						
Air Quality	$9,800 ($880 to $28,000)	$6,900 (-$900 to $21,000)	$2,900 (NA)	$26,000 (-$2,200 to $78,000)	$18,000 ($1,600 to $51,000)	$8,000 (NA)
Extreme Temp. Mortality	$43,000 ($28,000 to $73,000)	$32,000 ($21,000 to $48,000)	$11,000 ($2,100 to $25,000)	$140,000 ($82,000 to $200,000)	$59,000 ($37,000 to $110,000)	$82,000 ($42,000 to $120,000)
Labor	$44,000 ($25,000 to $70,000)	$35,000 ($19,000 to $56,000)	$9,000 (-$1,200 to $15,000)	$160,000 ($87,000 to $220,000)	$80,000 ($52,000 to $120,000)	$75,000 ($35,000 to $110,000)
Aeroallergens	$0.59 ($0.033 to $0.90)	$0.44 ($0.092 to $0.80)	$0.14 (-$0.059 to $0.40)	$1.2 ($0.43 to $1.7)	$0.52 (-$0.040 to $0.93)	$0.70 ($0.47 to $0.91)
Harmful Algal Blooms	$79 ($42 to $170)	$64 ($30 to $150)	$15 (-$17 to $49)	$200 ($130 to $390)	$110 ($54 to $230)	$89 ($22 to $180)
West Nile Virus	$1,100 ($780 to $1,500)	$870 ($610 to $1,200)	$200 ($160 to $280)	$3,300 ($2,000 to $4,700)	$1,800 ($1,200 to $2,500)	$1,600 ($820 to $2,200)
INFRASTRUCTURE						
Roads	$9,500 ($2,800 to $23,000)	$6,500 ($2,700 to $16,000)	$2,900 (-$680 to $7,200)	$20,000 ($7,000 to $37,000)	$8,100 ($3,300 to $20,000)	$12,000 ($3,700 to $17,000)
Bridges	$1,700 ($950 to $2,200)	$1,500 ($1,100 to $1,700)	$220 (-$140 to $650)	$1,000 ($670 to $1,300)	$510 ($310 to $740)	$490 ($270 to $910)
Rail	$1,800 ($1,300 to $2,200)	$1,500 ($1,100 to $1,800)	$270 (-$17 to $410)	$5,500 ($4,000 to $6,600)	$3,500 ($2,400 to $4,400)	$2,000 ($1,600 to $2,300)
Alaska Infrastructure	$180 ($170 to $180)	$120 ($110 to $130)	$60 ($55 to $66)	$170 ($130 to $220)	$82 ($80 to $84)	$92 ($49 to $140)
Urban Drainage	$3,700 ($2,100 to $4,600)	$4,300 ($3,500 to $4,900)	-$600 (-$2,100 to $63)	$5,600 ($3,300 to $7,000)	$4,100 ($2,900 to $5,900)	$1,500 (-$110 to $3,200)
Coastal Property	$75,000 (NA)	$69,000 (NA)	$6,800 (NA)	$120,000 (NA)	$92,000 (NA)	$26,000 (NA)
ELECTRICITY						
Electricity Demand and Supply	$3,200 ($2,700 to $4,200)	$2,000 ($1,400 to $2,600)	$1,200 ($390 to $1,600)	$9,200 ($6,500 to $11,000)	$3,400 ($2,300 to $5,000)	$5,800 ($3,500 to $7,600)

	2050			2090		
	RCP8.5	RCP4.5	Benefit	RCP8.5	RCP4.5	Benefit
WATER RESOURCES						
Municipal and Industrial Water Supply	$120 ($26 to $240)	$120 ($27 to $240)	$1.4 (-$85 to $89)	$320 ($190 to $640)	$210 (-$9.3 to $410)	$100 (-$32 to $230)
Inland Flooding	$5,100 (NA)	$4,300 (NA)	$770 (NA)	$8,100 (NA)	$4,300 (NA)	$3,800 (NA)
Water Quality	$1,900 ($1,300 to $2,800)	$1,500 ($1,100 to $2,200)	$390 ($260 to $610)	$4,600 ($3,200 to $5,700)	$3,000 ($1,700 to $4,200)	$1,600 ($1,100 to $2,200)
Winter Recreation	$780 (-$440 to $1,500)	-$430 (-$890 to -$38)	$1,200 (-$400 to $2,400)	$2,000 ($28 to $2,900)	-$130 (-$1,900 to $830)	$2,200 ($1,900 to $2,500)
AGRICULTURE						
Agriculture	$8.0 ($6.7 to $11)	$7.7 ($6.4 to $10)	$0.22 (-$1.7 to $1.2)	$12 ($11 to $13)	$11 ($9.3 to $13)	$1.3 (-$0.33 to $2.0)
ECOSYSTEMS						
Coral Reefs	$3,400 ($1,800 to $4,200)	$3,200 ($1,600 to $4,100)	$200 (-$330 to $720)	$4,100 ($3,800 to $4,200)	$3,600 ($1,900 to $4,100)	$500 (-$31 to $1,900)
Freshwater Fish	$1,900 (-$430 to $4,600)	$1,800 ($740 to $3,100)	$35 (-$1,200 to $1,500)	$3,100 (-$410 to $5,500)	$1,700 (-$300 to $3,700)	$1,400 (-$110 to $2,100)
Shellfish	$9.1 ($3.7 to $14)	$6.1 ($2.1 to $9.0)	$3.0 ($1.1 to $5.1)	$23 ($8.9 to $35)	$10 ($3.4 to $15)	$13 ($5.4 to $20)
Wildfire	-$67 (-$230 to $62)	-$150 (-$280 to -$5.6)	$82 (-$11 to $180)	-$110 (-$340 to $8.6)	-$250 (-$340 to -$170)	$140 (-$6.9 to $250)

Notes:
”NA” indicates analyses where GCM-specific results are not available.
Air Quality: Mean and upper/lower bounds based on confidence intervals from the BenMAP-CE model.
Harmful Algal Blooms: Range and mean values based on combined high and low growth scenarios.
Urban Drainage: Values represent results under the 50-year storm.
Coastal Property: Costs with no adaptation. See Modeling Framework section for a description of SLR uncertainty.
Electricity Demand and Supply: Values represent power system supply costs. Results are from the GCAM power sector model only.
Water Quality: Range and mean values based on combined results from US Basins and HAWQS.
Freshwater Fish: Values represent impacts to all three fishing guilds (coldwater, warmwater, and rough)
Wildfire: Results represent changes in both the contiguous U.S. and Alaska.

29. RISK REDUCTION THROUGH ADAPTATION

29.1 KEY FINDINGS

- Analysis of adaptation for the infrastructure sector suggests that adaptation is an important, cost-effective response strategy to reduce climate change impacts and enhance resilience. Under RCP8.5, well-timed adaptation could reduce over 75% of the cumulative impacts to coastal properties, roads, and the rail system in the U.S., resulting in hundreds of billions of dollars in cumulative benefits this century.
- Proactive adaptation measures implemented in anticipation of future climate change risks are projected to be more cost-effective than reactive repairs implemented after impacts have already occurred.
- Reduced climate change under RCP4.5 generally lowers the costs of adaptation, but the timing and magnitude varies by sector.
- For some infrastructure sectors, a portfolio of measures - reducing climate change and taking adaptive actions - achieves the greatest benefits in reducing climate change damages. The combined strategies can eliminate 91%, 89% and 91% of the cumulative climate change impacts that are otherwise projected to occur this century for coastal property, roads, and rail infrastructure, respectively.

29.2 BACKGROUND

Adaptation, along with substantial and sustained reductions in global GHG emissions, has the potential to limit climate change risks and reduce society's vulnerability to climate change impacts.[474,475] There are a wide range of adaptation options that can vary depending on the sector, the timing of implementation, and other factors. For example, adaptation can be a reactive response (i.e., implemented in response to climate change impacts that have already occurred) or proactive (i.e., planned and implemented in anticipation of future climate change risks). Adaptation measures can also be categorized as engineering and technology options (e.g., new crop varieties, coastal protection structures, improved drainage), management options (e.g., changes of crop planting dates and locations), ecosystem-based options (e.g., green infrastructure), economic options (e.g., financial incentives, insurance), institutional options (e.g., land use zoning laws, building codes, disaster risk management planning), or social options to enhance adaptive capacity (e.g., social safety nets for vulnerable population, education).[476] Adaptation options may be undertaken by different actors (e.g., households, private sector, governments) and at various geographic scales (local, national, and international).

---

[474] IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, 151 pp.

[475] Bierbaum, R., A. Lee, J. Smith, M. Blair, L. M. Carter, F. S. Chapin, III, P. Fleming, S. Ruffo, S. McNeeley, M. Stults, L. Verduzco, and E. Seyller, 2014: Ch. 28: Adaptation. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 670-706. doi:10.7930/J07H1GGT.

[476] Adapted from Noble, I.R., S. Huq, Y .A. Anokhin, J. Carmin, D. Goudou, F .P . Lansigan, B. Osman-Elasha, and A. Villamizar, 2014: Adaptation needs and options. 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. 833-868.

29.3 APPROACH TO ADAPTATION IN THE TECHNICAL REPORT

In this Technical Report, adaptation is explicitly analyzed for a number of impact categories to evaluate its effects on reducing climate damages, and to characterize interactions under different climate change scenarios. These analyses use a variety of approaches and scenarios to represent adaptation (see Table 29.1).

Table 29.1. Adaptation Approaches and Measures

Sector	Analytical Approach	Adaptation Measures Analyzed
Infrastructure		
Coastal Property	Estimates climate change damages and conducts a cost-benefit analysis of adaptation options in U.S. coastal areas using the National Coastal Property Model.	Beach nourishment, property elevation, shoreline armoring, property abandonment.
Roads*	Estimates climate change impacts and costs of reactive and proactive adaptation options for the U.S. road network to maintain current levels of service using the Infrastructure Planning Support System (IPSS) tool.	Change of road materials (e.g., asphalt mix), design modification (e.g., surface density), road upgrade (e.g., to paved or gravel road).
Rail*	Estimates climate change impacts (delays) and costs of reactive and proactive adaptation to the U.S. rail network using the IPSS tool.	Installation and use of temperature sensors that allow for better rail monitoring and reduced rail traffic delays.
Bridges	Evaluates climate change vulnerability on inland bridges across the U.S., and estimates the costs of proactive adaptation measures.	Proactive adaptation (repairs) using rip-rap and concrete strengthening.
Urban Drainage	Estimates the costs of proactive adaptation for urban drainage infrastructure in 100 modeled cities across the U.S. associated with three storm types.	Use of best management practices (e.g., temporary storage, and permeable pavement).
Health		
Extreme Temperature Mortality	Includes a sensitivity analysis assuming the human health response to extreme temperature in 49 U.S. cities is equal to that of Dallas, TX today (compared to the no-adaptation scenario's use of city-specific temperature thresholds).	Adaptive responses embedded in empirical damage functions (e.g., increased use of air conditioning, institutional/societal responses, and physiological adaptation of human body to warmer temperatures).

* Includes values reported in the Alaska Infrastructure section.

As shown in Table 29.1, the analysis of adaptation in this Technical Report focuses on the infrastructure sector and includes a sensitivity analysis for extreme temperature mortality. As discussed in more details in individual chapters, the analytical approaches used to evaluate costs and effects of adaptation on reducing climate change impacts vary across the impact categories. For example, the Coastal Property section quantifies damages from climate change with and without adaptation (adaptation response costs are embedded in estimated damages), allowing for analysis of the effects of adaptation on reducing damages to coastal properties and energy installations from sea level rise and storm surge. The Roads and Alaska Infrastructure analyses estimate the costs of climate change impacts in the form of reactive adaptation to maintain current levels of service, and evaluate the ability of proactive adaptation measures to improve resiliency and reduce costs. The Rail analysis quantifies the costs of reactive adaptation associated with delays resulting from increased temperatures under climate change, and the costs of proactive adaptation that include both the costs of implementing adaptation measures and residual impacts. For Bridges and Urban Drainage, the analyses assume that the modeled systems will adapt by making adjustments or investments to maintain consistent levels of service, and estimate the costs of implementing proactive adaptation measures.

The modeled adaptation responses for these sectors have a strong focus on structural- and technology-based adaptation options (e.g., infrastructure maintenance and upgrades). Other adaptation strategies, such as ecosystem-based, economic or institutional measures, are not considered in the analyses of this Technical Report. Similarly, adaptation analysis for other impact categories is not fully explored, due to limitations in the current modeling capability, data availability, and understanding of adaptation pathways. For Extreme Temperature Mortality, a sensitivity analysis was conducted using city-specific temperature thresholds to explore the potential effect of both physiological (acclimatization) and societal adaptive responses, such as increased use of air conditioning or early-warning systems.

In some other sectoral analyses of this Technical Report, behavioral or market adjustments are assumed to occur to minimize climate change impacts and damages without deliberate interventions. Examples include crop switching and changes in planting dates and locations in response to changes in water availability and temperature-induced changes in the agricultural sector; increased energy consumption for air conditioning in response to higher temperatures; and increased snowmaking to meet winter recreation demand. In addition, autonomous ecological adaptation is also assumed and modeled in a number of the ecosystem sectors, such as shifting distributions of freshwater fisheries in response to changes in suitable habitat, or vegetation changes in response to changing climate that in turn affect wildfire activity and carbon storage. In these cases, this autonomous adaptation is embedded in the analyses and the estimated damages reflect assumptions of behavioral, market, or ecological adjustments that take place without deliberate interventions.

29.4 RESULTS

The analysis below focuses on the infrastructure sector, including Coastal Property, Roads, Rails, Bridges, and Urban Drainage. This sector provides adaptation analyses that allow for comparison and the development of broad insights on the costs and effectiveness of adaptation in reducing climate change impacts. Table 29.2 presents the summary results of these sectoral analyses.

Table 29.2. Effects of Adaptation and Reduced Climate Change on Infrastructure Damages

Results, shown in billions of $2015, represent averages across the five GCMs by sector. Values shown in the dark blue cells represent the combined effects of reduced climate change and adaptation. Annual average results in the 2050 and 2090 columns are undiscounted, while the cumulative benefit estimates (through 2099) are discounted at 3%. Values may not sum due to rounding.

Sector	Scenarios	2050			2090			Cumulative Effect through 2099**
		RCP8.5	RCP4.5	Effect of Reduced Climate Change	RCP8.5	RCP4.5	Effect of Reduced Climate Change	
Coastal Property	Without adaptation	$75	$69	$6.8	$120	$92	$26	$83
	With adaptation	$8.6	$8.2	$0.45	$7.3	$5.7	$1.6	$15
	Damages avoided by adaptation	$67	$60	$67	$110	$87	$110	$900***
Roads*	Reactive adaptation	$9.6	$6.6	$2.9	$20	$8.2	$12	$79
	Proactive adaptation	-$1.2	-$0.94	-$0.25	-$7.3	-$3.1	-$4.2	-$20
	Damages avoided by proactive adaptation	$11	$7.6	$10	$27	$11	$23	$200
Rail*	Reactive adaptation	$1.8	$1.5	$0.27	$5.5	$3.5	$2	$11
	Proactive adaptation	$0.43	$0.23	$0.20	$1.6	$0.40	$1.2	$7
	Damages avoided by proactive adaptation	$1.3	$1.3	$1.5	$3.9	$3.1	$5.1	$46
Bridges	With proactive adaptation	$1.7	$1.5	$0.22	$1.0	$0.51	$0.49	
Urban Drainage	With adaptation	$3.7	$4.3	-$0.6	$5.6	$4.1	$1.5	

* These results include estimates for Alaska and therefore do not match the results presented in the Roads and Rail sections of this Technical Report.

** Represents the cumulative effect of reduced climate change through 2099. The time period used for deriving cumulative benefits in this table is 2015-2099 for coastal properties and roads, and 2016-2099 for rail.

*** This value is based on cumulative effects for 2015-2099 and therefore differs from the results presented in the Coastal Property section of this Technical Report, which present results for 2000-2099. The substantial difference in the two estimates is attributed to the fact that a large number of properties in the U.S. are estimated to already be vulnerable or to become vulnerable soon after the first year of the simulation (the model assumes optimal adaptation with near-term foresight, therefore leading to adaptation responses in the near-term that may otherwise be delayed).

Climate change is projected to result in significant damages to coastal property, but there is also substantial potential to reduce the magnitude of damages through adaptation in this sector (e.g., abandonment, shoreline armoring and beach nourishment). Adaptation measures are estimated to reduce 89% and 94% of climate change impacts under RCP8.5 in 2050 and 2090, respectively. Adaptation is also projected to be significant for the U.S. roads and rail systems when comparing costs under the proactive adaptation scenario and those under the reactive adaptation scenario. Under RCP8.5, adaptation responses are projected to reduce 98% of the cumulative costs of climate change ($220 billion in cumulative benefits) for roads and 77% of damages ($39 billion in cumulative benefits) for rail networks over the course of the century.

Analyses of roads and rail also suggest that proactive adaptation measures, when undertaken in anticipation of future climate change risks, can be far more cost-effective in reducing impacts from climate change than reactive adaptation measures. Proactive adaptation investments, made in advance of climate change impacts, more than compensate for the cost of reactive adaptation experienced by the road network, and reduce 76% and 71% of the cost of reactive adaptation to the rail system under RCP8.5 in 2050 and 2090, respectively.

Reduced climate change under RCP4.5 lowers the costs of adaptation, but the timing and magnitude of reduction varies by sector. For rail systems, RCP4.5 reduces adaptation costs by 47% and 75% in 2050 and 2090, respectively, compared to RCP8.5. For bridges, RCP4.5 reduces adaptation costs by 13% and 49% in 2050 and 2090, respectively, compared to RCP8.5. For urban drainage, reduced climate change under RCP4.5 (compared to RCP8.5) leads to 16% higher costs in the mid-century period, but results in 26% reduction in annual adaptation costs by 2090. For the road network, RCP4.5 is projected to increase the cost of adaptation in the mid-century (by 22% in 2050) due to reduced cost savings from responding to impacts of freeze-thaw on paved roads, but reduce the overall cost of adaptation later in the century (by 58% in 2090).

For some infrastructure sectors, a portfolio of measures – both reducing climate change and taking adaptive actions - achieves the greatest benefits in reducing damages. For coastal property, roads, and rail infrastructure, a portfolio of strategies can eliminate 91%, 89% and 91% of the climate change impacts that are otherwise projected to occur within this century, respectively (Table 29.3).[477]

[477] It is noted that the magnitude of aggregate damage reduction from a combination of GHG mitigation and adaptation is less than the sum of damage reductions from adaptation only and mitigation only, suggesting there may be some tradeoffs between mitigation and adaptation actions. However, the overall benefit of a portfolio of GHG mitigation and adaptation is greater than a mitigation-only or adaptation-only approach.

Table 29.3. Reduction in Damages Due to Adaptation and Reduced Climate Change

Unless noted, values represent the percent reduction in economic effects based on cumulative, discounted (3%) damages through 2099.

Sector	Damage Reduced by Proactive Adaptation[i]	Damage Reduced by Mitigation[ii]	Damage Reduced by Mitigation and Adaptation[iii]
Coastal Property[iv]	90%	8%	91%
Roads	98%	35%	89%
Rail	77%	21%	91%

[i] Damage reductions from adaptation under RCP8.5.

[ii] Difference in damage reductions between RCP8.5 and RCP4.5 without adaptation.
[iii] Difference in damage reductions between RCP8.5 without adaptation and RCP4.5 with adaptation.
[iv] This value is based on cumulative benefits for 2015-2099 and therefore differs from the results presented in the Coastal Property section of this Technical Report, which present results for 2000-2099.

29.5 DISCUSSION

Analyses of adaptation responses included in this Technical Report suggest the important role and cost-effectiveness of adaptation in reducing climate change impacts and risks. For coastal property, roads, and rail, well-timed adaptation measures can be very effective in reducing the negative impacts from climate change, suggesting investment opportunities in adaptation measures would avoid costly damages and ensure the resilience of these sectors. Proactive adaptation measures can be far more cost-effective in reducing damages than reactive measures. Moreover, a portfolio of responses to reduce climate change and adapt would significantly limit overall damages. These findings are consistent with the broad literature that points to the importance of strategically timed implementation of adaptation measures in the near- to medium-terms[478], and a portfolio approach to address the long-term climate risks.[479]

The analysis contributes to the literature by presenting quantitative estimates of the costs and cost-effectiveness of adaptation responses in selected infrastructure sectors in the U.S. However, several limitations should be noted and considered for future research. First, analysis of climate change impacts and responses should cover a broader set of sectors and adaptation measures (e.g., ecosystem-based, economic, and institutional measures) to improve estimates of climate change impacts and costs and benefits of adaptation. Analysis of other adaptation options and for other impact categories was not fully explored due to limitations in the current modeling capability, data availability, and understanding of adaptation pathways. Second, the sectoral analyses often model optimal adaptation behavior, which assumes well-timed, cost-minimizing implementation of responses. As such, they provide upper-bound estimates of the potential for adaptation to reduce vulnerabilities and risks. There is a need to better understand how uncertainty of future climate change and market, behavioral, and institutional barriers affect the implementation of adaptation measures, and costs and benefits of adaptation.[480] Third, there

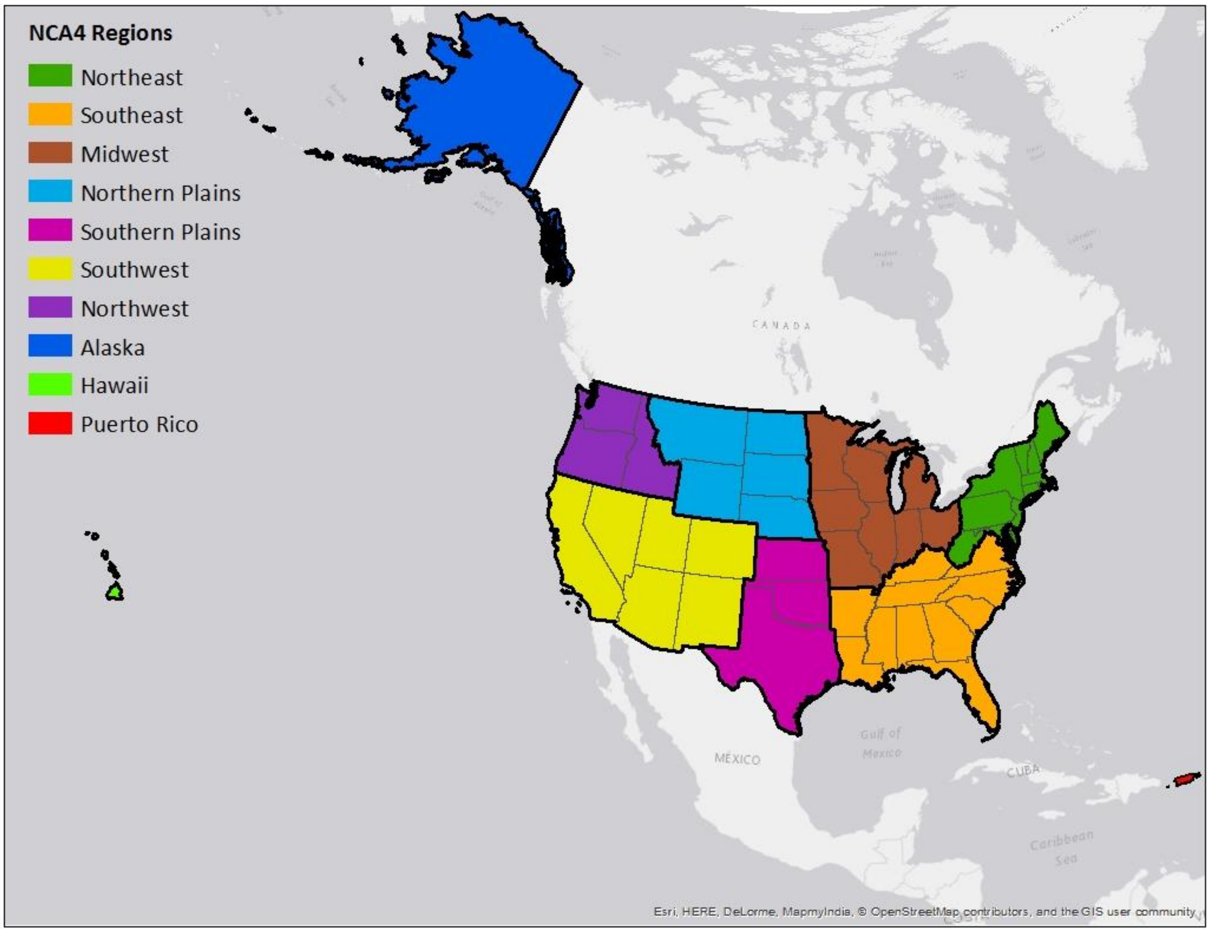
[478] IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, 151 pp.
[479] Bosello, F., C. Carraro, and E. De Cian, 2010: Climate policy and the optimal balance between mitigation, adaptation and unavoided damage. Climate Change Economics, 1, 71-92.
[480] Sussman, F., A. Grambsch, J. Li, and C.P. Weaver, 2014: Introduction to a special issue entitled Perspectives on Implementing Benefit-Cost Analysis in Climate Assessment. Journal of Benefit-Cost Analysis, 5, 333-346.

is a need to develop analytical frameworks to understand vulnerability of socioeconomic and environmental systems from climate change combined with other stressors (e.g., development and population pressure, land use changes, and ecosystem modifications), and evaluate the effects of adaptation responses across scales and sectors.

30. REGIONAL SUMMARIES

The sectoral modeling chapters demonstrate that climate change impacts will not be uniform across the U.S., with most sectors showing a complex pattern of regional-scale impacts. The following sections and tables provide regional summaries of the sectoral impacts described in this Technical Report using the NCA4 regional aggregations (Figure 30.1) under RCP8.5 and RCP4.5 in the years 2050 and 2090.

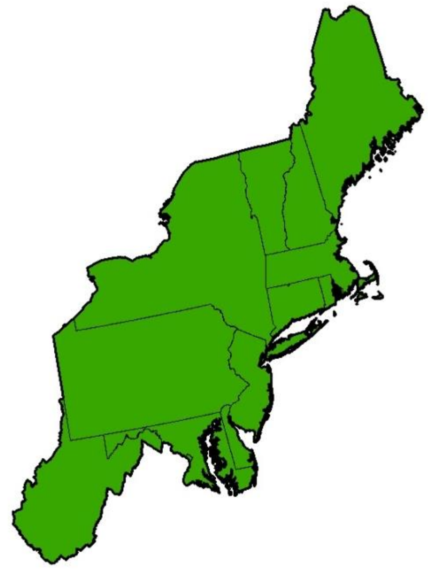
Figure 30.1. NCA4 Regional Aggregations



Several considerations are important to note regarding the regional tables in the following sections.

- The annual estimates provided here are not cumulative impacts for the entire 21st century, which would likely be much larger (see the sectoral sections for cumulative estimates where available).
- Many of the values do not estimate and monetize the full extent of potential impacts from climate change on that sector, and as such, the results should be treated as conservative.
- The individual monetized estimates are not aggregated, as only a subset of climate change impacts is quantified in this report. Also, many of the physical impacts have significant societal or iconic values that are not captured in the estimated economic impact.
- Not all sectors have results in all regions. For example, the coral reef modeling will not produce results for the Northeast and shellfish modeling will not produce results for the Midwest.
- Only some of the sectoral analyses produced discrete physical metric estimates, therefore not all sectors of this Technical Report are represented in the physical impact tables.
- Economic valuation of changes in agriculture welfare is only available at the national level and thus are not represented in the following tables. As described in the Carbon Storage section, monetized values are not estimated.
- The sectoral sections of this Technical Report provide detailed information on the methods, results, limitations, and supporting literature.
- Benefit values may not equate to differences between the RCPs due to rounding and the use of two significant figures.

30.1 NORTHEAST



Using the results presented throughout the sector sections of this Technical Report, this section summarizes the impacts projected to occur in the Northeast.

Key Findings

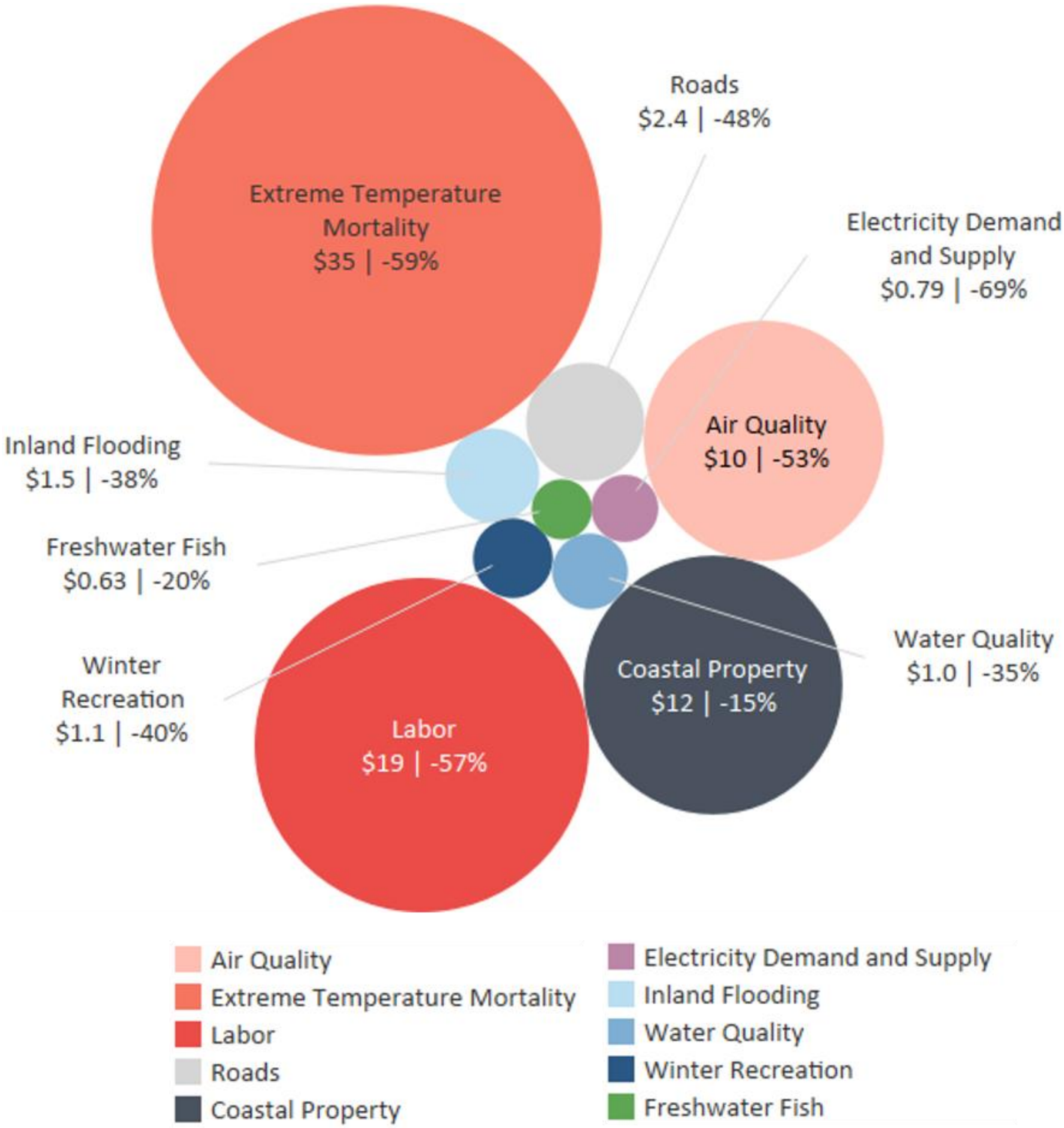
- The Northeast is projected to experience some of the largest adverse health impacts from climate change. Damages from lost labor hours and deaths associated with worsened air quality and increases in extreme temperature are on the order of billions of dollars in damage each year from climate change. Compared to RCP8.5, 1,400 premature deaths from extreme temperatures are projected to be avoided each year by 2090 under RCP4.5 in the Northeast, resulting in $21 billion in annual savings.
- Coastal property damages in the Northeast remain high under both climate scenarios, with annual costs under RCP8.5 projected to rise from $10 billion in 2050 to $12 billion in 2090. These values would decrease significantly with well-timed adaptation measures.
- In the shellfish and freshwater fish sectors, the Northeast is projected to experience some of the largest price increases in shellfish of all regions (particularly quahogs and scallops under RCP8.5, in response to decreases in supply), and large losses of coldwater fishing habitat, which is projected to nearly disappear this century throughout the Appalachians. Under RCP4.5, many of these projected losses are avoided.
- Climate change impacts on winter recreation (from lost downhill skiing and snowboarding and cross-country skiing visits) are projected to be more than a billion dollars a year by 2090 under RCP8.5 ($1.1 billion), or $0.7 billion each year under RCP4.5.

Discussion

Tables 30.1 and 30.2 present the estimated annual physical and economic effects of climate change in the Northeast under RCP8.5 and RCP4.5 in the years 2050 and 2090. As shown in Table 30.1, annual physical impacts of climate change in the Northeast are projected to increase over time in all sectors and under all climate scenarios, except corn yields and acres burned by wildfire (both under RCP4.5 only) and carbon storage. Adverse impacts are generally greater under RCP8.5 than under RCP4.5. As shown in Figure 30.2 and Table 30.2, annual economic damages also generally increase from 2050 to 2090 and from RCP4.5 to RCP8.5. However, some infrastructure sectors, like bridges and urban drainage, see higher costs in 2050 than in 2090, as many types of infrastructure are already vulnerable or will soon become vulnerable and require repair or adaptation costs early in the century.

Figure 30.2. Largest Damages of Climate Change in the Northeast

Annual damages for the ten sectors with the greatest projected costs in the Northeast in 2090 under RCP8.5 are shown by relative circle size and with the labeled monetary value (in $billions). The difference between RCP8.5 and RCP4.5 in 2090 is shown as the second value (in % change). The data underlying the sectors shown in the figure, as well as all other sectors modeled in the Northeast, can be found in Table 30.2 below.



The Northeast is projected to experience some of the largest impacts of climate change on health, infrastructure, shellfish and freshwater fishing. This region experiences the highest risk of increased emergency room visits from asthma attacks related to aeroallergens, and high projected losses in reservoir recreation from harmful algal blooms. Water quality is projected to decrease, especially under RCP8.5, with some of the largest projected damages occurring in the Northeast region. These health effects will likely be compounded by increases in climate-induced migration that are projected for the Northeast. In the shellfish and freshwater fish sectors, the Northeast is projected to experience some of the largest price increases in shellfish (particularly quahogs and scallops, in response to decreases in supply), and large losses of coldwater fishing habitat, which is projected to nearly disappear this century throughout the Appalachians. Northeast infrastructure is also at risk, with high projected damages to rail and roads. Roads in this region experience high temperature related damages, especially under RCP8.5, but also high savings from reduced maintenance costs associated with decreases in freeze-thaw stressors. There are also large increases in electricity costs in the Northeast to meet projected demand increases. Finally, there are significant reductions in winter recreation season length in the Northeast.

The most economically-significant impacts in the Northeast occur from coastal property loss, lost labor hours, and deaths associated with worsened air quality and increases in extreme temperature, all of which are on the order of billions of dollars in damage each year from climate change. There are significant benefits for human-health related damages under RCP4.5 compared to RCP8.5, particularly in 2090. For example, 1,400 deaths from extreme temperatures would be avoided each year under RCP4.5 compared to RCP8.5 by 2090, resulting in $21 billion in annual savings. Coastal damages remain high under both climate scenarios in Table 30.2, where no adaptation is assumed, but would decrease significantly with proactive adaptation measures (see Coastal Property and Risk Reduction through Adaptation sections of this Technical Report).

For additional considerations regarding the values shown in Tables 30.1 and 30.2, see the notes at the beginning of the Regional Summaries section and the footnotes to the National Summary table. For more detailed results, as well as background and modeling approaches, see the individual sectoral chapters.

Table 30.1. Projected Annual Physical Impacts of Climate Change in the Northeast

Positive numbers represent damages due to climate change, while negative numbers represent a reduction in damages compared to the reference period. Unless noted, upper and lower bounds are derived from values across the five GCMs. Not all sectoral analyses produced discrete physical metric estimates. See notes at the bottom of Table 30.2 for additional sector-specific information. Due to rounding, benefit values may not equate to differences between RCPs.

	2050			2090		
	RCP8.5	**RCP4.5**	**Benefit**	**RCP8.5**	**RCP4.5**	**Benefit**
HEALTH						
Air Quality: # deaths	230 (120 to 340)	200 (110 to 300)	30 (NA)	670 (360 to 980)	310 (160 to 450)	360 (NA)
Extreme Temperature Mortality: # deaths	640 (330 to 1,200)	650 (400 to 1,100)	-7.6 (-200 to 220)	2,300 (1,100 to 3,400)	960 (630 to 2,000)	1,400 (280 to 2,400)
Labor: Lost Labor Hours (millions)	92 (44 to 140)	82 (63 to 120)	9.8 (-19 to 36)	230 (100 to 360)	100 (46 to 190)	130 (54 to 220)
Aeroallergens: ED visits	490 (160 to 820)	480 (250 to 670)	4 (-95 to 230)	1,100 (560 to 1,300)	470 (150 to 750)	590 (400 to 780)
Harmful Algal Blooms: # Days above 100k cells/mL	22 (14 to 29)	20 (14 to 28)	2.5 (-3.0 to 12)	36 (22 to 47)	22 (6.7 to 34)	14 (0.060 to 27)
West Nile Virus: # Cases	170 (110 to 230)	130 (74 to 190)	41 (25 to 69)	490 (280 to 690)	210 (120 to 340)	280 (160 to 350)
INFRASTRUCTURE						
Bridges: # Vulnerable Bridges	510 (400 to 660)	350 (190 to 620)	160 (-180 to 300)	570 (370 to 880)	390 (200 to 660)	180 (68 to 280)
WATER RESOURCES						
Winter Recreation: Lost Visits (millions)	9.3 (5.4 to 13)	-0.80 (-5.3 to 2.0)	10 (6.0 to 19)	15 (11 to 17)	9.2 (4.5 to 13)	5.7 (3.7 to 9.4)
AGRICULTURE						
Agriculture: % Decrease in Corn Yields (example crop)	-2.9% (-9.5% to 9.2%)	-4.1% (-8.2% to 5.3%)	1.2% (-2.2% to 5.1%)	6.2% (-1.5% to 20%)	-4.9% (-9.7% to 9.9%)	11% (8.1% to 20%)

	2050			2090		
	RCP8.5	RCP4.5	Benefit	RCP8.5	RCP4.5	Benefit
ECOSYSTEMS						
Freshwater Fish: Cold Fishing Days Lost (millions)	33 (26 to 35)	32 (24 to 34)	1.0 (0.32 to 2.0)	35 (34 to 36)	33 (29 to 35)	2.2 (1.0 to 5.3)
Shellfish: % Decrease in Oyster Supply (example species)	23% (21% to 26%)	16% (13% to 17%)	7.8% (4.3% to 11%)	50% (48% to 53%)	23% (20% to 26%)	26% (24% to 29%)
Wildfire: Acres Burned (thousands)	1,400 (-80 to 2,600)	1,200 (-580 to 3,300)	180 (-2,600 to 2,600)	1,800 (510 to 3,200)	-370 (-1,700 to 1,800)	2,100 (320 to 3,400)
Carbon Storage: Metric Tons Lost (millions)	6.5 (0.47 to 17)	7.6 (1.1 to 14)	-1.1 (-5.4 to 3.3)	4.1 (-14 to 16)	4.6 (2.6 to 8.7)	-0.48 (-19 to 7.9)

Note: “NA” indicates analyses where GCM-specific results are not available.

Table 30.2. Projected Annual Economic Impacts of Climate Change in the Northeast

Positive numbers represent damages due to climate change, while negative numbers represent a reduction in damages compared to the reference period. Values shown in millions of undiscounted $2015. Unless noted, upper and lower bounds are derived from values across the GCMs. Regional economic impacts on agriculture yield and welfare are not available. Due to rounding, benefit values may not equate to differences between RCPs.

	2050			2090		
	RCP8.5	RCP4.5	Benefit	RCP8.5	RCP4.5	Benefit
HEALTH						
Air Quality	$2,900 ($260 to $8,200)	$2,500 ($230 to $7,200)	$400 (NA)	$10,000 ($910 to $29,000)	$4,700 ($420 to $13,000)	$5,300 (NA)
Extreme Temperature Mortality	$7,900 ($4,100 to $15,000)	$8,000 ($5,000 to $13,000)	-$94 (-$2,400 to $2,700)	$35,000 ($16,000 to $52,000)	$15,000 ($9,500 to $31,000)	$21,000 ($4,300 to $36,000)
Labor	$4,600 ($2,200 to $7,200)	$4,100 ($3,200 to $5,900)	$490 (-$950 to $1,800)	$19,000 ($8,300 to $29,000)	$8,300 ($3,800 to $15,000)	$11,000 ($4,500 to $18,000)
Aeroallergens	$0.24 ($0.08 to $0.4)	$0.24 ($0.12 to $0.33)	$0. (-$0.050 to $0.11)	$0.52 ($0.27 to $0.66)	$0.23 ($0.07 to $0.37)	$0.29 ($0.19 to $0.38)
Harmful Algal Blooms	$8.1 ($0.060 to $19)	$5.9 ($0 to $17)	$2.2 (-$3.7 to $12)	$28 ($18 to $32)	$15 ($0.48 to $22)	$13 ($5.1 to $20)
West Nile Virus	$140 ($93 to $190)	$110 ($62 to $160)	$35 ($21 to $58)	$500 ($280 to $710)	$210 ($120 to $350)	$280 ($160 to $360)
INFRASTRUCTURE						
Roads	$1,200 ($260 to $3,200)	$830 (-$62 to $2,100)	$420 (-$410 to $1,200)	$2,400 (-$1.1 to $6,200)	$1,300 (-$23 to $3,900)	$1,200 (-$210 to $2,400)
Bridges	$220 ($170 to $280)	$180 ($140 to $230)	$42 ($8 to $61)	$120 ($95 to $160)	$77 ($40 to $140)	$43 (-$9 to $71)
Rail	$160 ($120 to $200)	$130 ($96 to $170)	$24 ($14 to $33)	$530 ($360 to $640)	$320 ($220 to $430)	$210 ($140 to $260)
Urban Drainage	$280 ($19 to $530)	$240 ($5.6 to $400)	$36 (-$380 to $340)	$160 ($39 to $250)	$220 ($19 to $790)	-$68 (-$630 to $240)
Coastal Property	$10,000 (NA)	$9,700 (NA)	$720 (NA)	$12,000 (NA)	$9,800 (NA)	$1,800 (NA)

	2050			2090		
	RCP8.5	**RCP4.5**	**Benefit**	**RCP8.5**	**RCP4.5**	**Benefit**
ELECTRICITY						
Electricity Demand and Supply	$240 ($160 to $390)	$130 ($74 to $190)	$110 ($29 to $210)	$790 ($390 to $1,200)	$240 ($100 to $520)	$540 ($60 to $760)
WATER RESOURCES						
Municipal and Industrial Water Supply	$4.9 ($0.050 to $21)	$5.8 ($0.10 to $19)	-$0.92 (-$19 to $14)	$36 ($1.7 to $81)	$11 ($0.63 to $30)	$24 (-$0.64 to $63)
Inland Flooding	$1,600 (NA)	$620 (NA)	$1,000 (NA)	$1,500 (NA)	$950 (NA)	$580 (NA)
Water Quality	$430 ($260 to $610)	$360 ($300 to $520)	$71 ($6.4 to $150)	$1,000 ($620 to $1,300)	$650 ($370 to $940)	$350 ($250 to $440)
Winter Recreation	$720 ($420 to $1,000)	-$86 (-$440 to $130)	$800 ($480 to $1,500)	$1,100 ($850 to $1,300)	$710 ($350 to $1,000)	$440 ($290 to $730)
ECOSYSTEMS						
Freshwater Fish	$500 ($290 to $610)	$580 ($510 to $630)	-$84 (-$220 to $35)	$630 ($350 to $990)	$500 ($410 to $680)	$130 (-$100 to $420)
Wildfire	$6.0 (-$0.37 to $12)	$5.2 (-$2.6 to $15)	$0.81 (-$12 to $12)	$7.9 ($2.3 to $14)	-$1.7 (-$7.5 to $8.1)	$10 ($1.4 to $15)

Notes:
"NA" indicates analyses where GCM-specific results are not available.
Air Quality: Mean and upper/lower bounds based on confidence intervals from the BenMAP-CE model.
Harmful Algal Blooms: Range and mean values based on combined high and low growth scenarios.
Urban Drainage: Values represent results under the 50-year storm.
Coastal Property: Costs with no adaptation. See Modeling Framework section for a description of SLR uncertainty.
Electricity Demand and Supply: Values represent power system supply costs. Results are from the GCAM power sector model only.
Water Quality: Range and mean values based on combined results from US Basins and HAWQS.
Freshwater Fish: Values represent impacts to all three fishing guilds (coldwater, warmwater, and rough)
Wildfire: Results represent changes in both the contiguous U.S. and Alaska.

30.2 SOUTHEAST

Using the results presented throughout the sector sections of this Technical Report, this section summarizes the impacts projected to occur in the Southeast.

Key Findings

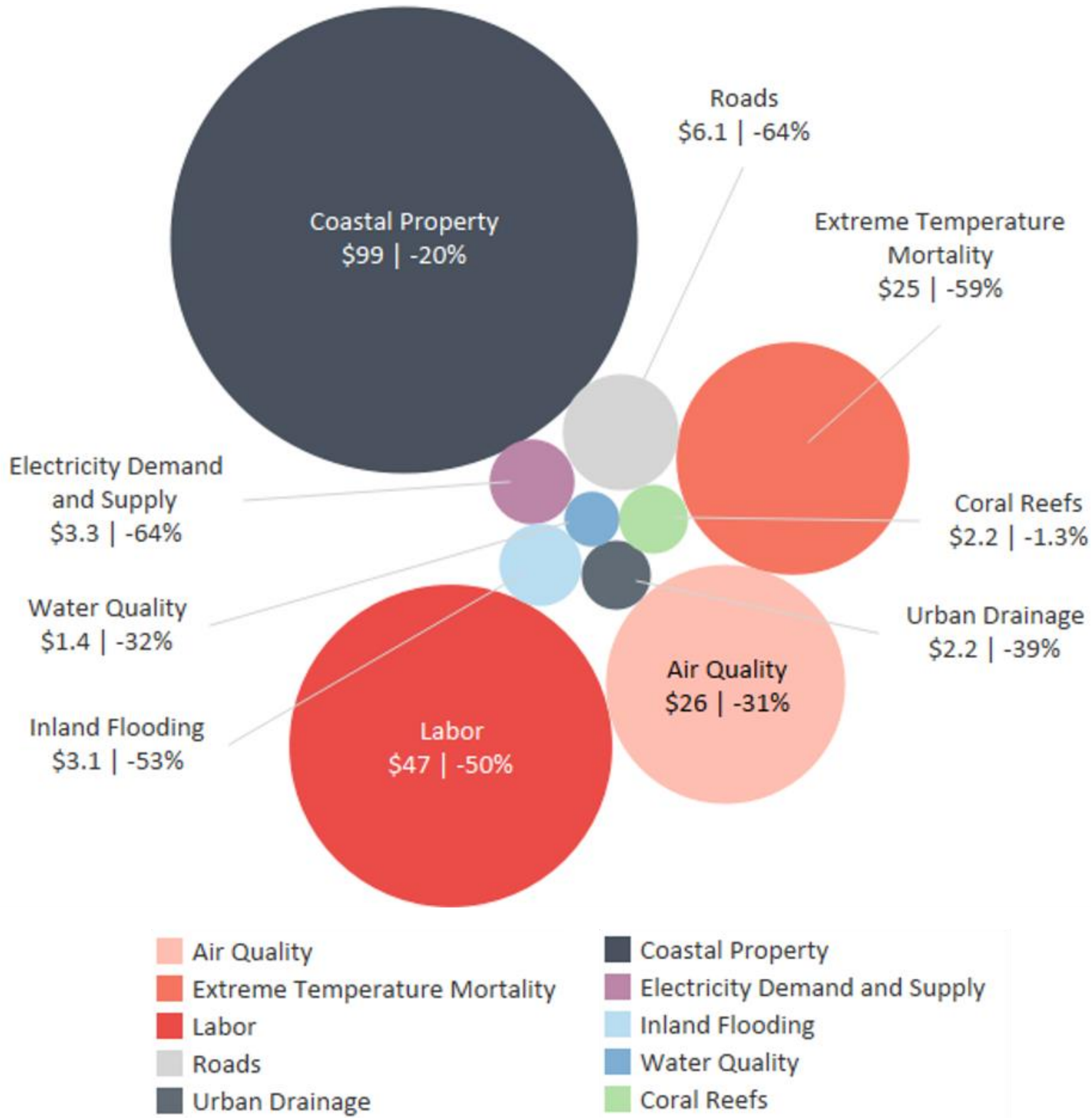
- Projected labor losses due to extreme heat by the end of the century total $47 billion each year under RCP8.5, with approximately one third of the national projected loss occurring in this region. These projected losses are halved under RCP4.5.
- The Southeast is projected to experience some of the largest adverse health impacts. For example, projected total cases of West Nile neuroinvasive disease grow from approximately 100 per year in the reference period to more than 1,100 per year by 2090. Damages associated with harmful algal blooms under RCP8.5 rise from $48 million per year in 2050 to $96 million per year in 2090, making up approximately half of the national total loss in reservoir recreation from climate change.
- Compared to other regions, the Southeast is projected to experience the highest costs associated with meeting increased electricity demands; by the end of the century annual costs are estimated at $3.3 billion each year under RCP8.5 and $1.2 billion each year under RCP4.5.
- Projected damages to infrastructure are very high in the Southeast. The region experiences some of the largest total damages to bridges and roads of all regions. Damages to coastal property under RCP8.5 rise from $60 billion each year in 2050 to $99 billion in 2090. Under RCP4.5, projected coastal property damages are $56 and $79 billion each year, respectively.

Discussion

Tables 30.3 and 30.4 present the estimated annual physical and economic effects of climate change in the Southeast under RCP8.5 and RCP4.5 in the years 2050 and 2090. As shown in Table 30.3, annual physical impacts of climate change in the Southeast are projected to increase over time in all sectors and under all climate scenarios, except in some measures of air quality (ozone and aeroallergens), carbon storage, and wildfire. Outside those sectors, adverse impacts are generally greater under RCP8.5 than under RCP4.5. As shown in Figure 30.3 and Table 30.4, annual economic damages also generally increase from 2050 to 2090 and from RCP4.5 to RCP8.5, though some infrastructure sectors see higher costs in 2050, as many types of infrastructure are already vulnerable or will soon become vulnerable and require repair costs early in the century. Benefits in the wildfire sector are estimated under RCP8.5 compared to RCP4.5.

Figure 30.3. Largest Damages of Climate Change in the Southeast

Annual damages for the ten sectors with the greatest projected costs in the Southeast in 2090 under RCP8.5 are shown by relative circle size and with the labeled monetary value (in $billions). The difference between RCP8.5 and RCP4.5 in 2090 is shown as the second value (in % change). The data underlying the sectors shown in the figure, as well as all other sectors modeled in the Southeast, can be found in Table 30.4 below.



The Southeast is unique in that it experiences milder air quality impacts, or even benefits, as compared to other regions. It is one of only two regions where climate change impacts on ozone result in projected avoided deaths (in 2050 under RCP4.5 and 2090 under RCP8.5). This is because climate-driven meteorological changes result in conditions slightly less conducive to ozone formation, potentially due to an increase in precipitation and wind trajectories that transport cleaner marine air into the region. Wildfire activity and associated response costs in the Southeast are among the smallest of the regions and this area is also projected to increase carbon stored in vegetation.

Projected labor losses in the Southeast are the highest of all regions, totaling in the tens of billions of dollars annually by mid-century, and making up approximately one third of the national projected loss. While the Southeast sees a smaller increase in oak pollen season lengths than the Northeast or Midwest, the region still experiences significant increases in asthma related emergency room visits, particularly among children aged 0-17. These additional visits are associated with costs in 2090 of $360,000 per year under RCP8.5 and $100,000 per year under RCP4.5. The Southeast is projected to experience the largest adverse effects of neuroinvasive West Nile virus, particularly under RCP8.5, where projected total cases grow from approximately 100 per year in the reference period to more than 1,100 per year by 2090. Economic impacts from harmful algal blooms are also highest in the Southeast, under all scenarios, time periods, and growth assumptions. These regional losses make up approximately half of the national total loss in reservoir recreation from climate change. The Southeast is projected to experience the highest costs associated with meeting increased electricity demands, with increased cumulative costs of $57 billion and $15 billion through 2050 under RCP8.5 under the ReEDS and GCAM models, respectively.

The Southeast is also projected to experience important effects of climate change on infrastructure and water resources. The region experiences the largest total damages to bridges (in 2090 under both climate scenarios) and roads of all the NCA regions. High damages to roads are partially due to the comparatively high number of lane miles in this area, as well as temperature related stress. Under both RCPs, the Southeast is projected to have the highest number of vulnerable bridges in 2050 and the second highest in 2090 of all the regions, making up roughly one third of the national total vulnerable bridges. Cumulative costs to rail by the end of the century are also highest in the Southeast region under both RCPs. Adaptation costs for urban drainage are second highest (behind Southern Plains) under RCP8.5 (based on 50-year storm estimates). Water quality is projected to decrease, particularly under RCP8.5, and associated damages in the Southeast are among the largest of all regions. However, unlike most regions, the municipal and industrial water supply analysis projects cumulative welfare gains in the Southeast.

The most economically-significant impacts in the Southeast occur from coastal property loss and lost labor hours, with very high damages also occurring from deaths associated with increases in extreme temperature and decreased air quality, all on the order of billions of dollars in damage each year from climate change. There are significant health benefits under RCP4.5 compared to RCP8.5, particularly in 2090. Annual labor and coastal property benefits due to global GHG mitigation are $24 billion and $20 billion, respectively, in 2090. Coastal damages remain high under both climate scenarios in Table 30.4, where no adaptation is assumed, but would decrease significantly with well-timed adaptation measures (see Coastal Property and Risk Reduction through Adaptation sections of this Technical Report). For inland flooding, the most significant difference between damages under RCP8.5 and those under RCP4.5 occurs in the Southeast, where the projected difference in the two trajectories is $1.6 billion per year by the end of the century.

For additional considerations regarding the values shown in Tables 30.3 and 30.4, see the notes at the beginning of the Regional Summaries section and the footnotes to the National Summary table. For more detailed results, as well as background and modeling approaches, see the individual sectoral chapters.

Table 30.3. Projected Annual Physical Impacts of Climate Change in the Southeast

Positive numbers represent damages due to climate change, while negative numbers represent a reduction in damages compared to the reference period. Unless noted, upper and lower bounds are derived from values across the five GCMs. Not all sectoral analyses produced discrete physical metric estimates. See notes at the bottom of Table 30.4 for additional sector-specific information. Due to rounding, benefit values may not equate to differences between RCPs.

	2050			2090		
	RCP8.5	**RCP4.5**	**Benefit**	**RCP8.5**	**RCP4.5**	**Benefit**
HEALTH						
Air Quality: # deaths	69 (37 to 100)	-40 (-21 to -59)	110 (NA)	-72 (-38 to -100)	88 (47 to 130)	-160 (NA)
Extreme Temperature Mortality: # deaths	600 (360 to 1,100)	460 (280 to 860)	140 (67 to 260)	1,600 (910 to 2,100)	660 (350 to 1,200)	960 (340 to 1,500)
Labor: Lost Labor Hours (millions)	270 (140 to 460)	220 (120 to 370)	48 (-2.5 to 88)	570 (340 to 820)	280 (190 to 430)	290 (140 to 430)
Aeroallergens: ED visits	360 (-150 to 620)	290 (-77 to 620)	71.0 (-73 to 300)	730 (97 to 1,200)	210 (-220 to 530)	520 (280 to 730)
Harmful Algal Blooms: # Days above 100k cells/mL	2.5 (1.1 to 5.5)	2.3 (1.5 to 4.2)	0.24 (-0.65 to 1.3)	5.2 (3.2 to 10)	2.9 (1.6 to 5.6)	2.3 (0.73 to 4.4)
West Nile Virus: # Cases	370 (220 to 640)	270 (130 to 470)	100 (61 to 170)	1,100 (570 to 1,800)	440 (230 to 790)	690 (340 to 960)
INFRASTRUCTURE						
Bridges: # Vulnerable Bridges	1,400 (1,100 to 1,800)	750 (560 to 920)	640 (240 to 1,300)	1,600 (780 to 2,300)	1,200 (810 to 1,600)	430 (-160 to 880)
WATER RESOURCES						
Winter Recreation: Lost Visits (millions)	0.56 (0.26 to 0.83)	-0.18 (-0.40 to 0.053)	0.74 (0.51 to 1.1)	0.88 (0.57 to 1.1)	0.39 (-0.10 to 0.85)	0.50 (0.21 to 0.86)
AGRICULTURE						
Agriculture: % Decrease in Corn Yields (example crop)	7.0% (0.29% to 21%)	3.3% (-0.72% to 13%)	3.7% (-2.0% to 8.9%)	22% (14% to 33%)	4.5% (-0.68% to 17%)	17% (13% to 26%)

ECOSYSTEMS						
Coral Reefs: % Lost Cover	95% (93% to 97%)	94% (89% to 96%)	1.6% (-1.1% to 8.5%)	97% (95% to 98%)	96% (95% to 97%)	0.57% (0.10% to 1.3%)
Freshwater Fish: Coldwater Fishing Days Lost (millions)	11 (6.2 to 17)	11 (6.5 to 16)	0.41 (-0.27 to 0.91)	15 (11 to 17)	11 (7.4 to 17)	4.4 (0 to 9.3)
Shellfish: % Decrease in Oyster Supply (example species)	21% (20% to 23%)	14% (13% to 16%)	7.6% (5.9% to 8.6%)	46% (44% to 48%)	20% (19% to 22%)	26% (24% to 27%)
Wildfire: Acres Burned (thousands)	-32 (-93 to 62)	-19 (-67 to 47)	-13 (-100 to 84)	76 (-67 to 220)	-37 (-88 to 44)	110 (15 to 180)
Carbon Storage: Metric Tons Lost (millions)	-11 (-27 to 5.8)	0.058 (-11 to 8.6)	-11 (-26 to -0.47)	-36 (-51 to -12)	-8.1 (-33 to 11)	-28 (-50 to 5.1)

Note: "NA" indicates analyses where GCM-specific results are not available.

Table 30.4. Projected Annual Economic Impacts of Climate Change in the Southeast

Positive numbers represent damages due to climate change, while negative numbers represent a reduction in damages compared to the reference period. Values shown in millions of undiscounted $2015. Unless noted, upper and lower bounds are derived from values across the GCMs. Regional economic impacts on agriculture are not available. Due to rounding, benefit values may not equate to differences between RCPs.

	2050			2090		
	RCP8.5	RCP4.5	Benefit	RCP8.5	RCP4.5	Benefit
HEALTH						
Air Quality	$9,800 ($880 to $28,000)	$6,900 (-$900 to $21,000)	$2,900 (NA)	$26,000 (-$2,200 to $78,000)	$18,000 ($1,600 to $51,000)	$8,000 (NA)
Extreme Temperature Mortality	$7,500 ($4,500 to $14,000)	$5,700 ($3,500 to $11,000)	$1,700 ($840 to $3,200)	$25,000 ($14,000 to $33,000)	$10,000 ($5,300 to $19,000)	$15,000 ($5,200 to $22,000)
Labor	$14,000 ($7,000 to $23,000)	$11,000 ($5,900 to $19,000)	$2,400 (-$130 to $4,400)	$47,000 ($28,000 to $68,000)	$23,000 ($16,000 to $36,000)	$24,000 ($12,000 to $36,000)
Aeroallergens	$0.18 (-$0.070 to $0.30)	$0.14 (-$0.040 to $0.30)	$0.030 (-$0.040 to $0.15)	$0.36 ($0.050 to $0.57)	$0.10 (-$0.11 to $0.26)	$0.26 ($0.14 to $0.36)
Harmful Algal Blooms	$48 ($23 to $91)	$38 ($18 to $78)	$9.2 ($1.5 to $24)	$96 ($73 to $140)	$63 ($38 to $110)	$33 ($7.2 to $85)
West Nile Virus	$310 ($190 to $540)	$230 ($110 to $400)	$85 ($51 to $140)	$1,200 ($590 to $1,800)	$450 ($240 to $810)	$700 ($350 to $980)
INFRASTRUCTURE						
Roads	$3,100 ($490 to $9,600)	$2,100 ($200 to $6,700)	$930 (-$320 to $2,900)	$6,100 ($1,400 to $13,000)	$2,200 ($29 to $6,900)	$3,900 ($510 to $6,200)
Bridges	$430 ($260 to $580)	$340 ($270 to $430)	$87 (-$24 to $170)	$300 ($220 to $380)	$150 ($120 to $170)	$140 ($47 to $260)
Rail	$320 ($250 to $400)	$280 ($200 to $340)	$40 (-$22 to $68)	$950 ($750 to $1,100)	$620 ($480 to $750)	$340 ($270 to $410)
Urban Drainage	$1,400 ($1,100 to $1,500)	$1,400 ($900 to $2,400)	-$32 (-$1,300 to $530)	$2,200 ($1,400 to $2,800)	$1,300 ($860 to $1,900)	$840 ($470 to $1,600)
Coastal Property	$60,000 (NA)	$56,000 (NA)	$3,700 (NA)	$99,000 (NA)	$79,000 (NA)	$20,000 (NA)

	2050			2090		
	RCP8.5	**RCP4.5**	**Benefit**	**RCP8.5**	**RCP4.5**	**Benefit**
ELECTRICITY						
Electricity Demand and Supply	$1,200 ($970 to $1,600)	$720 ($400 to $960)	$490 ($200 to $680)	$3,300 ($2,400 to $4,200)	$1,200 ($900 to $1,900)	$2,100 ($1,500 to $2,700)
WATER RESOURCES						
Municipal and Industrial Water Supply	$4.4 ($0.11 to $18)	$4.0 (-$0.050 to $16)	$0.43 (-$1.8 to $2.8)	$12 (-$3.6 to $32)	$1.1 (-$3.7 to $14)	$10 (-$1.2 to $29)
Inland Flooding	$1,700 (NA)	$1,800 (NA)	-$120 (NA)	$3,100 (NA)	$1,500 (NA)	$1,600 (NA)
Water Quality	$490 ($320 to $820)	$370 ($210 to $590)	$120 ($44 to $310)	$1,400 ($930 to $1,800)	$950 ($560 to $1,400)	$440 ($210 to $780)
Winter Recreation	$41 ($19 to $61)	-$14 (-$29 to $3.9)	$55 ($38 to $82)	$65 ($42 to $82)	$29 (-$7.6 to $63)	$37 ($16 to $64)
ECOSYSTEMS						
Coral Reefs	$2,200 ($2,100 to $2,200)	$2,100 ($1,900 to $2,200)	$57 (-$39 to $290)	$2,200 ($2,100 to $2,200)	$2,100 ($2,100 to $2,200)	$27 ($5 to $63)
Freshwater Fish	$450 (-$700 to $2,000)	$450 (-$37 to $1,300)	$0 (-$670 to $610)	$1,100 (-$560 to $2,000)	$280 (-$600 to $1,600)	$800 ($42 to $1,600)
Wildfire	-$1.2 (-$3.6 to $2.4)	-$0.73 (-$2.6 to $1.8)	-$0.51 (-$4.0 to $3.2)	$2.9 (-$2.6 to $8.5)	-$1.4 (-$3.4 to $1.7)	$4.4 ($0.58 to $6.8)

Notes:
"NA" indicates analyses where GCM-specific results are not available.
Air Quality: Mean and upper/lower bounds based on confidence intervals from the BenMAP-CE model.
Harmful Algal Blooms: Range and mean values based on combined high and low growth scenarios.
Urban Drainage: Values represent results under the 50-year storm.
Coastal Property: Costs with no adaptation. See Modeling Framework section for a description of SLR uncertainty.
Electricity Demand and Supply: Values represent power system supply costs. Results are from the GCAM power sector model only.
Water Quality: Range and mean values based on combined results from US Basins and HAWQS.
Freshwater Fish: Values represent impacts to all three fishing guilds (coldwater, warmwater, and rough)
Wildfire: Results represent changes in both the contiguous U.S. and Alaska.

30.3 MIDWEST

Using the results presented throughout the sector sections of this Technical Report, this section summarizes the impacts projected to occur in the Midwest.

Key Findings

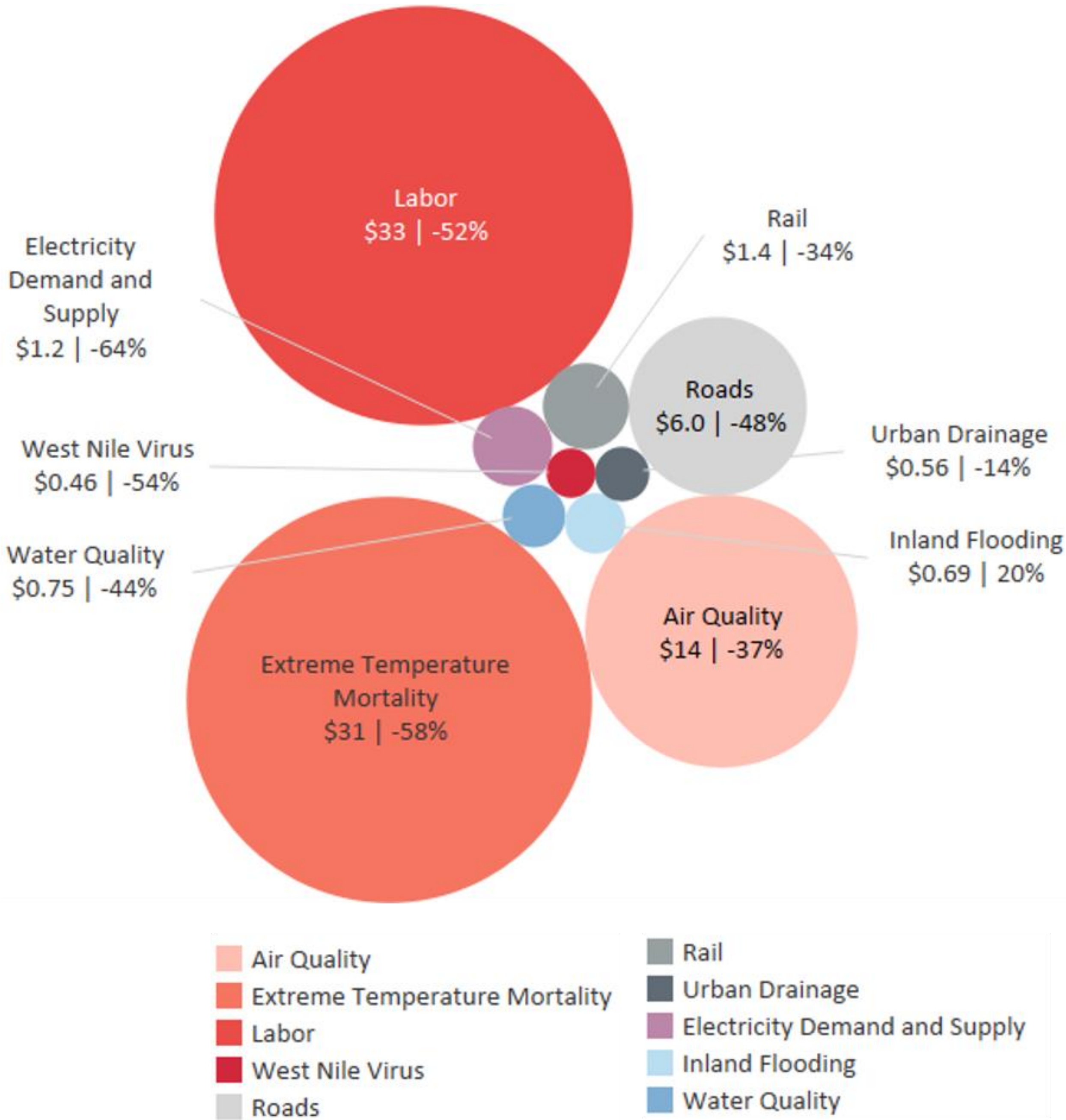
- The Midwest is projected to experience a large number of annual premature deaths from increased ground-level ozone, under both climate scenarios and in both 2050 and 2090, making up approximately half of the national total projected premature deaths. In 2090, damages associated with these premature deaths are projected to be $14 billion each year under RCP8.5 and $8.8 billion each year under RCP4.5.
- The largest increases in premature deaths from extreme temperatures are projected to occur in the Midwest, with significant losses in labor as well. Annual damages under RCP8.5 from these extreme temperature impacts are similar, with estimated impacts in 2050 of $9.8 billion for both premature mortality and lost labor. These costs rise to $31 billion and $33 billion per year by 2090, respectively.
- The Midwest is also among the regions with the largest damages to infrastructure, especially under RCP8.5; the region is projected to incur the second highest damages to roads and bridges. Damages from climate impacts on rail under RCP8.5 rise from $0.5 billion each year in 2050 to $1.4 billion each year by 2090.
- Rising temperatures will increase electricity demand across the Midwest, leading to estimated costs on the electric power system by 2090 of $1.2 billion each year under RCP8.5 and $0.43 billion each year under RCP4.5.
- Corn yields are projected to decline considerably under RCP8.5, from a 7.1% decrease in annual yield in 2050 to an 18% decrease in annual yield by the end of the century. Under RCP4.5, projected declines are estimated at 4.3% and 5.5%, respectively.

Discussion

Tables 30.5 and 30.6 present the estimated annual physical and economic effects of climate change in the Midwest under RCP8.5 and RCP4.5 in the years 2050 and 2090. As shown in Table 30.5, annual physical impacts of climate change in the Midwest are projected to increase over time in all sectors and under all climate scenarios, except for acres burned by wildfire and carbon storage loss. Impacts are greater under RCP8.5 than under RCP4.5 for all sectors but carbon storage. As shown in Figure 30.4 and Table 30.6, annual economic damages increase from 2050 to 2090 in all sectors but bridges and wildfire. The RCP4.5 scenario demonstrates economic benefits when compared to RCP8.5 in all sectors but freshwater fish in 2050 and inland flooding in 2090.

Figure 30.4. Largest Damages of Climate Change in the Midwest

Annual damages for the ten sectors with the greatest projected costs in the Midwest in 2090 under RCP8.5 are shown by relative circle size and with the labeled monetary value (in $billions). The difference between RCP8.5 and RCP4.5 in 2090 is shown as the second value (in % change). The data underlying the sectors shown in the figure, as well as all other sectors modeled in the Midwest, can be found in Table 30.6 below.



The Midwest is projected to experience the highest number of annual premature deaths from increased ground-level ozone under both climate scenarios and in both 2050 and 2090, making up approximately half of the national total projected premature deaths. The largest increases in deaths from extreme temperatures are projected to occur in the Midwest, with significant losses in labor due to extreme heat as well. Though this region has the largest increase in projected cyanobacteria concentration, it is not among the regions with the highest recreational damages associated with harmful algal blooms.

The Midwest is also among the regions with the largest damages to infrastructure, especially under RCP8.5; the region is projected to incur the second highest damages to roads and bridges (highest damages to bridges in 2050). There are also high increases in electricity costs in the Midwest to meet projected increases in demand. Large losses of suitable habitat are projected for warmwater species, such as small and largemouth bass, in this region by the end of the century. Corn yields are projected to decline considerably under RCP8.5, and losses in carbon storage of natural vegetation are projected. Water quality is projected to decrease, especially under RCP8.5, with damages in the Midwest among the highest of all the regions. Welfare losses associated with municipal and industrial water supply are among the greatest in the Midwest. Finally, while the few locations across the country that experience increases in winter recreation length in 2050 occur in the upper Midwest, this region as a whole experiences the most significant reductions in winter recreation season length, as the region's elevation is comparatively lower than the Rocky or Sierra Mountain regions and therefore particularly sensitive.

The most economically-significant impacts in the Midwest occur from lost labor hours and deaths associated with increases in extreme temperature and ozone, all of which are on the order of billions of dollars in damage each year from climate change. There are significant benefits in the health-related damages under RCP4.5 compared to RCP8.5, particularly in 2090. For example, 1,200 deaths from extreme temperatures are projected to be avoided each year under RCP4.5 compared to RCP8.5 by 2090, resulting in $18 billion in annual savings.

For additional considerations regarding the values shown in Tables 30.5 and 30.6, see the notes at the beginning of the Regional Summaries section and the footnotes to the National Summary table. For more detailed results, as well as background and modeling approaches, see the individual sectoral chapters.

Table 30.5. Projected Annual Physical Impacts of Climate Change in the Midwest

Positive numbers represent damages due to climate change, while negative numbers represent a reduction in damages compared to the reference period. Unless noted, upper and lower bounds are derived from values across the five GCMs. Not all sectoral analyses produced discrete physical metric estimates. See notes at the bottom of Table 30.6 for additional sector-specific information. Due to rounding, benefit values may not equate to differences between RCPs.

	2050			2090		
	RCP8.5	RCP4.5	Benefit	RCP8.5	RCP4.5	Benefit
HEALTH						
Air Quality: # deaths	380 (200 to 550)	300 (160 to 440)	80 (NA)	910 (490 to 1,300)	580 (310 to 840)	330 (NA)
Extreme Temperature Mortality: # deaths	790 (390 to 1,800)	690 (280 to 1,300)	97 (-160 to 520)	2,000 (1,300 to 3,300)	830 (340 to 2,100)	1,200 (620 to 2,000)
Labor: Lost Labor Hours (millions)	200 (95 to 380)	160 (75 to 310)	33 (-53 to 80)	400 (180 to 640)	200 (110 to 390)	200 (62 to 320)
Aeroallergens: ED visits	350 (58 to 520)	130 (-350 to 570)	220 (-82 to 870)	720 (210 to 1,100)	390 (-2.4 to 770)	330 (210 to 520)
Harmful Algal Blooms: # Days above 100k cells/mL	2.5 (1.3 to 7.3)	1.7 (0.36 to 4.5)	0.75 (-0.22 to 2.8)	7.5 (1.7 to 17)	2.8 (1.2 to 7.6)	4.7 (0.51 to 9.4)
West Nile Virus: # Cases	170 (120 to 250)	130 (93 to 190)	35 (26 to 54)	450 (260 to 690)	210 (140 to 310)	240 (120 to 380)
INFRASTRUCTURE						
Bridges: # Vulnerable Bridges	1,300 (770 to 1,900)	600 (270 to 1,100)	720 (160 to 1,400)	1,700 (510 to 2,900)	1,500 (660 to 2,000)	230 (-160 to 1,300)
WATER RESOURCES						
Winter Recreation: Lost Visits (millions)	3.4 (0.66 to 4.8)	-0.19 (-1.6 to 0.98)	3.6 (-0.32 to 5.5)	6.4 (4.0 to 7.5)	3.2 (0.61 to 5.0)	3.2 (2.3 to 5.0)
AGRICULTURE						
Agriculture: % Decrease in Corn Yields (example crop)	7.1% (-0.88% to 20%)	4.3% (-3.3% to 14%)	2.7% (-5.4% to 7.4%)	18% (7.7% to 30%)	5.5% (-3.1% to 18%)	13% (8.0% to 22%)

	2050			2090		
	RCP8.5	**RCP4.5**	**Benefit**	**RCP8.5**	**RCP4.5**	**Benefit**
ECOSYSTEMS						
Freshwater Fish: Coldwater Fishing Days Lost (millions)	12 (11 to 12)	12 (11 to 12)	0.23 (-0.030 to 0.88)	12 (12 to 13)	12 (11 to 12)	0.38 (0.17 to 0.79)
Wildfire: Acres Burned (thousands)	-39 (-190 to 120)	-110 (-230 to 68)	67 (-220 to 250)	-76 (-180 to 41)	-170 (-220 to -92)	90 (-32 to 190)
Carbon Storage: Metric Tons Lost (millions)	6.3 (1.1 to 14)	8.8 (3.2 to 17)	-2.5 (-11 to 3.5)	3.4 (-14 to 10)	3.6 (1.8 to 5.7)	-0.19 (-17 to 4.4)

Note: “NA” indicates analyses where GCM-specific results are not available.

Table 30.6. Projected Annual Economic Impacts of Climate Change in the Midwest

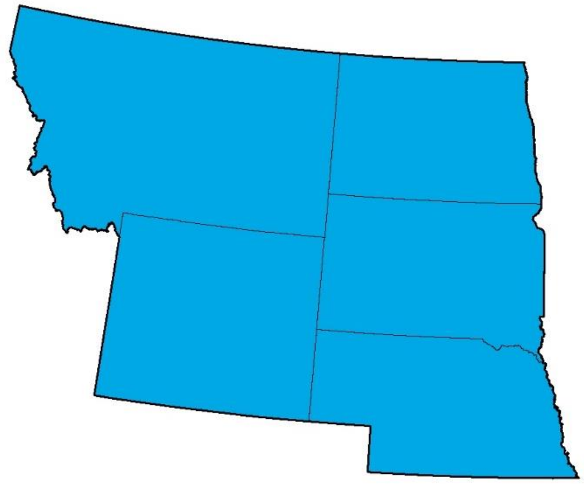
Positive numbers represent damages due to climate change, while negative numbers represent a reduction in damages compared to the reference period. Values shown in millions of undiscounted $2015. Unless noted, upper and lower bounds are derived from values across the GCMs. Regional economic impacts on agriculture yield and welfare are not available. Due to rounding, benefit values may not equate to differences between RCPs.

	2050			2090		
	RCP8.5	**RCP4.5**	**Benefit**	**RCP8.5**	**RCP4.5**	**Benefit**
HEALTH						
Air Quality	$4,700 ($420 to $13,000)	$3,700 ($330 to $11,000)	$1,000 (NA)	$14,000 ($1,200 to $39,000)	$8,800 ($790 to $25,000)	$5,200 (NA)
Extreme Temperature Mortality	$9,800 ($4,800 to $22,000)	$8,600 ($3,500 to $16,000)	$1,200 (-$2,000 to $6,500)	$31,000 ($19,000 to $50,000)	$13,000 ($5,100 to $31,000)	$18,000 ($9,500 to $30,000)
Labor	$9,800 ($4,800 to $19,000)	$8,200 ($3,800 to $16,000)	$1,600 (-$2,700 to $4,000)	$33,000 ($15,000 to $53,000)	$17,000 ($9,400 to $32,000)	$17,000 ($5,200 to $26,000)
Aeroallergens	$0.17 ($0.029 to $0.25)	$0.064 (-$0.17 to $0.28)	$0.11 (-$0.04 to $0.43)	$0.35 ($0.10 to $0.55)	$0.19 (-$0.0012 to $0.38)	$0.16 ($0.10 to $0.26)
Harmful Algal Blooms	$4.2 ($0 to $27)	$2.7 ($0 to $18)	$1.5 (-$0.52 to $8.5)	$27 ($0 to $84)	$4.4 ($0 to $25)	$22 ($0 to $59)
West Nile Virus	$140 ($100 to $210)	$110 ($78 to $160)	$29 ($22 to $46)	$460 ($260 to $700)	$210 ($140 to $320)	$250 ($120 to $380)
INFRASTRUCTURE						
Roads	$3,300 ($800 to $7,500)	$2,400 ($1,000 to $5,000)	$970 (-$230 to $2,400)	$6,000 ($2,600 to $10,000)	$3,100 ($730 to $7,200)	$2,900 ($1,800 to $3,900)
Bridges	$430 ($200 to $670)	$390 ($230 to $500)	$45 (-$33 to $270)	$270 ($160 to $380)	$110 ($52 to $200)	$160 ($41 to $290)
Rail	$500 ($390 to $650)	$430 ($310 to $530)	$68 (-$55 to $120)	$1,400 ($1,000 to $1,600)	$940 ($650 to $1,200)	$470 ($390 to $570)
Urban Drainage	$440 ($120 to $880)	$330 ($160 to $600)	$110 (-$450 to $720)	$560 ($80 to $840)	$480 ($41 to $1,200)	$79 (-$310 to $550)

	2050			2090		
	RCP8.5	**RCP4.5**	**Benefit**	**RCP8.5**	**RCP4.5**	**Benefit**
ELECTRICITY						
Electricity Demand and Supply	$460 ($390 to $620)	$280 ($200 to $360)	$180 ($22 to $300)	$1,200 ($870 to $1,400)	$430 ($220 to $680)	$770 ($440 to $1,000)
WATER RESOURCES						
Municipal and Industrial Water Supply	$29 (-$9.6 to $99)	$29 (-$15 to $85)	$0.39 (-$68 to $60)	$58 (-$39 to $150)	$57 (-$37 to $110)	$0.40 (-$32 to $47)
Inland Flooding	$670 (NA)	$540 (NA)	$120 (NA)	$690 (NA)	$830 (NA)	-$140 (NA)
Water Quality	$390 ($220 to $560)	$310 ($150 to $480)	$73 ($36 to $120)	$750 ($440 to $1,100)	$420 ($200 to $690)	$330 ($220 to $390)
Winter Recreation	$190 ($43 to $270)	-$26 (-$110 to $47)	$220 (-$3.9 to $330)	$360 ($230 to $420)	$180 ($38 to $280)	$170 ($130 to $280)
ECOSYSTEMS						
Freshwater Fish	$180 (-$370 to $670)	$180 (-$150 to $620)	-$4.9 (-$550 to $380)	$420 (-$710 to $900)	$270 (-$460 to $660)	$150 (-$250 to $380)
Wildfire	$0.52 (-$6.0 to $7.3)	-$2.5 (-$7.6 to $5.2)	$3.1 (-$9.5 to $11)	-$1.1 (-$5.4 to $3.6)	-$5.0 (-$7.4 to -$1.7)	$3.9 (-$1.5 to $8.2)

Notes:
"NA" indicates analyses where GCM-specific results are not available.
Air Quality: Mean and upper/lower bounds based on confidence intervals from the BenMAP-CE model.
Harmful Algal Blooms: Range and mean values based on combined high and low growth scenarios.
Urban Drainage: Values represent results under the 50-year storm.
Electricity Demand and Supply: Values represent power system supply costs. Results are from the GCAM power sector model only.
Water Quality: Range and mean values based on combined results from US Basins and HAWQS.
Freshwater Fish: Values represent impacts to all three fishing guilds (coldwater, warmwater, and rough)
Wildfire: Results represent changes in both the contiguous U.S. and Alaska.

30.4 NORTHERN PLAINS



Using the results presented throughout the sector sections of this Technical Report, this section summarizes the impacts projected to occur in the Northern Plains.

Key Findings

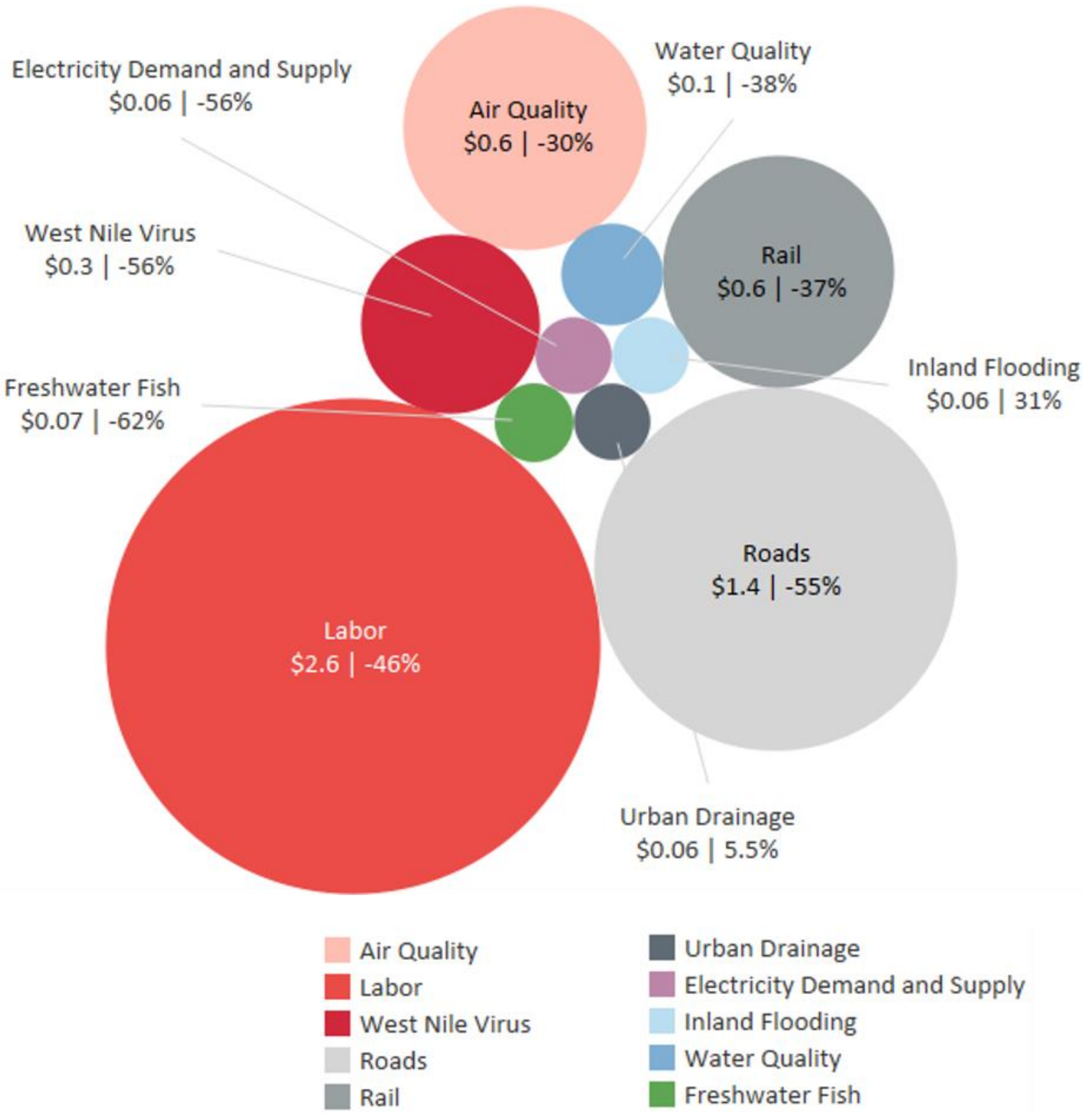
- Many of the climate impacts projected to occur in the Northern Plains are smaller in relative magnitude than in other regions, owing to comparatively smaller populations and development. For instance, the Northern Plains is among the regions with the lowest projected proactive adaptation costs for bridges, the lowest cumulative rail impacts, and the lowest projected damages from inland flooding under both RCPs and time periods.
- Lost labor hours from changes in extreme temperature are projected to rise under RCP8.5 from $690 million each year in 2050 to $2.6 billion each year in 2090.
- Damages associated with projected increases in fatal and non-fatal cases of West Nile neuroinvasive disease under RCP8.5 rise from $86 million each year in 2050 to $340 million each year in 2090.
- As climate change leads to a loss of coldwater fishing habitat and a shift in habitat suitable for warmwater species into areas suitable for rough water species, lost freshwater fishing days in the Northern Plains will result in $66 million in damages per year under RCP8.5 and $25 million damages per year under RCP4.5 by the end of the century.
- Air quality, West Nile virus, roads, rail, and winter recreation are all projected to experience economic benefits under RCP4.5 when compared to RCP8.5.

Discussion

Tables 30.7 and 30.8 present the estimated annual physical and economic effects of climate change in the Northern Plains under RCP8.5 and RCP4.5 in the years 2050 and 2090. As shown in Table 30.7, annual physical impacts of climate change in the Northern Plains are projected to increase over time in all sectors except winter recreation (under RCP4.5 only), acres burned by wildfire, and carbon storage (under RCP4.5 only). Physical impacts are greater under RCP8.5 than RCP4.5 for all sectors in 2050 except corn yields and carbon storage, and for all sectors in 2090, except bridges and carbon storage. As shown in Figure 30.5 and Table 30.8, annual economic damages also generally increase from 2050 to 2090 and from RCP4.5 to RCP8.5. However, bridges, urban drainage, municipal and industrial water supply, and inland flooding all see higher costs under RCP4.5 compared to RCP8.5 for at least one of the two time periods. The bridges, municipal and industrial water supply, and wildfire sectors all see higher costs in 2050 than in 2090 for at least one of the two RCPs.

Figure 30.5. Largest Damages of Climate Change in the Northern Plains

Annual damages for the ten sectors with the greatest projected costs in the Northern Plains in 2090 under RCP8.5 are shown by relative circle size and with the labeled monetary value (in $billions). The difference between RCP8.5 and RCP4.5 in 2090 is shown as the second value (in % change). The data underlying the sectors shown in the figure, as well as all other sectors modeled in the Northern Plains, can be found in Table 30.8 below.



As one of the least-populated areas of the contiguous U.S., many of the climate impacts projected to occur in the Northern Plains are milder than those projected in other NCA regions.[481] Though the Northern Plains is among the regions with the largest increase in cyanobacteria in recreational reservoirs, it is the only region with a projected increase in recreation days under a low algal growth scenario compared to the control scenario (population growth but no climate change). Even under a high growth scenario, the Northern Plains are projected to have the fewest lost reservoir recreation days of any NCA region. The Northern Plains is also among the regions with the lowest proactive adaptation costs for bridges under both climate scenarios and time periods, the lowest cumulative rail reactive adaptation costs under both RCPs, and the lowest projected damages from inland flooding under both RCPs and time periods. These results are largely influenced by the comparatively small amount of infrastructure and development in the Northern Plains compared to other regions. However, beyond economic impacts, damages to roads, rail systems, and bridges could be particularly meaningful in the Northern Plains where there is a lack of infrastructure redundancy.

The Northern Plains is projected to have the lowest increases in cumulative electricity supply costs of all the regions. Carbon storage is projected to increase in the Northern Plain under both RCPs, especially in 2090, and losses in corn yields are modest under RCP8.5, but reach 12% by 2090. Modest welfare losses are projected in the municipal and industrial water supply sector, while the Northern Plains has the second highest damages among the regions associated with urban drainage under RCP4.5. Both of these effects are largely driven by projected increases in annual average precipitation for this region.

The most economically-significant impacts in the Northern Plains are projected to occur from damages to roads (in 2090 under RCP8.5) and lost labor hours. Under RCP8.5, the estimated annual economic damages by 2090 to roads and lost labor wages are on the order of billions of dollars. There are significantly lower damages associated with labor loss under RCP4.5 compared to RCP8.5, particularly in 2090. Air quality, West Nile virus, roads, rail, and winter recreation are all projected to experience economic benefits under RCP4.5 when compared to RCP8.5.

As climate change leads to a loss of coldwater fishing habitat and a shift of current warmwater fishing habitat to rough water habitat, lost freshwater fishing days in the Northern Plains will result in $66 million in damages per year under RCP8.5 and $25 million damages per year under RCP4.5 by the end of the century. In 2090, the Northern Plains is projected to lose 0.54 million recreational visits a year under RCP8.5, equating to $47 million per year in damages. Under RCP4.5, winter recreational visitation would see an increase of 1.1 million visits per year by 2090 (the net effect of losses due to climate and increasing recreation due to population growth), resulting in $75 million in annual benefits.

For additional considerations regarding the values shown in Tables 30.7 and 30.8, see the notes at the beginning of the Regional Summaries section and the footnotes to the National Summary table. For more detailed results, as well as background and modeling approaches, see the individual sectoral chapters.

[481] Noting that none of the 49 cities modeled in the Extreme Temperature Mortality section were located in the Northern Plains.

Table 30.7. Projected Annual Physical Impacts of Climate Change in the Northern Plains

Positive numbers represent damages due to climate change, while negative numbers represent a reduction in damages compared to the reference period. Unless noted, upper and lower bounds are derived from values across the five GCMs. Not all sectoral analyses produced discrete physical metric estimates. See notes at the bottom of Table 30.8 for additional sector-specific information. Due to rounding, benefit values may not equate to differences between RCPs.

	2050			2090		
	RCP8.5	**RCP4.5**	**Benefit**	**RCP8.5**	**RCP4.5**	**Benefit**
HEALTH						
Air Quality: # deaths	23 (12 to 33)	20 (11 to 30)	3.0 (NA)	42 (22 to 61)	29 (16 to 43)	13 (NA)
Labor: Lost Labor Hours (millions)	14 (5.6 to 21)	11 (3.7 to 16)	2.8 (-5.9 to 8.6)	31 (14 to 42)	16 (9.1 to 24)	15 (5.1 to 20)
Harmful Algal Blooms: # Days above 100k cells/mL	5.7 (0.96 to 9.7)	5.2 (2.7 to 10)	0.43 (-2.9 to 4.5)	15 (3.0 to 28)	8.0 (1.4 to 17)	7.5 (1.7 to 15)
West Nile Virus: # Cases	100 (51 to 150)	79 (40 to 120)	23 (11 to 31)	330 (150 to 480)	150 (64 to 220)	190 (86 to 260)
INFRASTRUCTURE						
Bridges: # Vulnerable Bridges	260 (110 to 480)	160 (79 to 250)	100 (-54 to 310)	410 (190 to 630)	430 (260 to 580)	-18 (-240 to 230)
WATER RESOURCES						
Winter Recreation: Lost Visits (millions)	-0.47 (-1.2 to -0.13)	-0.50 (-0.83 to -0.32)	0.030 (-0.83 to 0.34)	0.54 (-1.2 to 1.4)	-1.1 (-2.2 to -0.44)	1.6 (1.0 to 1.9)
AGRICULTURE						
Agriculture: % Decrease in Corn Yields (example crop)	0.94% (-5.9% to 6.8%)	1.8% (-7.3% to 13%)	-0.90% (-14% to 5.0%)	12% (-1.3% to 17%)	2.0% (-7.7% to 11%)	9.5% (2.7% to 22%)
ECOSYSTEMS						
Freshwater Fish: Coldwater Fishing Days Lost (millions)	0.68 (0.47 to 0.91)	0.58 (0.46 to 0.65)	0.098 (-0.030 to 0.26)	1.2 (0.75 to 2.0)	0.69 (0.57 to 0.89)	0.48 (0.16 to 1.1)

	2050			2090		
	RCP8.5	**RCP4.5**	**Benefit**	**RCP8.5**	**RCP4.5**	**Benefit**
Wildfire: Acres Burned (thousands)	-41 (-230 to 130)	-100 (-300 to 92)	62 (-4.5 to 130)	-85 (-260 to 55)	-190 (-310 to 40)	100 (-19 to 220)
Carbon Storage: Metric Tons Lost (millions)	-6.3 (-25 to 4.7)	-5.0 (-10 to 2.8)	-1.2 (-14 to 9.1)	-7.2 (-34 to 6.7)	2.7 (-3.3 to 11)	-9.8 (-31 to 3.5)

Note: “NA” indicates analyses where GCM-specific results are not available.

Table 30.8. Projected Annual Economic Impacts of Climate Change in the Northern Plains

Positive numbers represent damages due to climate change, while negative numbers represent a reduction in damages compared to the reference period. Values shown in millions of undiscounted $2015. Unless noted, upper and lower bounds are derived from values across the GCMs. Regional economic impacts on agriculture yield and welfare are not available. Due to rounding, benefit values may not equate to differences between RCPs.

	2050			2090		
	RCP8.5	**RCP4.5**	**Benefit**	**RCP8.5**	**RCP4.5**	**Benefit**
HEALTH						
Air Quality	$280 ($25 to $810)	$250 ($23 to $720)	$30 (NA)	$630 ($57 to $1,800)	$440 ($40 to $1,300)	$190 (NA)
Labor	$690 ($280 to $1,000)	$550 ($190 to $780)	$140 (-$300 to $430)	$2,600 ($1,200 to $3,400)	$1,300 ($750 to $2,000)	$1,200 ($420 to $1,600)
Harmful Algal Blooms	-$0.86 (-$4.2 to $3.3)	-$0.94 ($0.56 to $1.7)	$0.080 (-$2.1 to $2.0)	$0.27 (-$4.8 to $6.1)	-$0.58 (-$5.4 to $4.8)	$0.85 (-$0.46 to $3.8)
West Nile Virus	$86 ($43 to $120)	$67 ($34 to $99)	$19 ($9.2 to $26)	$340 ($150 to $490)	$150 ($65 to $230)	$190 ($87 to $270)
INFRASTRUCTURE						
Roads	$580 ($300 to $920)	$420 ($200 to $650)	$160 ($63 to $280)	$1,400 ($610 to $2,000)	$590 ($200 to $950)	$770 ($410 to $1,100)
Bridges	$89 ($55 to $120)	$91 ($66 to $120)	-$1.7 (-$27 to $32)	$42 ($18 to $66)	$25 ($14 to $38)	$17 ($3.6 to $41)
Rail	$180 ($130 to $220)	$160 ($100 to $190)	$23 (-$18 to $53)	$570 ($370 to $690)	$360 ($190 to $470)	$210 ($180 to $240)
Urban Drainage	$21 ($0 to $42)	$42 ($0 to $87)	-$21 (-$48 to $17)	$62 ($0 to $130)	$65 ($0 to $110)	-$3.4 (-$81 to $88)
ELECTRICITY						
Electricity Demand and Supply	$16 ($13 to $18)	$10 ($7.0 to $18)	$5.8 (-$4.9 to $11)	$61 ($42 to $80)	$27 ($9.1 to $42)	$34 ($15 to $59)

	2050			2090		
	RCP8.5	**RCP4.5**	**Benefit**	**RCP8.5**	**RCP4.5**	**Benefit**
WATER RESOURCES						
Municipal and Industrial Water Supply	$0.24 (-$1.8 to $3.6)	$3.0 (-$0.25 to $9.2)	-$2.7 (-$9.2 to $3.8)	$0.43 (-$7.2 to $12)	$2.1 (-$4.4 to $12)	-$1.7 (-$10 to $4.8)
Inland Flooding	$58 (NA)	$74 (NA)	-$16 (NA)	$61 (NA)	$80 (NA)	-$19 (NA)
Water Quality	$56 ($33 to $79)	$46 ($26 to $74)	$10 ($2.8 to $20)	$110 ($69 to $160)	$66 ($22 to $110)	$42 ($34 to $47)
Winter Recreation	-$27 (-$90 to -$4.4)	-$23 (-$47 to $4.9)	-$3.4 (-$95 to $25)	$47 (-$87 to $110)	-$75 (-$160 to -$27)	$120 ($77 to $140)
ECOSYSTEMS						
Freshwater Fish	$18 (-$13 to $37)	$16 ($0.16 to $38)	$1.9 (-$22 to $20)	$66 ($20 to $88)	$25 (-$1.3 to $40)	$41 ($7.3 to $56)
Wildfire	-$9.5 (-$52 to $32)	-$24 (-$69 to $23)	$15 ($0.99 to $35)	-$22 (-$62 to $11)	-$44 (-$72 to $4.6)	$22 (-$5.6 to $48)

Notes:
"NA" indicates analyses where GCM-specific results are not available.
Air Quality: Mean and upper/lower bounds based on confidence intervals from the BenMAP-CE model.
Harmful Algal Blooms: Range and mean values based on combined high and low growth scenarios.
Urban Drainage: Values represent results under the 50-year storm.
Electricity Demand and Supply: Values represent power system supply costs. Results are from the GCAM power sector model only.
Water Quality: Range and mean values based on combined results from US Basins and HAWQS.
Freshwater Fish: Values represent impacts to all three fishing guilds (coldwater, warmwater, and rough)
Wildfire: Results represent changes in both the contiguous U.S. and Alaska.

30.5 SOUTHERN PLAINS

Using the results presented throughout the sector sections of this Technical Report, this section summarizes the impacts projected to occur in the Southern Plains.

Key Findings

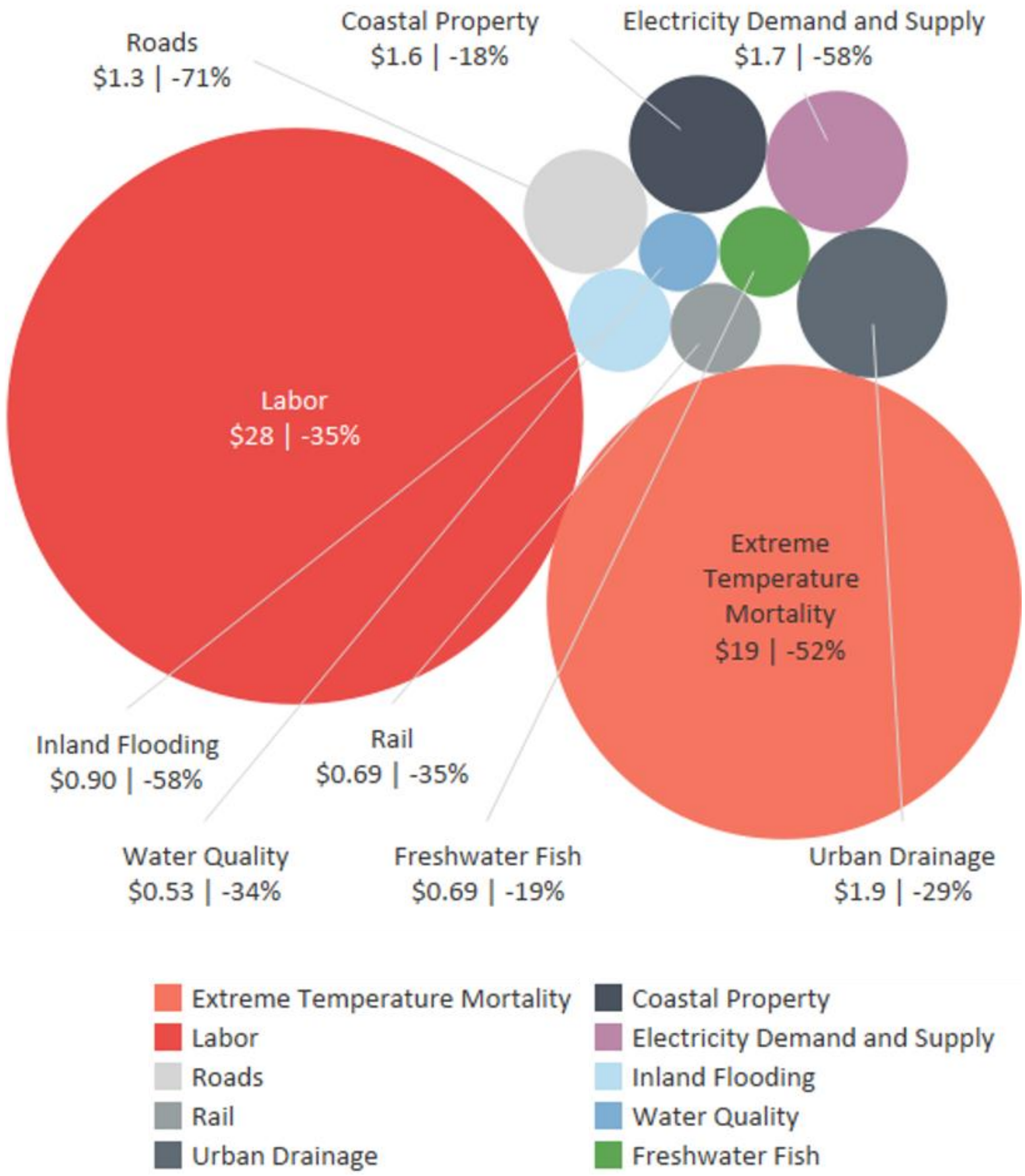
- The most economically-significant impacts in the Southern Plains occur from lost labor wages and premature deaths associated with increases in extreme temperature, with losses in 2090 under RCP8.5 equaling $28 billion per year and $19 billion per year, respectively. There are significant economic benefits in labor and deaths from extreme temperature under RCP4.5 compared to RCP8.5. For instance, in 2090 annual avoided damages are $9.9 billion from labor and $9.8 billion for avoided premature deaths from extreme temperature under RCP8.5.
- The Southern Plains is projected to have some of the largest increases in cyanobacteria concentrations and associated losses in recreation of all the regions due to harmful algal blooms. Under RCP8.5, the number of days where recreational reservoirs surpass the cyanobacteria concentration threshold representing a very high risk of short or long-term adverse health effects rise from an additional 11 days per year in 2050 to an additional 15 days per year in 2090.
- Projected climate impacts to infrastructure in the Southern Plains, such as rail and urban drainage, are among the highest of all regions. Increases in electricity costs to meet projected increases in demand in the Southern Plains are high, rising from $0.57 billion per year in 2050 to $1.7 billion per year by 2090 under RCP8.5.
- Corn yields are projected to decline considerably under RCP8.5 in the Southern Plains, with yield losses in 2090 of 23% under RCP8.5 and 7% under RCP4.5.

Discussion

Tables 30.9 and 30.10 present the estimated annual physical and economic effects of climate change in the Southern Plains under RCP8.5 and RCP4.5 in the years 2050 and 2090. As shown in Table 30.9, annual impacts in the Southern Plains are projected to increase over time in all sectors, except for carbon storage and air quality under RCP8.5, and harmful algal blooms under RCP4.5. Adverse impacts are projected to be greater under RCP8.5 than RCP4.5 in all sectors except carbon storage and air quality in 2090. As shown in Figure 30.6 and Table 30.10, annual economic damages also generally increase from 2050 to 2090, with the exception of at least one of the RCPs projecting damages in air quality, roads, bridges, urban drainage, inland flooding, and wildfire. Some infrastructure sectors are projected to have higher costs in 2050 than in 2090, as many types of infrastructure are already vulnerable or will soon become vulnerable and require repair or adaptation costs early in the century.

Figure 30.6. Largest Damages of Climate Change in the Southern Plains

Annual damages for the ten sectors with the greatest projected costs in the Southern Plains in 2090 under RCP8.5 are shown by relative circle size and with the labeled monetary value (in $billions). The difference between RCP8.5 and RCP4.5 in 2090 is shown as the second value (in % change). The data underlying the sectors shown in the figure, as well as all other sectors modeled in the Southern Plains, can be found in Table 30.10 below.



The Southern Plains is one of only two NCA regions where climate change is projected to result in fewer premature deaths from ground-level ozone (in 2050 under RCP4.5 and 2090 under RCP8.5). This is because climate-driven meteorological changes result in conditions slightly less conducive to ozone formation, potentially due to an increase in precipitation. The Southern Plains also have among the lowest increase in mortality from extreme temperatures of any region under both RCPs and time periods. Though carbon storage is projected to increase over time under RCP8.5, it will decrease under RCP4.5.

With one of the largest projected increases in cyanobacteria concentrations, the Southern Plains will have some of the largest projected losses in recreation due to harmful algal blooms. Projected costs to the rail network in the Southern Plains are among the highest with proactive adaptation and the highest under reactive adaptation of all the NCA regions under both RCPs. Projected average damages to urban drainage for 25-year storms are among the highest under RCP8.5 and the highest for 50-year storms under both RCPs. Increases in electricity costs to meet projected increases in demand in the Southern Plains are high. Corn yields are also projected to decline considerably under RCP8.5, and cumulative welfare loss in the municipal and industrial water supply sector is highest in the Southern Plains region under RCP8.5.

The most economically-significant impacts in the Southern Plains occur from lost labor wages and deaths associated with increases in extreme temperature, with losses in 2090 under RCP8.5 equaling $28 billion a year and $19 billion a year, respectively. There are significant economic benefits in labor and deaths from extreme temperature under RCP4.5 compared to RCP8.5, particularly in 2090. In 2090, climate change impacts on electricity demand and supply are also large, with annual damages estimated at $1.7 billion under RCP8.5 and $0.7 billion under RCP4.5.

For additional considerations regarding the values shown in Tables 30.9 and 30.10, see the notes at the beginning of the Regional Summaries section and the footnotes to the National Summary table. For more detailed results, as well as background and modeling approaches, see the individual sectoral chapters.

Table 30.9. Projected Annual Physical Impacts of Climate Change in the Southern Plains

Positive numbers represent damages due to climate change, while negative numbers represent a reduction in damages compared to the reference period. Unless noted, upper and lower bounds are derived from values across the five GCMs. Not all sectoral analyses produced discrete physical metric estimates. See notes at the bottom of Table 30.10 for additional sector-specific information. Due to rounding, benefit values may not equate to differences between RCPs.

	2050			2090		
	RCP8.5	**RCP4.5**	**Benefit**	**RCP8.5**	**RCP4.5**	**Benefit**
HEALTH						
Air Quality: # deaths	3.2 (1.7 to 4.7)	-4.2 (-6.2 to -2.3)	7.4 (NA)	-37 (-54 to -20)	89 (48 to 130)	-130 (NA)
Extreme Temperature Mortality: # deaths	550 (280 to 840)	350 (170 to 480)	200 (34 to 380)	1,300 (960 to 1,500)	620 (280 to 930)	650 (570 to 690)
Labor: Lost Labor Hours (millions)	180 (110 to 260)	140 (56 to 200)	40 (9.4 to 55)	330 (210 to 440)	210 (170 to 270)	120 (40 to 170)
Harmful Algal Blooms: # Days above 100k cells/mL	11 (5.5 to 23)	10 (7.9 to 18)	0.69 (-4.9 to 4.9)	15 (4.3 to 32)	7.9 (3.1 to 15)	7.1 (0.91 to 17)
West Nile Virus: # Cases	220 (180 to 260)	200 (160 to 220)	25 (12 to 34)	450 (350 to 530)	330 (280 to 370)	120 (67 to 160)
INFRASTRUCTURE						
Bridges: # Vulnerable Bridges	810 (300 to 1,200)	420 (27 to 760)	390 (-94 to 810)	1,100 (160 to 1,700)	1,000 (470 to 1,400)	25 (-320 to 500)
AGRICULTURE						
Agriculture: % Decrease in Corn Yields (example crop)	9.4% (0.46% to 22%)	5.7% (-1.5% to 12%)	3.7% (-4.0% to 10%)	23% (13% to 30%)	7.0% (1.7% to 14%)	16% (10% to 25%)
ECOSYSTEMS						
Freshwater Fish: Coldwater Fishing Days Lost (millions)	Values too small to differentiate from zero			Values too small to differentiate from zero		
Wildfire: Acres Burned (thousands)	-50 (-84 to -22)	-39 (-92 to 13)	-11 (-46 to 70)	140 (-8.1 to 240)	-37 (-84 to 12)	180 (37 to 280)
Carbon Storage: Metric Tons Lost (millions)	1.1 (-7.0 to 9.0)	-2.0 (-7.3 to 4.6)	3.1 (-6.8 to 16)	-17 (-19 to -15)	-1.1 (-6.9 to 5.0)	-16 (-23 to -9.2)

Note: “NA” indicates analyses where GCM-specific results are not available.

Table 30.10. Projected Annual Economic Impacts of Climate Change in the Southern Plains

Positive numbers represent damages due to climate change, while negative numbers represent a reduction in damages compared to the reference period. Values shown in millions of undiscounted $2015. Unless noted, upper and lower bounds are derived from values across the GCMs. Regional economic impacts on agriculture yield and welfare are not available. Due to rounding, benefit values may not equate to differences between RCPs.

	2050			2090		
	RCP8.5	**RCP4.5**	**Benefit**	**RCP8.5**	**RCP4.5**	**Benefit**
HEALTH						
Air Quality	$40 ($3.6 to $110)	-$53 (-$150 to -$4.7)	$93 (NA)	-$560 (-$1,600 to -$50)	$1,400 ($120 to $3,800)	-$2,000 (NA)
Extreme Temperature Mortality	$6,800 ($3,400 to $10,000)	$4,400 ($2,200 to $5,900)	$2,400 ($420 to $4,800)	$19,000 ($15,000 to $23,000)	$9,400 ($4,300 to $14,000)	$9,800 ($8,600 to $10,000)
Labor	$8,900 ($5,300 to $13,000)	$6,900 ($2,800 to $10,000)	$2,000 ($470 to $2,800)	$28,000 ($17,000 to $36,000)	$18,000 ($14,000 to $22,000)	$9,900 ($3,300 to $14,000)
Harmful Algal Blooms	$12 (-$4.1 to $29)	$13 ($3.8 to $38)	-$0.69 (-$37 to $16)	$38 ($5.6 to $98)	$20 (-$3.3 to $56)	$18 (-$3.3 to $41)
West Nile Virus	$190 ($150 to $210)	$160 ($130 to $190)	$21 ($10 to $29)	$460 ($360 to $540)	$340 ($290 to $370)	$130 ($69 to $170)
INFRASTRUCTURE						
Roads	$420 ($96 to $890)	$370 ($61 to $700)	$46 (-$310 to $350)	$1,300 ($630 to $2,300)	$360 ($98 to $630)	$920 ($410 to $1,700)
Bridges	$300 ($110 to $440)	$300 ($170 to $410)	$0.25 (-$100 to $110)	$180 ($44 to $320)	$83 ($6.1 to $170)	$100 (-$19 to $220)
Rail	$240 ($180 to $300)	$210 ($130 to $260)	$36 (-$14 to $61)	$690 ($500 to $790)	$450 ($330 to $530)	$240 ($180 to $280)
Urban Drainage	$950 ($170 to $1,600)	$1,600 ($670 to $2,400)	-$690 (-$2,000 to $890)	$1,900 ($290 to $2,600)	$1,300 ($620 to $1,900)	$560 (-$1,300 to $1,600)
Coastal Property	$840 (NA)	$800 (NA)	$49 (NA)	$1,600 (NA)	$1,300 (NA)	$290 (NA)

	2050			2090		
	RCP8.5	**RCP4.5**	**Benefit**	**RCP8.5**	**RCP4.5**	**Benefit**
ELECTRICITY						
Electricity Demand and Supply	$570 ($490 to $690)	$390 ($230 to $540)	$180 (-$15 to $270)	$1,700 ($1,400 to $1,900)	$720 ($460 to $900)	$990 ($670 to $1,200)
WATER RESOURCES						
Municipal and Industrial Water Supply	$48 ($8.2 to $75)	$37 ($15 to $68)	$11 (-$15 to $42)	$100 ($27 to $190)	$63 ($32 to $110)	$41 (-$4.5 to $76)
Inland Flooding	$510 (NA)	$810 (NA)	-$300 (NA)	$900 (NA)	$380 (NA)	$520 (NA)
Water Quality	$220 ($98 to $350)	$170 ($45 to $270)	$52 ($15 to $120)	$530 ($400 to $620)	$350 ($260 to $470)	$180 ($130 to $240)
ECOSYSTEMS						
Freshwater Fish	$630 ($220 to $880)	$500 ($230 to $760)	$120 (-$94 to $290)	$690 ($360 to $1,100)	$570 ($310 to $830)	$130 ($43 to $270)
Wildfire	-$4.6 (-$7.6 to -$2.1)	-$3.8 (-$8.3 to -$0.41)	-$0.82 (-$4.6 to $6.2)	$11 (-$0.87 to $21)	-$4.0 (-$7.9 to $1.2)	$15 ($3.6 to $27)

Notes:
"NA" indicates analyses where GCM-specific results are not available.
Air Quality: Mean and upper/lower bounds based on confidence intervals from the BenMAP-CE model.
Harmful Algal Blooms: Range and mean values based on combined high and low growth scenarios.
Urban Drainage: Values represent results under the 50-year storm.
Electricity Demand and Supply: Values represent power system supply costs. Results are from the GCAM power sector model only.
Water Quality: Range and mean values based on combined results from US Basins and HAWQS.
Freshwater Fish: Values represent impacts to all three fishing guilds (coldwater, warmwater, and rough)
Wildfire: Results represent changes in both the contiguous U.S. and Alaska.

30.6 SOUTHWEST

Using the results presented throughout the sector sections of this Technical Report, this section summarizes the impacts projected to occur in the Southwest.

Key Findings

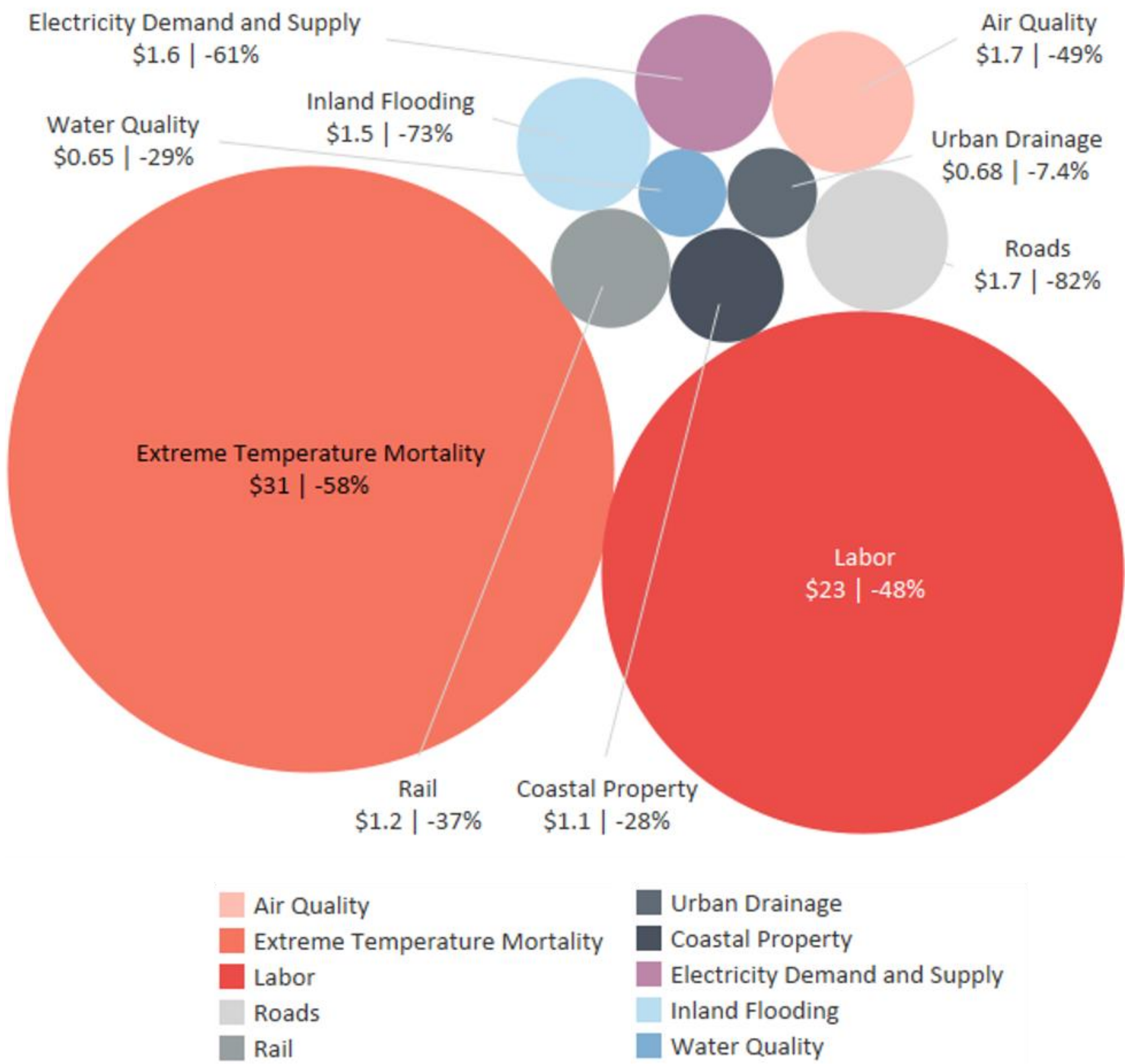
- The Southwest is projected to experience high levels of premature mortality associated with extreme temperatures. Compared to RCP8.5, RCP4.5 is projected to substantially reduce extreme temperature damages; 1,200 deaths from extreme temperatures would be avoided each year under RCP4.5 by 2090, resulting in $18 billion in annual savings.
- Extreme heat in the region leads to high labor losses; in 2090, losses of high-risk labor hours are as much as 6.5% in Southwest counties under RCP8.5. Lost wages in 2090 are estimated at $23 billion per year under RCP8.5 and $12 billion per year under RCP4.5.
- Projected reactive adaptation costs from increased temperatures on the rail system in the Southwest are among the highest across the nation. Under RCP8.5, reactive adaptation costs associated with temperature impacts on rail rise from $0.32 billion per year in 2050 to $1.2 billion per year by 2090.
- The Southwest is projected to be the region with the largest level of future wildfire activity under both RCPs, particularly in Colorado and Nevada. As a result, this region will incur the highest cumulative wildfire response costs through the end of the century, making up more than half the national total losses.
- The Southwest is projected to be among the regions with the largest lost welfare associated with municipal and industrial water supply, with losses reaching $110 million per year under RCP8.5 in 2090. Large losses of coldwater fish habitat are also projected under both RCPs, with the number of lost fishing days under RCP8.5 rising from 8.3 million per year in 2050 to 18 million per year by 2090.

Discussion

Tables 30.11 and 30.12 present the estimated annual physical and economic effects of climate change in the Southwest under RCP8.5 and RCP4.5 in the years 2050 and 2090. As shown in Table 30.11, annual impacts in the Southwest are projected to increase over time in all sectors, except under RCP4.5 in the air quality, winter recreation, and wildfire sectors. While physical damages are generally greater under RCP8.5 than RCP4.5, air quality, harmful algal blooms, and carbon storage sectors project greater damages under RCP4.5 in 2050 and greater carbon storage damages in 2090. As shown in Figure 30.7 and Table 30.12, annual economic damages also generally increase from 2050 to 2090 and from RCP4.5 to RCP8.5. However, some sectors, including air quality, harmful algal blooms, urban drainage, municipal and industrial water supply, and freshwater fish see higher damages in RCP4.5 than RCP8.5 in at least one time period.

Figure 30.7. Largest Damages of Climate Change in the Southwest

Annual damages for the ten sectors with the greatest projected costs in the Southwest in 2090 under RCP8.5 are shown by relative circle size and with the labeled monetary value (in $billions). The difference between RCP8.5 and RCP4.5 in 2090 is shown as the second value (in % change). The data underlying the sectors shown in the figure, as well as all other sectors modeled in the Southwest, can be found in Table 30.12 below.



The Southwest region is projected to incur significant damages associated with increased temperatures. Large increases in mortality from extreme temperatures are projected, particularly under RCP8.5, where the Southwest is the region with the highest mortality. Extreme heat also leads to high labor losses; in 2090, losses of high-risk labor hours are as much as 6.5% in counties within the Southwest under RCP8.5. The Southwest is one of the regions with the highest projected increase in future cases of neuroinvasive West Nile virus, particularly in 2050. Increasing temperatures will also affect the rail system, with projected reactive adaptation costs in the Southwest among the highest across the nation, especially under RCP8.5.

Large losses of coldwater fish habitat are projected under both RCPs, but especially under RCP8.5 by 2090. The Southwest is projected to be the region with the largest level of future wildfire activity under both RCPs, particularly in Colorado and Nevada. This region will also incur the highest cumulative wildfire response costs through the end of the century, making up more than half the national total losses (cumulative values not shown in Table 30.12; see wildfire sector). While corn yield losses are moderate and carbon storage increases under both RCPs, especially later in the century, the Southwest is projected to be among the regions with the largest lost welfare associated with municipal and industrial water supply. Climate change will have slight adverse effects on winter recreation season lengths and will therefore lead to fewer visits; however, these effects do not lead to net economic damages because of increased visits due to population growth and relatively high lift ticket prices.

The most economically-significant impacts in the Southwest under RCP8.5 stem from extreme temperature mortality and lost labor wages, on the order of billions to tens of billions of dollars in damages each year from climate change. RCP4.5 is projected to substantially reduce extreme temperature and labor related damages compared to RCP8.5, particularly in 2090. For example, 1,200 deaths from extreme temperatures would be avoided each year under RCP4.5 compared to RCP8.5 by 2090, resulting in $18 billion in annual savings. Avoided costs under RCP4.5, compared to RCP8.5, are also very high (more than $1 billion per year) for roads, winter recreation, inland flooding, and electricity demand and supply in 2090.

For additional considerations regarding the values shown in Tables 30.11 and 30.12, see the notes at the beginning of the Regional Summaries section and the footnotes to the National Summary table. For more detailed results, as well as background and modeling approaches, see the individual sectoral chapters.

Table 30.11. Projected Annual Physical Impacts of Climate Change in the Southwest

Positive numbers represent damages due to climate change, while negative numbers represent a reduction in damages compared to the reference period. Unless noted, upper and lower bounds are derived from values across the five GCMs. Not all sectoral analyses produced discrete physical metric estimates. See notes at the bottom of Table 30.12 for additional sector-specific information. Due to rounding, benefit values may not equate to differences between RCPs.

	2050			2090		
	RCP8.5	**RCP4.5**	**Benefit**	**RCP8.5**	**RCP4.5**	**Benefit**
HEALTH						
Air Quality: # deaths	62 (33 to 91)	71 (38 to 100)	-9.0 (NA)	110 (59 to 160)	57 (30 to 83)	53 (NA)
Extreme Temperature Mortality: # deaths	850 (460 to 1,600)	400 (180 to 790)	450 (190 to 800)	2,000 (1,200 to 3,000)	830 (380 to 1,500)	1,200 (820 to 1,700)
Labor: Lost Labor Hours (millions)	120 (91 to 160)	78 (61 to 94)	43 (22 to 62)	280 (200 to 350)	150 (89 to 200)	130 (110 to 170)
Harmful Algal Blooms: # Days above 100k cells/mL	12 (1.5 to 19)	12 (12 to 17)	-0.26 (-4.5 to 3.2)	15 (-0.60 to 26)	12 (0.57 to 19)	3.2 (-1.2 to 7.6)
West Nile Virus: # Cases	240 (230 to 250)	230 (220 to 240)	9.0 (6.8 to 10)	420 (390 to 440)	380 (360 to 390)	37 (30 to 48)
INFRASTRUCTURE						
Bridges: # Vulnerable Bridges	160 (73 to 290)	120 (51 to 170)	46 (-32 to 130)	360 (200 to 530)	260 (120 to 370)	94 (-86 to 290)
WATER RESOURCES						
Winter Recreation: Lost Visits (millions)	-2.6 (-7.8 to 0.52)	-2.6 (-3.4 to -1.4)	0.023 (-6.4 to 3.6)	1.5 (-10 to 6.5)	-10 (-19 to -6.4)	12 (9.0 to 14)
AGRICULTURE						
Agriculture: % Decrease in Corn Yields (example crop)	-2.3% (-6.4% to 6.9%)	-4.5% (-8.4% to -0.61%)	2.2% (-1.9% to 7.5%)	9.8% (4.8% to 16%)	-3.7% (-8.8% to -0.19%)	14% (8.9% to 19%)

	2050			2090		
	RCP8.5	**RCP4.5**	**Benefit**	**RCP8.5**	**RCP4.5**	**Benefit**
ECOSYSTEMS						
Freshwater Fish: Coldwater Fishing Days Lost (millions)	8.3 (6.0 to 13)	5.8 (2.9 to 9.9)	2.5 (0.63 to 3.3)	18 (12 to 26)	8.3 (4.1 to 13)	9.9 (6.5 to 14)
Wildfire: Acres Burned (thousands)	-850 (-1,700 to -440)	-960 (-1,400 to -300)	100 (-300 to 390)	-840 (-1,700 to -56)	-1,100 (-1,400 to -730)	300 (-250 to 670)
Carbon Storage: Metric Tons Lost (millions)	-9.6 (-29 to 10)	-6.7 (-20 to 5.2)	-2.9 (-12 to 10)	-20 (-37 to -3.8)	-5.5 (-14 to 7.2)	-14 (-33 to 2.4)

Note: “NA” indicates analyses where GCM-specific results are not available.

Table 30.12. Projected Annual Economic Impacts of Climate Change in the Southwest

Positive numbers represent damages due to climate change, while negative numbers represent a reduction in damages compared to the reference period. Values shown in millions of undiscounted $2015. Unless noted, upper and lower bounds are derived from values across the GCMs. Due to rounding, benefit values may not equate to differences between RCPs.

	2050			2090		
	RCP8.5	RCP4.5	Benefit	RCP8.5	RCP4.5	Benefit
HEALTH						
Air Quality	$770 ($69 to $2,200)	$880 ($79 to $2,500)	-$110 (NA)	$1,700 ($150 to $4,800)	$860 ($77 to $2,500)	$840 (NA)
Extreme Temperature Mortality	$11,000 ($5,700 to $20,000)	$5,000 ($2,300 to $9,800)	$5,600 ($2,400 to $9,900)	$31,000 ($18,000 to $45,000)	$13,000 ($5,800 to $22,000)	$18,000 ($13,000 to $26,000)
Labor	$6,100 ($4,600 to $7,800)	$3,900 ($3,000 to $4,700)	$2,100 ($1,100 to $3,100)	$23,000 ($17,000 to $29,000)	$12,000 ($7,300 to $16,000)	$11,000 ($8,800 to $14,000)
Harmful Algal Blooms	$7.6 ($3.2 to $13)	$4.9 ($0.12 to $10)	$2.7 (-$1.3 to $11)	$6.6 (-$4.5 to $15)	$7.9 ($2.8 to $12)	-$1.3 (-$11 to $7.0)
West Nile Virus	$200 ($190 to $210)	$190 ($180 to $200)	$7.6 ($5.8 to $8.8)	$420 ($390 to $450)	$390 ($360 to $400)	$38 ($31 to $49)
INFRASTRUCTURE						
Roads	$490 (-$81 to $1,000)	$240 ($30 to $360)	$250 (-$110 to $660)	$1,700 ($470 to $3,300)	$280 ($130 to $510)	$1,400 ($340 to $2,800)
Bridges	$120 ($68 to $200)	$95 ($53 to $120)	$30 (-$47 to $92)	$54 ($18 to $110)	$37 ($12 to $65)	$17 (-$2.6 to $47)
Rail	$320 ($240 to $400)	$250 ($190 to $310)	$66 ($46 to $88)	$1,200 ($860 to $1,500)	$730 ($470 to $940)	$440 ($380 to $530)
Urban Drainage	$570 ($170 to $1,100)	$590 ($470 to $810)	-$22 (-$390 to $640)	$680 ($250 to $970)	$630 ($240 to $1,200)	$50 (-$460 to $430)
Coastal Property	$980 (NA)	$970 (NA)	$12 (NA)	$1,100 (NA)	$790 (NA)	$310 (NA)
ELECTRICITY						
Electricity Demand and Supply	$520 ($390 to $660)	$370 ($230 to $470)	$150 ($92 to $240)	$1,600 ($1,100 to $2,000)	$620 ($420 to $770)	$980 ($590 to $1,200)

	2050			2090		
	RCP8.5	**RCP4.5**	**Benefit**	**RCP8.5**	**RCP4.5**	**Benefit**
WATER RESOURCES						
Municipal and Industrial Water Supply	$31 (-$3.5 to $78)	$37 ($25 to $68)	-$6.9 (-$29 to $10)	$110 ($11 to $200)	$79 (-$0.24 to $180)	$29 (-$49 to $200)
Inland Flooding	$450 (NA)	$360 (NA)	$90 (NA)	$1,500 (NA)	$410 (NA)	$1,100 (NA)
Water Quality	$290 ($140 to $470)	$240 ($280 to $370)	$44 (-$69 to $120)	$650 ($350 to $940)	$460 ($130 to $780)	$190 ($55 to $320)
Winter Recreation	-$250 (-$780 to $67)	-$240 (-$330 to -$58)	-$13 (-$730 to $390)	$170 (-$1,000 to $700)	-$1,100 (-$2,000 to -$660)	$1,200 ($920 to $1,400)
ECOSYSTEMS						
Freshwater Fish	$130 (-$130 to $450)	$150 ($46 to $300)	-$19 (-$170 to $150)	$170 (-$610 to $560)	$140 (-$94 to $390)	$34 (-$520 to $290)
Wildfire	-$91 (-$210 to -$28)	-$120 (-$180 to -$37)	$25 (-$29 to $55)	-$100 (-$230 to -$35)	-$160 (-$200 to -$91)	$56 (-$30 to $130)

Notes:
"NA" indicates analyses where GCM-specific results are not available.
Air Quality: Mean and upper/lower bounds based on confidence intervals from the BenMAP-CE model.
Harmful Algal Blooms: Range and mean values based on combined high and low growth scenarios.
Urban Drainage: Values represent results under the 50-year storm.
Electricity Demand and Supply: Values represent power system supply costs. Results are from the GCAM power sector model only.
Water Quality: Range and mean values based on combined results from US Basins and HAWQS.
Freshwater Fish: Values represent impacts to all three fishing guilds (coldwater, warmwater, and rough)
Wildfire: Results represent changes in both the contiguous U.S. and Alaska.

30.7 NORTHWEST

Using the results presented throughout the sector sections of this Technical Report, this section summarizes the impacts projected to occur in the Northwest.

Key Findings

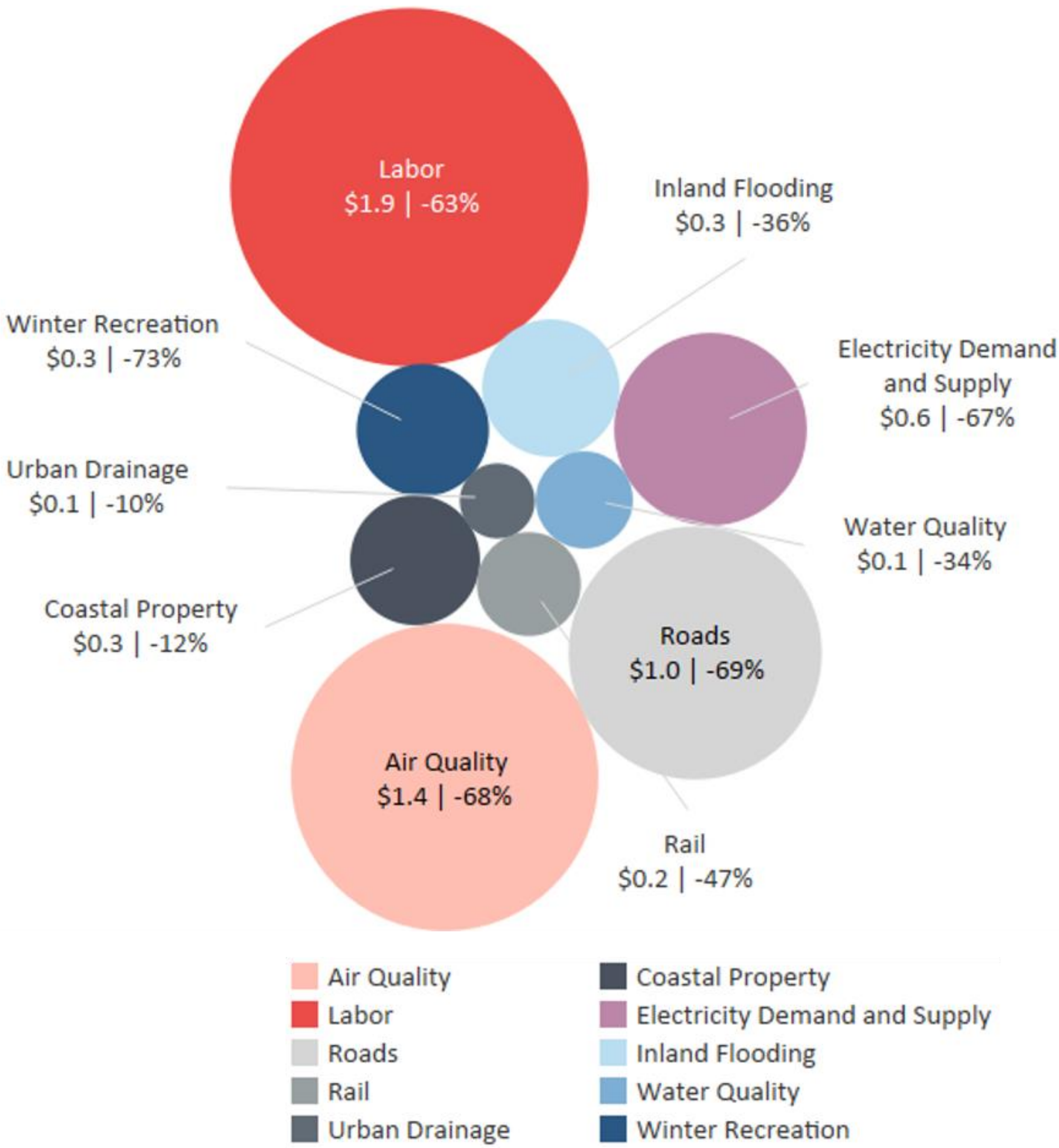
- The Northwest is among the regions with the highest projected acres burned and will experience the second highest cumulative wildfire response costs, on the order of billions of dollars through the end of the century. Acres burned and associated response costs are higher in 2050 than 2090, in part due to shifts in vegetation type.
- The Northwest is projected to have the highest damages to urban drainage for 10-year storms under both RCPs; projected estimates in all other regions besides the Southeast are less than half the costs in the Northwest. Damages under RCP8.5 are $84 million per year in both 2050 and 2090.
- Rising atmospheric CO_2 concentrations and climate change leads to losses associated with shellfish and freshwater fishing. Large decreases in the supply of geoducks and oysters (with subsequent price increases) are projected in the Northwest due to ocean acidification. Large losses in coldwater fishing habitats in mountain regions lead to an annual loss of 8.1 million fishing days under RCP8.5 and 2.1 million fishing days under RCP4.5 by 2090.
- Compared to other regions, cities located in the Northwest have low mortality rates from extreme heat, with no significant projected changes in premature deaths in the future. Though damages associated with air quality and labor losses are on the order of billions of dollars each year by 2090, this region has relatively low increases in ozone related premature deaths in 2050 compared to other regions.
- Climate impacts on roads under RCP8.5 are projected to rise in the Northwest from $360 million per year in 2050 to $950 million per year by 2090.

Discussion

Tables 30.13 and 30.14 present the estimated annual physical and economic effects of climate change in the Northwest under RCP8.5 and RCP4.5 in the years 2050 and 2090. As shown in Table 30.13, annual impacts in the Northwest are projected to increase over time in all sectors except wildfire under both RCPs, and carbon storage and extreme temperature mortalities under RCP8.5. Annual impacts are also greater under RCP8.5 than under RCP4.5 in all sectors except air quality and carbon storage, both in 2050 only, and extreme temperature mortality in 2090. As shown in Figure 30.8 and Table 30.14, annual economic damages also generally increase from 2050 to 2090 and from RCP4.5 to RCP8.5. However, several sectors, such as bridges and wildfire, see larger damages in 2050. Some infrastructure sectors see higher costs in 2050 as many types of infrastructure are already vulnerable or will soon become vulnerable and require repair costs early in the century. There are also a few sectors, including extreme temperature mortality, harmful algal blooms, municipal and industrial water supply, and inland flooding where damages are higher under RCP4.5 than under RCP8.5 in at least one time period.

Figure 30.8. Largest Damages of Climate Change in the Northwest

Annual damages for the ten sectors with the greatest projected costs in the Northwest in 2090 under RCP8.5 are shown by relative circle size and with the labeled monetary value (in $billions). The difference between RCP8.5 and RCP4.5 in 2090 is shown as the second value (in % change). The data underlying the sectors shown in the figure, as well as all other sectors modeled in the Northwest, can be found in Table 30.14 below.



The Northwest region is projected to experience generally moderate climate impacts in some sectors compared to some other NCA regions. For example, the Northwest will have relatively low increases in ozone related premature deaths due to climate change in 2050. Cities located in the Northwest have low mortality rates from extreme heat in both the reference and future years, such that there are no significant projected changes in premature deaths from extreme heat in this region. This region also has the smallest projected increase in neuroinvasive West Nile virus cases and relatively low costs from harmful algal bloom damages among the regions. Projections result in relatively low inland flooding damages, the fewest vulnerable bridges, and the lowest bridge repair costs. It is one of just two regions projected to see cumulative welfare gains in municipal and industrial water supply under both RCPs.

Conversely, the Northwest is among the regions with the highest cumulative costs for rail in RCP8.5, particularly when assuming that proactive adaptation measures are taken. Damages to urban drainage are projected to be highest in the Northwest for 10-year storms under both RCPs; projected estimates in all other regions besides the Southeast are less than half the costs in the Northwest. The Northwest is projected to experience large decreases in the supply of geoducks and oysters (with subsequent price increases) due to ocean acidification, and large losses in coldwater fishing habitats in mountain regions under both RCPs. Furthermore, this region is among those with the highest projected acres burned and will experience the second highest cumulative wildfire response costs, on the order of billions of dollars through the end of the century (cumulative values not shown in Table 30.14; see wildfire sector). However, the Northwest is projected to experience increases in corn yields, and the largest increase in stored carbon through 2100 under both RCPs, which results in large benefits, particularly under RCP8.5.

The most economically-significant impacts in the Northwest are damages associated with air quality and labor, both of which are on the order of billions of dollars each year by 2090. Several sectors, including air quality, labor, roads, and electricity demand and supply are projected to see significant benefits (avoided damages) under RCP4.5 compared to RCP8.5, particularly in 2090.

For additional considerations regarding the values shown in Tables 30.13 and 30.14, see the notes at the beginning of the Regional Summaries section and the footnotes to the National Summary table. For more detailed results, as well as background and modeling approaches, see the individual sectoral chapters.

Table 30.13. Projected Annual Physical Impacts of Climate Change in the Northwest

Positive numbers represent damages due to climate change, while negative numbers represent a reduction in damages compared to the reference period. Unless noted, upper and lower bounds are derived from values across the five GCMs. Not all sectoral analyses produced discrete physical metric estimates. See notes at the bottom of Table 30.14 for additional sector-specific information. Due to rounding, benefit values may not equate to differences between RCPs.

	2050			2090		
	RCP8.5	**RCP4.5**	**Benefit**	**RCP8.5**	**RCP4.5**	**Benefit**
HEALTH						
Air Quality: # deaths	20 (10 to 29)	5.2 (2.8 to 7.6)	15 (NA)	93 (50 to 140)	29 (16 to 43)	64 (NA)
Extreme Temperature Mortality: # deaths	3.3 (-0.58 to 12)	1.1 (-1.0 to 3.7)	2.2 (-1.7 to 13)	-0.38 (-1.1 to 0.94)	3.1 (0.68 to 7.8)	-3.4 (-6.9 to -1.2)
Labor: Lost Labor Hours (millions)	6.9 (3.3 to 16)	4.3 (1.7 to 8.8)	2.6 (0.81 to 6.8)	23 (12 to 40)	8.8 (3.1 to 22)	15 (9.1 to 18)
Harmful Algal Blooms: # Days above 100k cells/mL	0.19 (-0.040 to 0.54)	0.13 (0.020 to 0.43)	0.060 (-0.090 to 0.38)	1.1 (-0.010 to 3.0)	0.30 (-0.040 to 1.1)	0.78 (0.040 to 2.0)
West Nile Virus: # Cases	6.5 (6.3 to 6.6)	6.4 (6.2 to 6.5)	0.11 (0.054 to 0.15)	11 (11 to 11)	11 (10 to 11)	0.49 (0.38 to 0.61)
INFRASTRUCTURE						
Bridges: # Vulnerable Bridges	120 (59 to 200)	83 (12 to 160)	37 (-47 to 93)	200 (76 to 290)	160 (96 to 210)	42 (-36 to 130)
WATER RESOURCES						
Winter Recreation: Lost Visits (millions)	1.5 (-0.81 to 3.1)	-0.26 (-1.1 to 0.34)	1.8 (-1.1 to 3.5)	3.6 (0.37 to 5.5)	1.0 (-2.1 to 3.4)	2.5 (2.1 to 3.1)
AGRICULTURE						
Agriculture: % Decrease in Corn Yields (example crop)	-14% (-22% to -8.7%)	-15% (-20% to -11%)	1.5% (-2.3% to 5.3%)	0.42% (-10% to 10%)	-14% (-18% to -8.3%)	14% (7.8% to 21%)

	2050			2090		
	RCP8.5	**RCP4.5**	**Benefit**	**RCP8.5**	**RCP4.5**	**Benefit**
ECOSYSTEMS						
Freshwater Fish: Coldwater Fishing Days Lost (millions)	2.1 (0.67 to 3.3)	0.93 (-0.60 to 1.9)	1.2 (0.75 to 1.5)	8.1 (2.4 to 15)	2.1 (0.80 to 3.7)	6.0 (0.50 to 11)
Shellfish: % Decrease in Oyster Supply (example species)	26% (24% to 29%)	21% (16% to 27%)	5.7% (1.9% to 8.4%)	52% (49% to 55%)	27% (22% to 33%)	25% (22% to 28%)
Wildfire: Acres Burned (thousands)	110 (-98 to 440)	56 (-64 to 190)	51 (-46 to 320)	-15 (-220 to 110)	-80 (-180 to 95)	64 (-44 to 190)
Carbon Storage: Metric Tons Lost (millions)	-15 (-28 to -7.5)	-12 (-18 to -6.2)	-2.2 (-10 to 1.5)	-16 (-31 to -6.2)	-7.0 (-11 to -0.92)	-8.8 (-20 to -2.1)

Note: "NA" indicates analyses where GCM-specific results are not available.

Table 30.14. Projected Annual Economic Impacts of Climate Change in the Northwest

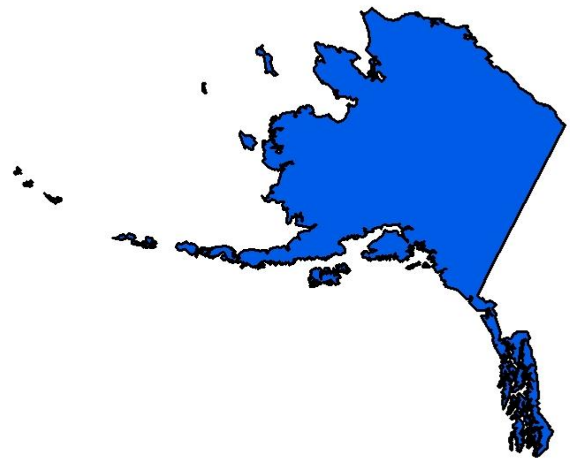
Positive numbers represent damages due to climate change, while negative numbers represent a reduction in damages compared to the reference period. Values shown in millions of undiscounted $2015. Unless noted, upper and lower bounds are derived from values across the GCMs. Regional economic impacts on agriculture yield and welfare are not available. Due to rounding, benefit values may not equate to differences between RCPs.

	2050			2090		
	RCP8.5	**RCP4.5**	**Benefit**	**RCP8.5**	**RCP4.5**	**Benefit**
HEALTH						
Air Quality	$240 ($22 to $690)	$65 ($5.8 to $180)	$180 (NA)	$1,400 ($130 to $4,000)	$450 ($40 to $1,300)	$950 (NA)
Extreme Temperature Mortality	$41 (-$7.2 to $150)	$14 (-$13 to $46)	$27 (-$21 to $160)	-$5.8 (-$16 to $14)	$46 ($10 to $120)	-$52 (-$100 to -$19)
Labor	$350 ($170 to $790)	$220 ($87 to $440)	$130 ($41 to $340)	$1,900 ($1,000 to $3,300)	$730 ($260 to $1,800)	$1,200 ($750 to $1,500)
Harmful Algal Blooms	$0.18 (-$0.050 to $0.69)	$0.22 (-$0.050 to $0.73)	-$0.030 (-$0.18 to $0.060)	$3.5 (-$0.19 to $16)	$0.15 (-$0.10 to $0.61)	$3.4 (-$0.12 to $16)
West Nile Virus	$5.5 ($5.3 to $5.6)	$5.4 ($5.2 to $5.5)	$0.090 ($0.045 to $0.13)	$11 ($11 to $12)	$11 ($10 to $11)	$0.50 ($0.38 to $0.62)
INFRASTRUCTURE						
Roads	$360 ($200 to $500)	$210 ($90 to $320)	$150 ($71 to $280)	$950 ($580 to $1,400)	$300 ($160 to $450)	$660 ($310 to $960)
Bridges	$83 ($48 to $130)	$71 ($56 to $86)	$13 (-$7.9 to $42)	$31 ($18 to $51)	$22 ($2.6 to $42)	$9.1 (-$11 to $30)
Rail	$45 ($33 to $63)	$36 ($24 to $57)	$8.7 ($5.7 to $11)	$160 ($96 to $230)	$89 ($42 to $130)	$75 ($54 to $110)
Urban Drainage	$84 ($46 to $130)	$70 ($45 to $93)	$14 (-$47 to $71)	$84 ($61 to $120)	$75 ($65 to $83)	$8.7 (-$22 to $47)
Coastal Property	$250 (NA)	$240 (NA)	$11 (NA)	$250 (NA)	$220 (NA)	$29 (NA)

	2050			2090		
	RCP8.5	**RCP4.5**	**Benefit**	**RCP8.5**	**RCP4.5**	**Benefit**
ELECTRICITY						
Electricity Demand and Supply	$160 ($98 to $240)	$100 ($54 to $150)	$57 ($25 to $94)	$550 ($270 to $880)	$180 ($87 to $280)	$370 ($190 to $610)
WATER RESOURCES						
Municipal and Industrial Water Supply	-$0.44 (-$0.52 to -$0.37)	-$0.40 (-$0.52 to -$0.26)	-$0.040 (-$0.16 to $0.15)	-$0.27 (-$0.61 to $0.46)	-$0.33 (-$0.63 to $0.32)	$0.070 (-$0.60 to $0.57)
Inland Flooding	$100 (NA)	$130 (NA)	-$21 (NA)	$280 (NA)	$170 (NA)	$100 (NA)
Water Quality	$58 ($18 to $96)	$45 ($38 to $80)	$13 ($1.8 to $24)	$140 ($60 to $210)	$90 ($9.7 to $150)	$47 ($27 to $69)
Winter Recreation	$110 (-$57 to $220)	-$44 (-$120 to $34)	$160 (-$91 to $290)	$260 ($27 to $400)	$76 (-$150 to $240)	$190 ($160 to $220)
ECOSYSTEMS						
Freshwater Fish	-$42 (-$84 to -$8.6)	-$59 (-$100 to -$24)	$17 (-$17 to $37)	$34 (-$34 to $120)	-$56 (-$100 to -$2.9)	$90 (-$31 to $180)
Wildfire	$22 (-$20 to $110)	$7.8 (-$16 to $35)	$15 (-$18 to $71)	-$15 (-$63 to $19)	-$29 (-$61 to $22)	$14 (-$7.4 to $44)

Notes:
”NA” indicates analyses where GCM-specific results are not available.
Air Quality: Mean and upper/lower bounds based on confidence intervals from the BenMAP-CE model.
Harmful Algal Blooms: Range and mean values based on combined high and low growth scenarios.
Urban Drainage: Values represent results under the 50-year storm.
Electricity Demand and Supply: Values represent power system supply costs. Results are from the GCAM power sector model only.
Water Quality: Range and mean values based on combined results from US Basins and HAWQS.
Freshwater Fish: Values represent impacts to all three fishing guilds (coldwater, warmwater, and rough)
Wildfire: Results represent changes in both the contiguous U.S. and Alaska.

30.8 ALASKA



This section presents infrastructure and wildfire projections for Alaska.

Key Findings

- In Alaska, wildfire acres burned each year by 2090 are projected to be 260,000 acres under RCP8.5, leading to response costs of $11 million each year. However, a decrease in area burned of 370,000 acres occurs under RCP4.5, avoiding a total of 640,000 acres from burning.
- The largest increase in area burned under RCP8.5 is projected in the southwestern part of the state. Under all scenarios and timeframes, the eastern parts of the state show a decrease in wildfire activity.
- Road flooding associated with increased precipitation is projected to be the largest source of infrastructure damages in Alaska, followed by damages to buildings associated with permafrost thaw. Smaller damages are estimated for Alaskan airports, rail, and pipelines. Overall, infrastructure damages from climate change by 2090 are $170 million per year under RCP8.5 and $82 million per year under RCP4.5.

Discussion

As described above, only a subset of sectors described in this Technical Report were run for the state of Alaska. As shown in Table 30.15, wildfire acres burned decrease under RCP4.5 and increase under RCP8.5 across much of the state, with higher impacts under 2090 than 2050. The largest increase in area burned under RCP8.5 is projected in the southwest part of the state. Under all scenarios and timeframes, the eastern parts of the state show a decrease in wildfire activity. The benefits of RCP4.5 compared to RCP8.5 are on the order of hundreds of thousands of acres burned per year. This results in economic benefits in terms of avoided wildfire response costs, as seen in Table 30.16.

Also shown in Table 30.16, annual damages to Alaskan infrastructure are greater under RCP8.5 than RCP4.5, but are also slightly less in 2090 than in 2050. This finding is consistent with some infrastructure results across regions of the contiguous U.S., as many types of infrastructure are already vulnerable or will soon become vulnerable and require repair costs earlier in the century. Road flooding associated with increased precipitation is projected to be the largest source of reactive repair costs, followed by impacts to buildings associated with permafrost thaw. Smaller reactive adaptation costs are estimated for Alaskan airports, railroads, and pipelines. Beyond economic effects, climate-driven changes to infrastructure could be particularly meaningful in Alaska where there is a lack of redundancy across most of the state.

For additional considerations regarding the values shown in Tables 30.15 and 30.16, see the notes at the beginning of the Regional Summaries section. For more detailed results, as well as background and modeling approaches, see the individual sectoral chapters.

Table 30.15. Projected Annual Physical Impacts of Climate Change in Alaska

Positive numbers represent damages due to climate change, while negative numbers represent a reduction in damages compared to the reference period. Unless noted, upper and lower bounds are derived from values across the GCMs. Not all sectoral analyses produced discrete physical metric estimates.

	2050			2090		
	RCP8.5	**RCP4.5**	**Benefit**	**RCP8.5**	**RCP4.5**	**Benefit**
ECOSYSTEMS						
Wildfire: Acres Burned (thousands)	220 (-160 to 600)	-700 (-760 to -650)	920 (600 to 1,200)	260 (130 to 400)	-370 (-570 to -180)	640 (310 to 970)

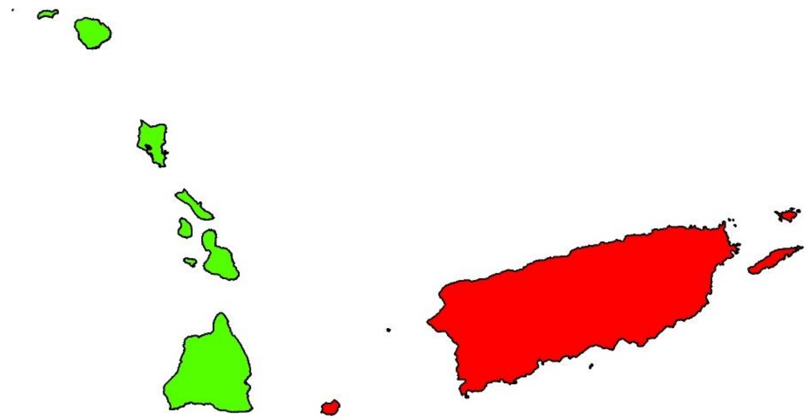
Table 30.16. Projected Annual Economic Impacts of Climate Change in Alaska

Positive numbers represent damages due to climate change, while negative numbers represent a reduction in damages compared to the reference period. Values shown in millions of undiscounted $2015. Unless noted, upper and lower bounds are derived from values across the GCMs. Due to rounding, benefit values may not equate to differences between RCPs.

	2050			2090		
	RCP8.5	**RCP4.5**	**Benefit**	**RCP8.5**	**RCP4.5**	**Benefit**
INFRASTRUCTURE						
Alaska Infrastructure (Reactive adaptation costs only)	$180 ($170 to $180)	$120 ($110 to $130)	$60 ($55 to $66)	$170 ($130 to $220)	$82 ($80 to $84)	$92 ($49 to $140)
ECOSYSTEMS						
Wildfire	$10 ($1.3 to $19)	-$15 (-$16 to -$14)	$25 ($18 to $33)	$11 ($7.0 to $15)	-$5.2 (-$9.6 to -0.74)	$16 ($7.7 to $25)

30.9 HAWAI'I AND PUERTO RICO

This section summarizes the coral reef projections for Hawai'i and Puerto Rico.



Key Findings

- Extensive loss of coral reefs is projected for Hawai'i and Puerto Rico under all scenarios and time periods.
- In Hawai'i, the annual percent of coral cover lost under RCP8.5 rises from 70% in 2050 to 96% in 2090. This loss leads to damages of $1.3 billion per year in 2050 and $1.9 billion per year in 2090. In 2090, RCP4.5 would avoid 16% of coral cover loss and $470 million per year compared to RCP8.5.
- In Puerto Rico, coral reefs pass a critical ecosystem threshold in the first several decades of the century, such that the differences between annual percent coral cover lost between time periods or under alternative climate scenarios is small. Under RCP8.5, coral cover loss in Puerto Rico rises from 93% in 2050 to 95% in 2090.

As described above, results for Hawai'i and Puerto Rico only cover the coral reef sector. As shown in Table 30.17, extensive loss of coral reefs is projected for Hawai'i and Puerto Rico under all scenarios and time periods. Damages increase over time and are higher in RCP8.5 than in RCP4.5 in Hawai'i. As Puerto Rican reefs pass critical thresholds for ecosystem loss, the difference between RCP8.5 and RCP4.5 are small. Coral reef recreation is projected to decline considerably under all scenarios, though slightly less under RCP4.5. In most cases, more than 90% of the value of reference period coral reef recreation is lost by the end of the century. Economic impacts, as shown in Table 30.18, are on the order of billions of dollars each year in Hawai'i, with larger damages under RCP8.5 compared to RCP4.5 and in 2090 compared to 2050. Damages are smaller in Puerto Rico, as the values only represent recreational losses for non-tourist residents.

For additional considerations regarding the values shown in Tables 30.15 and 30.16, see the notes at the beginning of the Regional Summaries section. For more detailed results, as well as background and modeling approaches, see the individual sectoral chapters.

Table 30.17. Projected Annual Physical Impact of Climate Change on Coral Reefs in Hawai'i and Puerto Rico

Positive numbers represent damages due to climate change, while negative numbers represent a reduction in damages compared to the reference period. Unless noted, upper and lower bounds are derived from values across the five GCMs. Not all sectoral analyses produced discrete physical metric estimates. Due to rounding, benefit values may not equate to differences between RCPs.

	2050			2090		
	RCP8.5	**RCP4.5**	**Benefit**	**RCP8.5**	**RCP4.5**	**Benefit**
ECOSYSTEMS						
Hawaiian Coral: % Loss Cover	70% (11% to 97%)	64% (7.3% to 94%)	5.6% (-11% to 17%)	96% (88% to 98%)	79% (26% to 97%)	16% (-1.2% to 63%)
Puerto Rican Coral: % Loss Cover	93% (89% to 95%)	93% (85% to 96%)	-0.80% (-6.7% to 9.7%)	95% (92% to 98%)	97% (96% to 97%)	-1.4% (-3.9% to 0.88%)

Table 30.18. Projected Annual Economic Impact of Climate Change on Coral Reefs in Hawai'i and Puerto Rico

Positive numbers represent damages due to climate change, while negative numbers represent a reduction in damages compared to the reference period. Values shown in millions of undiscounted $2015. Unless noted, upper and lower bounds are derived from values across the GCMs. Due to rounding, benefit values may not equate to differences between RCPs.

	2050			2090		
	RCP8.5	**RCP4.5**	**Benefit**	**RCP8.5**	**RCP4.5**	**Benefit**
ECOSYSTEMS						
Hawaiian Coral	$1,300 (-$240 to $1,900)	$1,100 (-$330 to $1,900)	$140 (-$290 to $420)	$1,900 ($1,700 to $2,000)	$1,400 (-$120 to $1,900)	$470 (-$36 to $1,800)
Puerto Rican Coral	$0.24 ($0.22 to $0.24)	$0.24 ($0.21 to $0.25)	-$0.0026 (-$0.022 to $0.032)	$0.24 ($0.23 to $0.25)	$0.25 ($0.25 to $0.25)	-$0.0054 (-$0.015 to $0.0033)

Errata:

The following minor changes have been made to the report since its finalization on May 11, 2017:

- Section 3 (Air Quality): clarified source for base non-GHG emissions data.
- Section 7 (West Nile Virus): corrected Southeast and Midwest case estimates for RCP4.5 in 2090. Matching edits made to the Regional Summaries for the Southeast (Section 30.2) and Midwest (Section 30.3).
- Section 12 (Bridges): corrected proactive adaptation response cost estimates. Matching edits made to the National Summary (Section 28).
- Section 23 (Coral Reefs): corrected summation error for Puerto Rico recreation damages (Table 23.1).
- Updated several references to include final journal publication information (e.g., DOI numbers, volume/page numbers), including updates to Table 2.2.

EPA
United States
Environmental Protection
Agency

United States
Environmental Protection Agency
1200 Pennsylvania Avenue, N.W. (6207A)
Washington, DC 20460

Official Business
Penalty for Private Use $300

EPA 430-R-17-001
May 2017