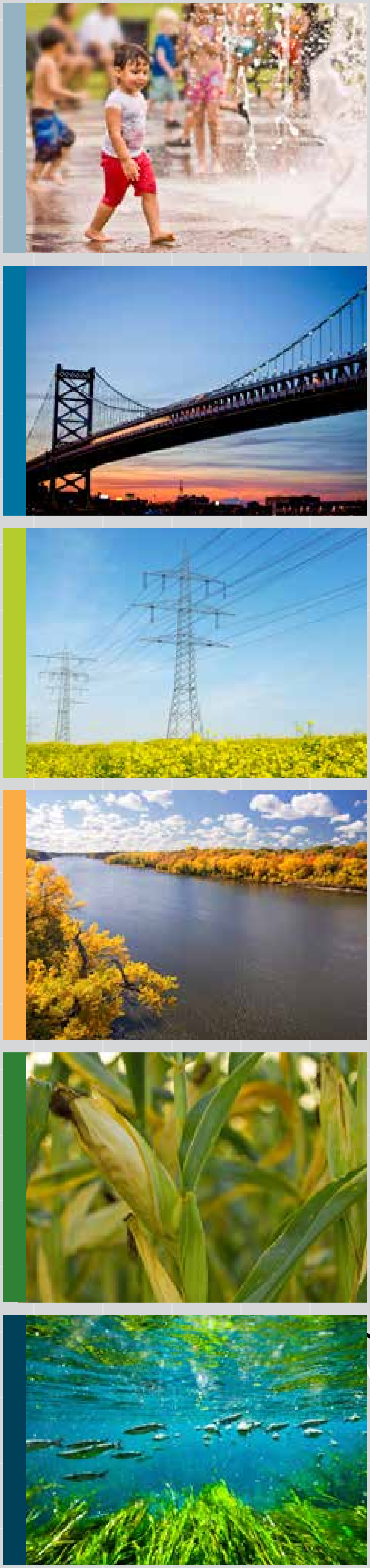
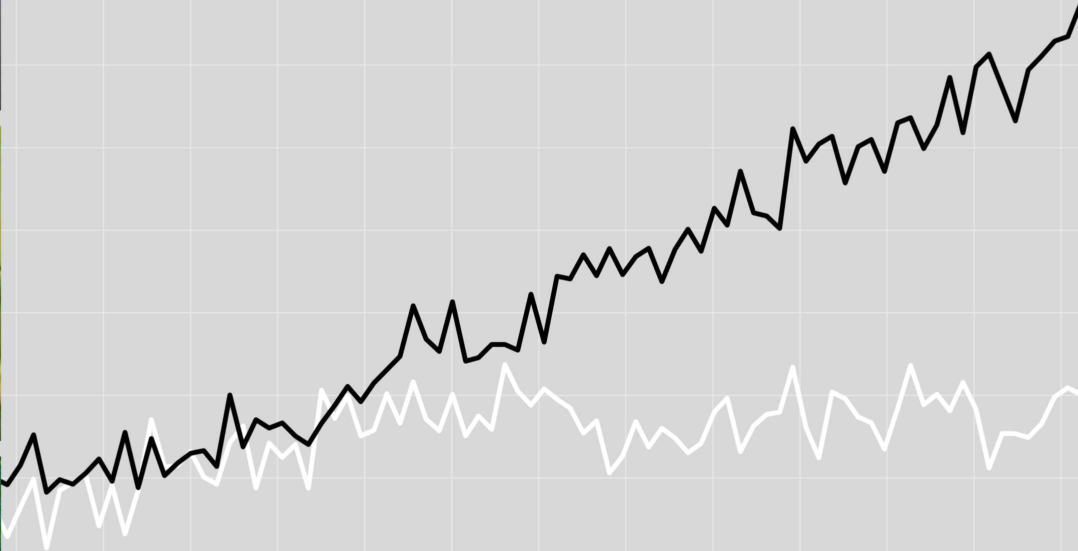


United States
Environmental Protection
Agency

CLIMATE CHANGE IN THE UNITED STATES

Benefits of Global Action



FIND US ONLINE

EPA's climate change website features a user-friendly interface for this report with downloadable graphics. To view information about EPA's Climate Change Impacts and Risk Analysis (CIRA) project, share your thoughts on this effort, and access the corresponding Technical Appendix for this report, please visit EPA's website at: www.epa.gov/cira.

Contents

Acknowledgments

CONTRIBUTORS

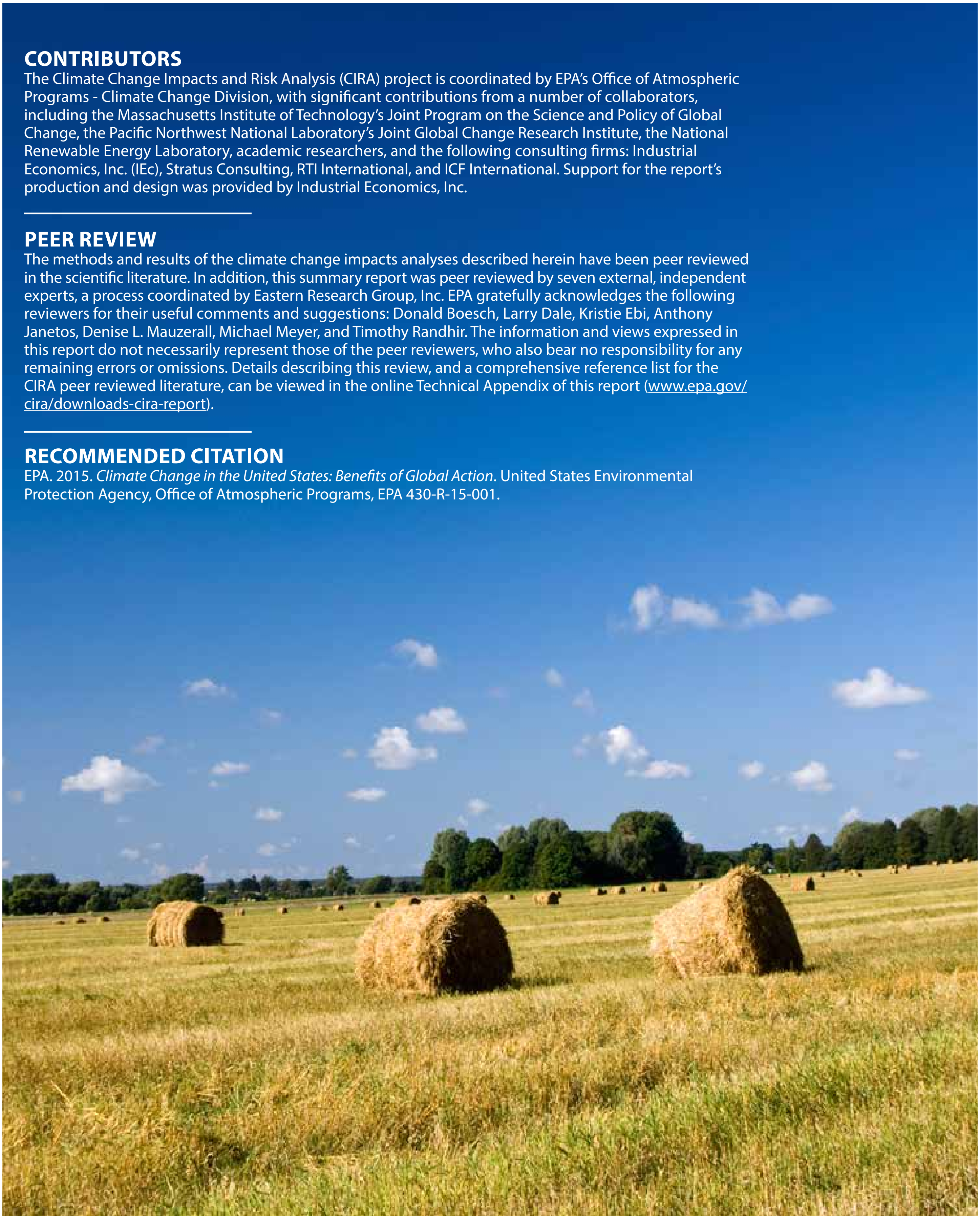
The Climate Change Impacts and Risk Analysis (CIRA) project is coordinated by EPA's Office of Atmospheric Programs - Climate Change Division, with significant contributions from a number of collaborators, including the Massachusetts Institute of Technology's Joint Program on the Science and Policy of Global Change, the Pacific Northwest National Laboratory's Joint Global Change Research Institute, the National Renewable Energy Laboratory, academic researchers, and the following consulting firms: Industrial Economics, Inc. (IEc), Stratus Consulting, RTI International, and ICF International. Support for the report's production and design was provided by Industrial Economics, Inc.

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 summary report was peer reviewed by seven external, independent experts, a process coordinated by Eastern Research Group, Inc. EPA gratefully acknowledges the following reviewers for their useful comments and suggestions: Donald Boesch, Larry Dale, Kristie Ebi, Anthony Janetos, Denise L. Mauzerall, Michael Meyer, and Timothy Randhir. 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 viewed in the online Technical Appendix of this report (www.epa.gov/cira/downloads-cira-report).

RECOMMENDED CITATION

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.



Introduction

The Earth's changing climate is affecting human health and the environment in many ways. Across the United States (U.S.), temperatures are rising, snow and rainfall patterns are shifting, and extreme climate events are becoming more common. Scientists are confident that many of the observed changes in the climate are caused by the increase in greenhouse gases (GHGs) in the atmosphere. As GHG emissions from human activities increase, many climate change impacts are expected to increase in both magnitude and frequency over the coming decades, with risks to human health, the economy, and the environment.

Actions can be taken now to reduce GHG emissions and avoid many of the adverse impacts of climate change. Quantifying the benefits of reducing GHG emissions (i.e., how GHG mitigation reduces or avoids impacts) requires comparing projections of climate change impacts and damages in a future with policy actions and a future without policy actions. Looking across a large number of sectors, this report communicates estimates of these benefits to the U.S. associated with global action on climate change.

Introduction

About this Report

This report summarizes and communicates the results of EPA's ongoing Climate Change Impacts and Risk Analysis (CIRA) project. The goal of this work is to estimate to what degree climate change impacts and damages to multiple U.S. sectors (e.g., human health, infrastructure, and water resources) may be avoided or reduced in a future with significant global action to reduce GHG emissions, compared to a future in which current emissions continue to grow. Importantly, only a small portion of the impacts of climate change are estimated, and therefore this report captures just some of the total benefits of reducing GHGs.

To achieve this, a multi-model framework was developed to estimate the impacts and damages to the human health and welfare of people in the U.S. The CIRA framework uses consistent inputs (e.g., socioeconomic and climate scenarios) to enable consistent 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."[1] The research papers underlying the modeling and results presented herein are cited throughout this report and are listed in Section B of the Technical Appendix.

Interpreting the Results

This 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., in futures with and without global GHG mitigation. The CIRA analyses are intended to provide insights about the potential direction and magnitude of climate change impacts and the benefits (avoided impacts) to the U.S. of global emissions reductions. However, none of the estimates presented in this report should be interpreted as definitive predictions of future impacts at a particular place or time.

The CIRA analyses do not evaluate or assume specific GHG mitigation or adaptation policies in the U.S. or in other world regions. Instead, they consider plausible scenarios to illustrate potential benefits of significant GHG emission reductions compared to a business-as-usual future. The results should not be interpreted as supporting any particular domestic or global mitigation policy or target. A wide range of global mitigation scenarios could be modeled in the CIRA framework,[2] and results would vary accordingly. For ease of communicating results, however, this report focuses on a future where the increase in average global temperature is limited to approximately 2°C (3.6°F) above preindustrial levels—a goal relevant to international discussions on GHG emission reductions.[3]

This report includes as many climate change impacts as feasible at present, but is not all-inclusive. It is not intended to be as comprehensive as major assessments, such as those conducted by the U.S. Global Change Research Program (USGCRP), which capture a wider range of impacts from the published literature.[4] By using a consistent set of socioeconomic and climate scenarios, CIRA produces apples-to-apples comparisons of impacts across sectors and regions—something that is not always achieved, or even sought, in the major assessments. Also, the assessments typically do not monetize damages, nor do they focus on quantifying mitigation benefits. CIRA's ability to estimate how global GHG mitigation may benefit the U.S. by reducing or avoiding climate change impacts helps to fill an important literature and knowledge gap.

The CIRA analyses do not serve the same analytical purpose nor use the same methodology as the Social Cost of Carbon (SCC), an economic metric quantifying the marginal global benefit of reducing one ton of carbon dioxide (CO_2).[5] In addition, the costs of reducing GHG emissions,[6] and the health benefits associated with co-reductions in other air pollutants, are well-examined elsewhere in the literature[7] and are beyond the scope of this report.

Roadmap to the Report

SUMMARY OF KEY FINDINGS	Provides an overview of key findings and highlights of the report.
CIRA FRAMEWORK	Introduces the CIRA project, describes and briefly presents the climate projections used in the analyses, and discusses key uncertainties and boundaries of analysis.
SECTORS Health Infrastructure Electricity Water Resources Agriculture and Forestry Ecosystems	Summarizes the major findings of each of the 20 impact analyses within the six broad sectors listed to the left, including: • Background on the impact being estimated, along with a brief summary of the analytical approach to estimating the impact; • Key findings and graphics depicting the risks of inaction and the benefits of global-scale GHG mitigation; and • References to the underlying peer-reviewed research upon which these estimates are based.
OVERVIEW OF RESULTS	Presents national and regional highlights from the 20 sectoral impact analyses.
CONCLUSION	Describes the over-arching conclusions of the report.
TECHNICAL APPENDIX *(available at www.epa.gov/cira)*	• Provides a list of all peer-reviewed research papers underlying the CIRA project; • Provides comparisons of key CIRA findings to those of the assessment literature; and • Describes the treatment of adaptation across the sectoral analyses.

Summary of Key Findings

Climate change poses significant risks to humans and the environment. The CIRA project quantifies and monetizes the risks of inaction and benefits to the U.S. of global GHG mitigation within six broad sectors (water resources, electricity, infrastructure, health, agriculture and forestry, and ecosystems). Looking across the impact estimates presented in this report, several common themes emerge.[1]

Global GHG Mitigation Reduces the Frequency of Extreme Weather Events and Associated Impacts

Global GHG mitigation is projected to have a substantial effect on reducing the incidence of extreme temperature and precipitation events by the end of the century, as well as the impacts to humans and the environment associated with these extreme events.[2] For example, by 2100 mitigation is projected to avoid 12,000 deaths annually associated with extreme temperatures in 49 U.S. cities, compared to a future with no emission reductions. Inclusion of the entire U.S. population would greatly increase the number of avoided deaths, while accounting for adaptation could reduce this number.

Global GHG Mitigation Avoids Costly Damages in the U.S.

For nearly all sectors analyzed, global GHG mitigation is projected to prevent or substantially reduce adverse impacts in the U.S. this century compared to a future without emission reductions. For many sectors, the projected benefits of mitigation are substantial; for example, in 2100 mitigation is projected to result in cost savings of \$4.2-\$7.4 billion associated with avoided road maintenance. Global GHG mitigation is also projected to avoid the loss of 230,000-360,000 acres of coldwater fish habitat across the country compared to a future without emissions reductions.

The Benefits of GHG Mitigation Increase over Time

For a large majority of sectors analyzed, the benefits of GHG mitigation are projected to be greater in 2100 than in 2050. In addition, the benefits of GHG mitigation are often not apparent until mid-century. This delay in benefits is consistent with many studies,[3] and is attributable to inertia in the climate system. Therefore, decisions we make today can have long-term effects, and delaying action will likely increase the risks of significant and costly impacts in the future.

Adaptation Can Reduce Overall Damages in Certain Sectors

Adaptation can substantially reduce certain impacts of climate change regardless of whether future GHG levels are low or high. For example, the estimated damages to coastal property from sea level rise and storm surge in the contiguous U.S. are $5.0 trillion through 2100 (discounted at 3%[4]) in a future without emission reductions. When cost-effective adaptation along the coast is included, the estimated damages are reduced to $810 billion.

Impacts Vary across Time and Space

Important regional changes may be masked when results are presented at the national level. For example, the wildfire analysis reveals that the projected changes in the Southwest and Rocky Mountain regions are the primary drivers of national trends of increasing wildfire activity over time.

The temporal scale of climate change impacts is also important. While some impacts are likely to occur gradually over time, others may exhibit threshold (tipping point) responses to climate change, as large changes manifest over a short period of time. For example, high-temperature bleaching events projected to occur by 2025 are estimated to severely affect coral reefs in the Caribbean. Therefore, simply analyzing an impact in one time period (e.g., 2100) may mask important temporal dynamics that are relevant to decision makers.

SUMMARY OF KEY FINDINGS

Estimated Benefits to the U.S. in 2100

This graphic presents a selection of the estimated benefits of global GHG mitigation in 2100 for major U.S. sectors. Unless otherwise noted, the results presented below are estimates of annual benefits (or disbenefits) of mitigation in the year 2100.[*] Importantly, only a small portion of the impacts of climate change are estimated, and therefore this report captures just some of the total benefits of reducing GHGs.

HEALTH

AIR QUALITY

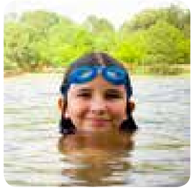
An estimated 57,000 fewer deaths from poor air quality in 2100

EXTREME TEMPERATURE

In 49 major U.S. cities, an estimated 12,000 fewer deaths from extreme temperature in 2100

LABOR

Approximately $110 billion in avoided damages from lost labor due to extreme temperatures in 2100



WATER QUALITY

An estimated $2.6-$3.0 billion in avoided damages from poor water quality in 2100[†]

ELECTRICITY

ELECTRICITY DEMAND

An avoided increase in electricity demand of 1.1%-4.0% in 2050[‡]

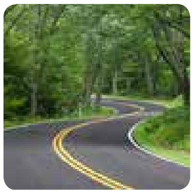
ELECTRICITY SUPPLY

An estimated $10-$34 billion in savings on power system costs in 2050[‡]

INFRASTRUCTURE

BRIDGES

An estimated 720-2,200 fewer bridges made structurally vulnerable in 2100[†]



ROADS

An estimated $4.2-$7.4 billion in avoided adaptation costs in 2100[†]

URBAN DRAINAGE

In 50 U.S. cities, an estimated $50 million-$6.4 billion in avoided adaptation costs in 2100[†]

COASTAL PROPERTY

Approximately $3.1 billion in avoided damages and adaptation costs from sea level rise and storm surge in 2100

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[*] Monetary estimates for this summary are presented for either 2050 or 2100 only, and are undiscounted (2014$). See the Sectors section for the use of discounting throughout this report.

[†] Estimated range of results relies upon climate projections from two climate models showing different patterns of precipitation in the U.S. The IGSM-CAM projects a relatively "wetter" future for most of the U.S. compared to the drier MIROC model (see the CIRA Framework section of this report for more information).

# of Reducing Global GHG Emissions

For detailed information on the results, please refer to the Sectors section of this report.

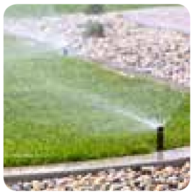
WATER RESOURCES

INLAND FLOODING

Estimates range from approximately $2.8 billion in avoided damages to $38 million in increased damages in 2100†

DROUGHT

An estimated 40%-59% fewer severe and extreme droughts in 2100†



SUPPLY & DEMAND

An estimated $11-$180 billion in avoided damages from water shortages in key economic sectors in 2100†

AGRICULTURE AND FORESTRY

AGRICULTURE

An estimated $6.6-$11 billion in avoided damages to agriculture in 2100

FORESTRY

An estimated $520 million to $1.5 billion in avoided damages to forestry in 2100

ECOSYSTEMS

CORAL REEFS

An avoided loss of approximately 35% of current Hawaiian coral in 2100, with a recreational value of $1.1 billion

SHELLFISH

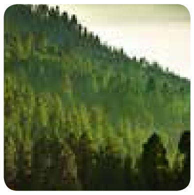
An avoided loss of approximately 34% of the U.S. oyster supply, 37% of scallops, and 29% of clams in 2100

WILDFIRE

An estimated 6.0-7.9 million fewer acres burned by wildfires in 2100†

FRESHWATER FISH

An estimated 230,000-360,000 acres of cold-water fish habitat preserved in 2100†



CARBON STORAGE

An estimated 1.0-26 million fewer tons of carbon stored in vegetation in 2100†§

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† Results reflect the estimated range of benefits from the reduction in demand and system costs resulting from lower temperatures associated with GHG mitigation. The Electricity section in this report presents an analysis that includes the costs to the electric power sector of reducing GHG emissions.

§ See the Carbon Storage section of this report for cumulative results from 2000-2100, which show benefits of GHG mitigation for parts, and in some cases all, of the century.

CIRA Framework

The primary goal of the CIRA project is to estimate the degree to which climate change impacts in the U.S. are avoided or reduced in the 21st century under significant global GHG mitigation. The CIRA framework is designed to assess the physical impacts and economic damages of climate change in the U.S. In this report, the benefits (or disbenefits) of global GHG mitigation are assessed as the difference between the impacts in futures with and without mitigation policy, using multiple models driven by →

1| Design GHG Emissions Scenarios

GHG emissions from human activities, and the resulting climate change impacts and damages, depend on future socioeconomic development (e.g., population growth, economic development, energy sources, and technological change). Emissions scenarios provide scientifically credible starting points for examining questions about an uncertain future and help us visualize alternative futures.[2] They are neither forecasts nor predictions, and the report does not assume that any scenario is more or less likely than another. GHG emissions scenarios are illustrations of how the release of different amounts of climate-altering gases and particles into the atmosphere will produce different climate conditions in the U.S. and around the globe.

To allow for a better understanding of the potential benefits of global-scale GHG mitigation, the CIRA results presented in this report consider two emissions scenarios (see Table 1): a business-as-usual future in which GHG emissions continue to increase unchecked (referred to as the Reference scenario), and a mitigation scenario in which global GHG emissions are substantially reduced (referred to as the Mitigation scenario).[3, 4] These scenarios were developed using the Massachusetts Institute of Technology's Emissions Predictions and Policy Analysis (EPPA) model,[5] the human systems component within the Integrated Global System Model (IGSM). EPPA provides projections of world economic development and emissions, including analysis of proposed emissions control measures. These measures include, for example, limiting GHGs from major emitting sectors, such as electricity production and transportation. EPPA-IGSM, along with a linked climate model, provide a consistent framework to develop GHG emission and climate scenarios for impacts assessment.

Table 1 provides information on the characteristics of each emissions scenario in 2100. Similar to the Representative Concentration Pathways (RCPs) used by the Intergovernmental Panel on Climate Change (IPCC) in its Fifth Assessment Report,[6] the CIRA scenarios are based on different trajectories of GHG emissions and radiative forcing—a metric of the additional heat added to the Earth's climate system caused by anthropogenic and natural emissions.

Figure 1 compares the two primary CIRA scenarios used throughout this report to the RCPs, showing that these scenarios fall within the range of IPCC's latest projections. The CIRA emissions scenarios provide illustrations for analytical comparison and do not represent specific policies. For more information about the design of these scenarios, please refer to Paltsev et al. (2013).[7]

Table 1. Characteristics of the Reference and Mitigation Scenarios in 2100

BUSINESS AS USUAL “REFERENCE”	GLOBAL EMISSIONS REDUCTIONS “MITIGATION”
GHG RADIATIVE FORCING (IPCC/RCP METHOD)	
9.8 W/m^2 (8.6 W/m^2)	3.6 W/m^2 (3.2 W/m^2)
GLOBAL GHG EMISSIONS	
~2.5 x 2005 levels	~0.28 x 2005 levels
ATMOSPHERIC CO$_2$ CONCENTRATION	
826 ppm	462 ppm
ATMOSPHERIC GHG CONCENTRATION (CO$_2$ EQUIVALENT)	
1750 ppm	500 ppm

STEP 1 | DESIGN GHG EMISSIONS SCENARIOS

Two scenarios are used throughout this report:

- Business as usual or the “**Reference**” scenario
- Global emissions reductions or the “**Mitigation**” scenario

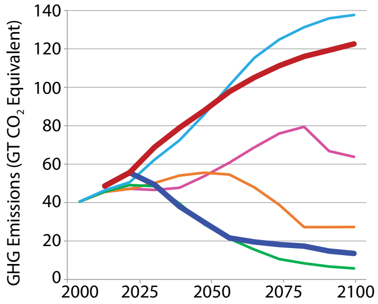
STEP 2 | PROJECT FUTURE CLIMATE

- Temperature
- Precipitation
- Sea level rise
- CO$_2$ concentration
- Sea surface temperature
- Cloud cover
- Wind speed
- Relative humidity
- Solar radiation

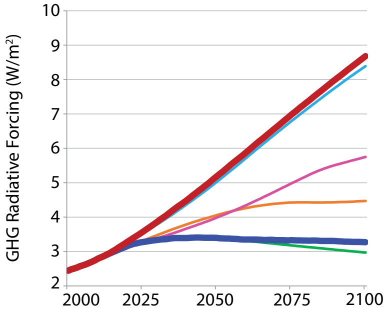
a consistent set of climatic, socioeconomic, and technological scenarios. A three-step approach for assessing benefits includes developing GHG emissions scenarios; simulating future climate under these scenarios; and applying these projections in a series of coordinated impacts analyses encompassing six sectors (health, infrastructure, electricity, water resources, agriculture and forestry, and ecosystems). For more information on the objectives and design of the CIRA framework, please refer to Martinich et al. (2015).[1]

Figure 1. Comparison of CIRA Scenarios to the IPCC RCPs[8]

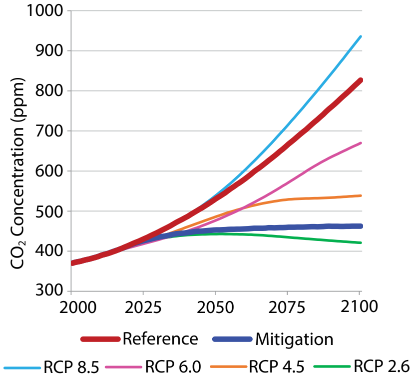
1a. GHG Emissions



1b. Radiative Forcing[9]



1c. CO_2 Concentration



2 | Project Future Climate

To simulate future climate in the U.S., CIRA primarily uses the IGSM-CAM framework, which links the IGSM to the National Center for Atmospheric Research's Community Atmosphere Model (CAM). The IGSM-CAM simulates changes in a large number of climate variables, such as temperature and precipitation, at various temporal scales. Other outputs include: sea level rise, atmospheric CO_2 concentration, cloud cover, wind speed, relative humidity, and solar radiation.[10] The CIRA climate projections are briefly described in the following pages of this report. As described in the Levels of Certainty section, results using other climate models with different patterns of projected precipitation are compared to the IGSM-CAM results for sectoral analyses that are sensitive to changes in precipitation (e.g., drought and flooding). Specifically, results under the IGSM-CAM projections, which estimate a wetter future for most of the contiguous U.S., are complemented with drier projections to investigate the influence on impact estimates. Additional information on the development and characteristics of the CIRA climate projections can be found in Monier et al. (2014).[11]

3 | Analyze Sectoral Impacts

This report analyzes 20 specific climate change impacts in the U.S., which are categorized into six broad sectors (health, infrastructure, electricity, water resources, agriculture and forestry, and ecosystems). The impacts were selected based on the following criteria: sufficient understanding of how climate change affects the sector; the existence of data to support the methodologies; availability of modeling applications that could be applied in the CIRA framework; and the economic, iconic, or cultural significance of impacts and damages in the sector to the U.S. It is anticipated that the coverage of sectoral impacts in the CIRA project will expand in future work.

To quantify climate change impacts in each sector, process-based or statistical models were applied using the socioeconomic and climate scenarios described above. This approach, which ensures that each model is driven by the same inputs, enables consistent comparison of impacts across sectors and in-depth analysis across regions and time. Many of the analyses explore the potential for adaptation to reduce risks and quantify the costs associated with adaptive actions (see the Sectors section of this report and Section D of the Technical Appendix for more information).[12] Lastly, the CIRA analyses investigate key sources of variability in projecting future climate, as further discussed in the Levels of Certainty section.

STEP 3 | ANALYZE SECTORAL IMPACTS

HEALTH
- Air quality
- Extreme temperature
- Labor
- Water quality

INFRASTRUCTURE
- Bridges
- Roads
- Urban drainage
- Coastal property

ELECTRICITY
- Electricity demand
- Electricity supply

WATER RESOURCES
- Inland flooding
- Drought
- Water supply and demand

AGRICULTURE AND FORESTRY
- Crop and forest yields
- Market impacts

ECOSYSTEMS
- Coral reefs
- Shellfish
- Freshwater fish
- Wildfire
- Carbon storage

CIRA FRAMEWORK

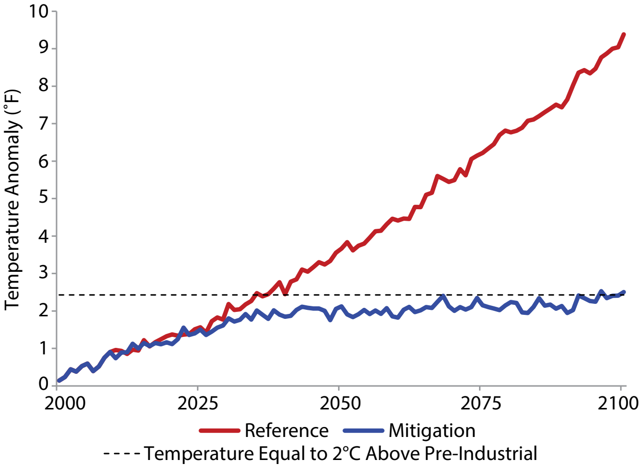
Temperature Projections

Global Temperature Change

Global mean temperature under the CIRA Reference scenario is projected to increase by over 9°F by 2100 (Figure 1). This estimated increase is consistent with the USGCRP Third National Climate Assessment, which projects a range of 5-11°F by 2100.[13,14] To help illustrate the magnitude of such a change in global mean temperature, the last ice age, which covered the northern contiguous U.S. with ice sheets, was approximately 9°F cooler than today. While some areas will experience greater increases than others, Figure 1 presents the average change that is projected to occur across the globe under the Reference and Mitigation scenarios. As shown, temperatures in the Mitigation scenario eventually stabilize, though due to the inertia of the climate system, stabilization is not reached until several decades after the peak in radiative forcing. The Reference scenario continues to warm, reaching a temperature increase of almost five times that of the Mitigation scenario by the end of the century. This demonstrates that significant GHG mitigation efforts can stabilize temperatures and avoid an additional 7°F of warming this century, but due to climate system inertia, benefits may not be apparent for several decades.

Figure 1. Change in Global Mean Temperature with and without Global GHG Mitigation

Time series of global annual mean surface air temperature relative to present-day (1980-2009 mean) for IGSM-CAM under the Reference and Mitigation scenarios with a climate sensitivity (CS)[15] of 3°C.



Limiting Future Warming to 2°C

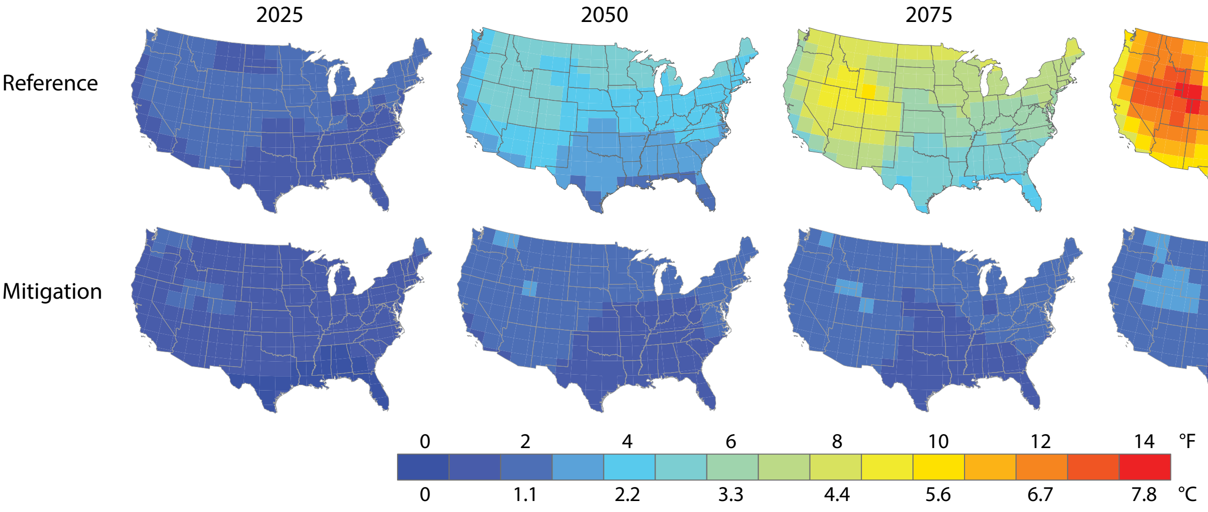
Limiting the future increase in global average surface temperature to below 2°C (3.6°F) above preindustrial levels is a commonly regarded goal for avoiding dangerous climate change impacts.[16] Global temperatures, however, have already warmed 0.85°C (1.5°F) from preindustrial times.[17,18] The level of global GHG mitigation achieved under the CIRA Mitigation scenario is consistent with the amount required to meet the 2°C target (Figure 1),[19] and therefore the estimates presented in this report describing the potential benefits to the U.S. of global GHG mitigation are a reasonable approximation of the benefits that would result from meeting this goal.

Temperature Change in the U.S.

Under the Reference scenario, the largest increases in average temperature across the contiguous U.S. by 2100 are projected to occur in the Mountain West—up to a 14°F increase from present-day average temperature (Figure 2). The northern regions are also likely to see larger temperature increases than the global average (up to 12°F, compared to a global average of 9.3°F), while the Southeast is projected to experience a relatively lower level of overall warming (but comparable to the global average increase). Under the Mitigation scenario, temperature increases across the country are far lower compared to the Reference, with no regions experiencing increases of more than 4°F.

Figure 2. Distribution of Temperature Change with and without Global GHG Mitigation

Change in annual mean surface air temperature relative to present-day (1980-2009 average) for IGSM-CAM under the Reference and Mitigation scenarios (CS 3°C).



Seasonal and Extreme Temperatures

Just as presenting global average temperature changes masks geographic patterns of variability, presenting annual average temperature changes conceals seasonal patterns of change. Some seasons are expected to warm faster than others, and the impacts of warming will also vary by season. For example, in some regions, greater levels of warming may occur in the winter, but warming in summer will matter most for changes in the frequency and intensity of heat waves. Figure 3 provides an illustrative example of the changes in average summertime temperature that select states may experience over time with and without global GHG mitigation. Under the Reference scenario, summertime temperatures in some northern states are projected to feel more like the present-day summertime conditions in southern states. However, under the Mitigation scenario, states are projected to experience substantially smaller changes.

In addition to increasing average summertime temperatures, climate change is projected to result in an increase in extreme temperatures across most of the contiguous U.S. In the Mountain West, for example, the hottest days of the year are estimated to be over 14°F hotter than today under the Reference scenario by the end of the century (Figure 4). Many parts of the Midwest and Northeast are projected to experience increases in extreme temperatures ranging from 7-10°F, an amount similar to the increase in average summertime temperatures. These changes are projected to be far less severe under the Mitigation scenario, however, with no regions experiencing increases of more than 4°F.

Figure 3. Change in Summertime Temperatures for Select States with and without Global GHG Mitigation

The map compares mean summertime (June, July, and August) temperature in South Dakota, Illinois, and Maryland in 2050 and 2100 under the Reference and Mitigation scenarios to states with similar present-day temperatures. For example, the projected mean summertime temperature in Illinois in 2100 under the Reference scenario (83°F) is projected to be analogous to the mean summertime temperature in Louisiana from 1980-2009 (81°F). In other words, without global GHG mitigation, Illinois summers by 2100 are projected to "feel like" present-day Louisiana summers. The maps are not perfect representations of projected climate, as other factors such as humidity are not included, but they do provide a way of visualizing the magnitude of possible changes in the summertime conditions of the future.

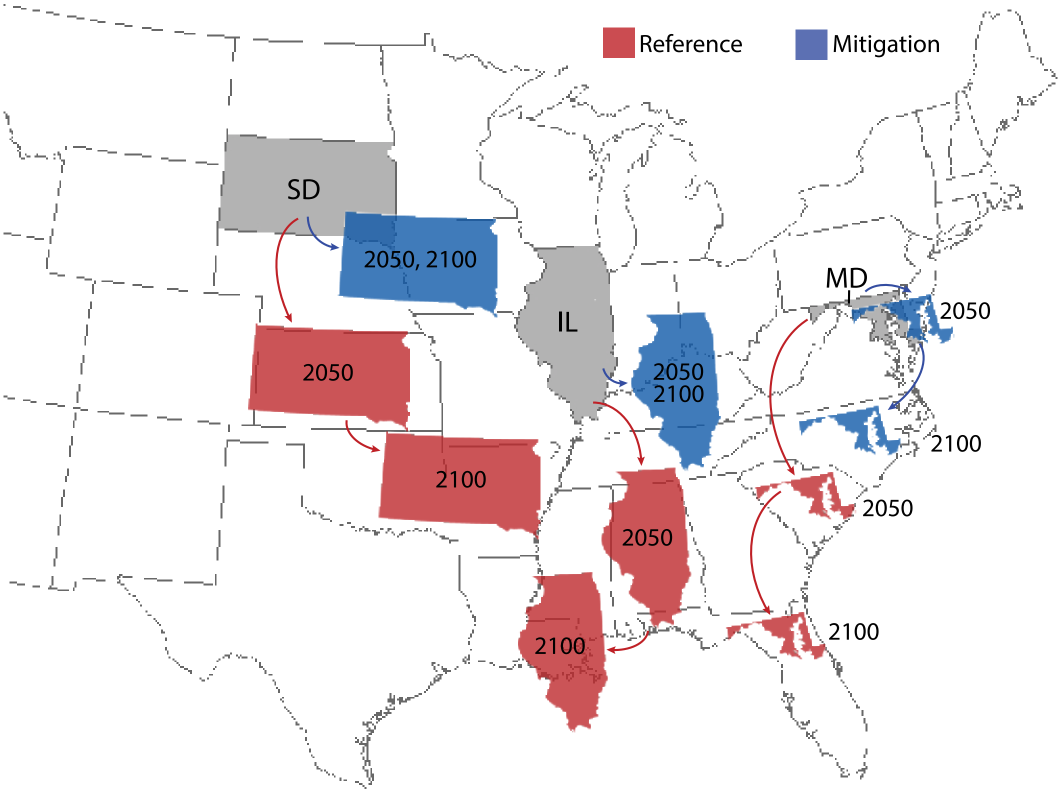
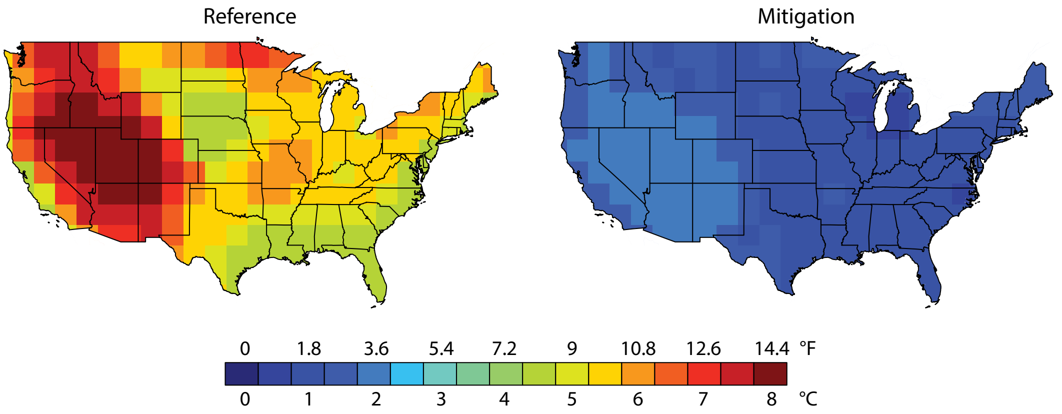


Figure 4. Change in Magnitude of Extreme Heat Events with and without Global GHG Mitigation

Change in the extreme heat index (T99)—the temperature of the hottest four days, or 99th percentile, of the year—simulated by the IGSM-CAM for 2100 (average 2085-2115) relative to the baseline (average 1981-2010) (CS 3°C).[20]



Precipitation Projections

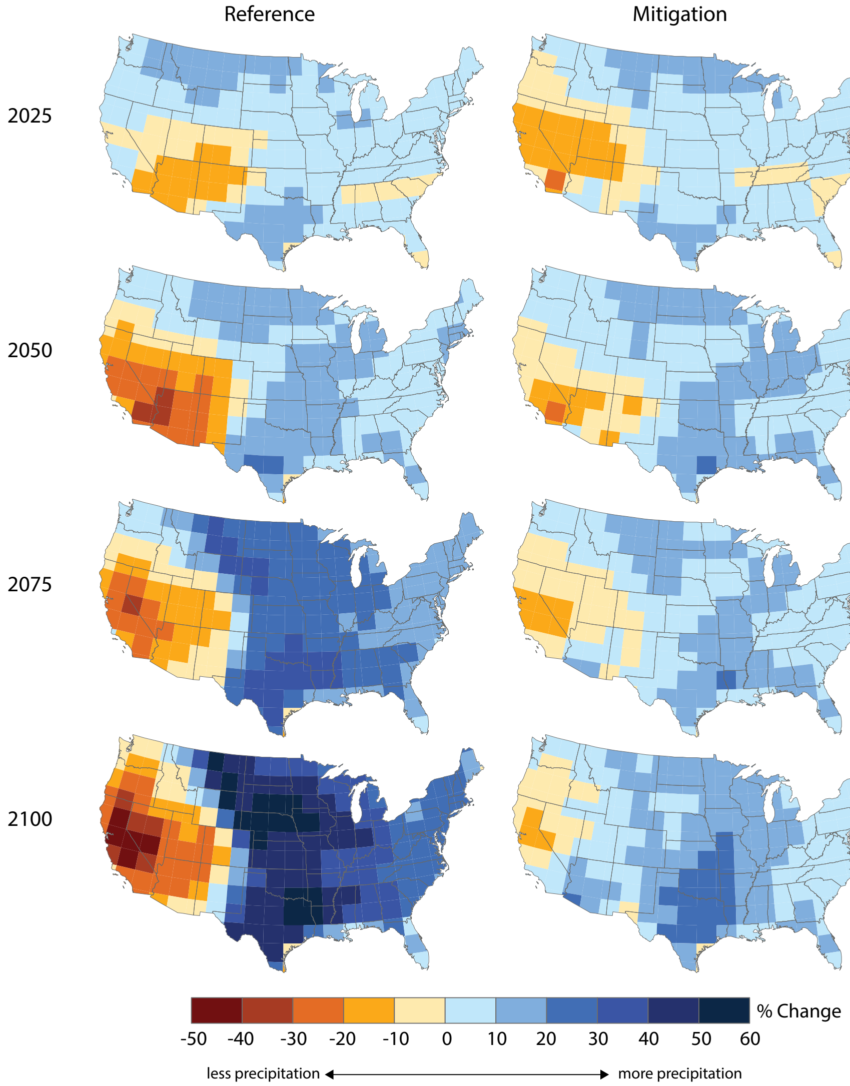
Precipitation in the U.S.

The IGSM-CAM projects future changes in annual mean precipitation over the course of the 21st century under the Reference and Mitigation scenarios (Figure 1). Under the CIRA Reference scenario, the model estimates increasing precipitation over much of the U.S., especially over the Great Plains. However, the western U.S. is estimated to experience a decrease in precipitation compared to present day. Under the Mitigation scenario, a similar but less intense pattern of increasing precipitation is projected over much of the country, particularly in the central states.

As projections of future precipitation vary across individual climate models, the CIRA analyses use outputs from additional climate models (see the Levels of Certainty section of this report). Compared to multi-model ensemble projections presented in the IPCC and USGCRP, the CIRA projections exhibit some regional differences in the pattern of projected precipitation. A comparison between the CIRA climate projections and those presented in these assessment reports can be found in Section E of the Technical Appendix.

Figure 1. Percentage Change in Annual Mean Precipitation with and without Global GHG Mitigation

Percentage change in annual mean precipitation from the historical period (1980-2009) for IGSM-CAM under the Reference and Mitigation scenarios (CS 3°C).

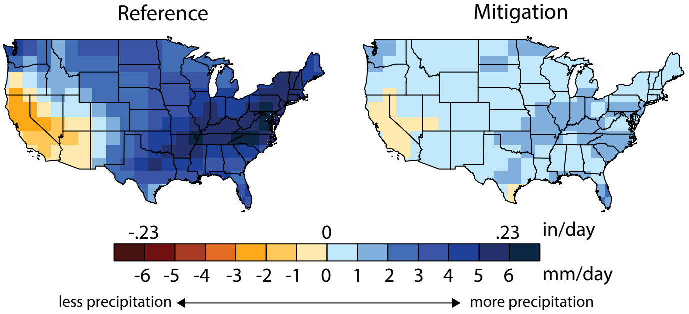


Extreme Precipitation

Figure 2 shows the change in the intensity of extreme precipitation events from present day to 2100. Blue areas on this map indicate that the future's heaviest precipitation events will be more intense compared to today. Under the Reference, the IGSM-CAM shows a general increase in the intensity of extreme precipitation events, except over California. The increase is particularly strong over the Northeast, Midwest, and Southeast. Global GHG mitigation is likely to greatly reduce the increase in intensity of extreme precipitation events, as shown in the right panel of Figure 2.

Figure 2. Change in the Intensity of Extreme Precipitation with and without Global GHG Mitigation

Change in the extreme precipitation index (P99) simulated by IGSM-CAM for the 2085-2115 period relative to the 1981-2010 period (CS 3°C). The P99 index reflects the precipitation of the four most rainy days of the year, or the 99th percentile.[21]



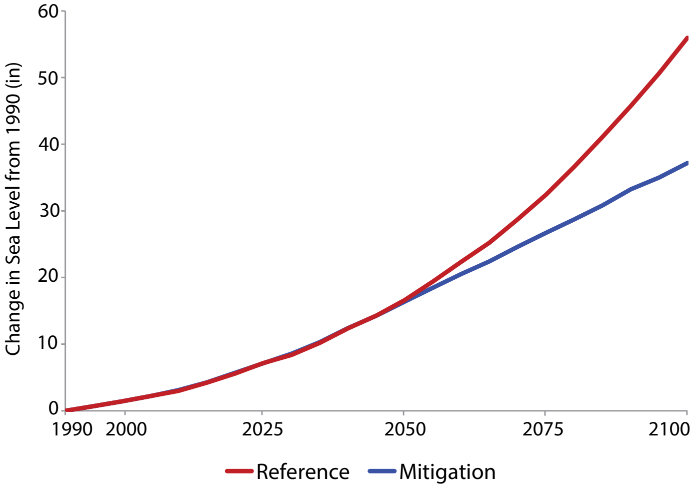
Sea Level Rise Projections

Global Sea Level Rise

Figure 1 shows the change in global mean sea level from present day to 2100 under the Reference and Mitigation scenarios. Global mean sea levels are projected to rise about 56 inches by 2100 under the Reference and about 37 inches under the Mitigation scenario. These results fall within the range for risk planning presented in the Third National Climate Assessment of 8-79 inches by 2100, with the Reference scenario's rate being slightly larger than the Assessment's likely range of 12-48 inches.[22, 23] As shown in Figure 1, global sea level rise is similar across the CIRA scenarios through mid-century, primarily due to inertia in the global climate system and lasting effects from past GHG emissions. As a result, it is not until the second half of the century that global GHG mitigation results in a reduction in sea level rise compared to the Reference.

The projections for global sea level rise account for dynamic ice-sheet melting by estimating the rapid response of sea levels to atmospheric temperature change.[24] These adjustments incorporate estimates of ice-sheet melt from the empirical model of Vermeer and Rahmstorf (2009),[25, 26] using the decadal trajectory of global mean surface air temperature results from the IGSM as inputs.[27]

Figure 1. Change in Global Mean Sea Level with and without Global GHG Mitigation

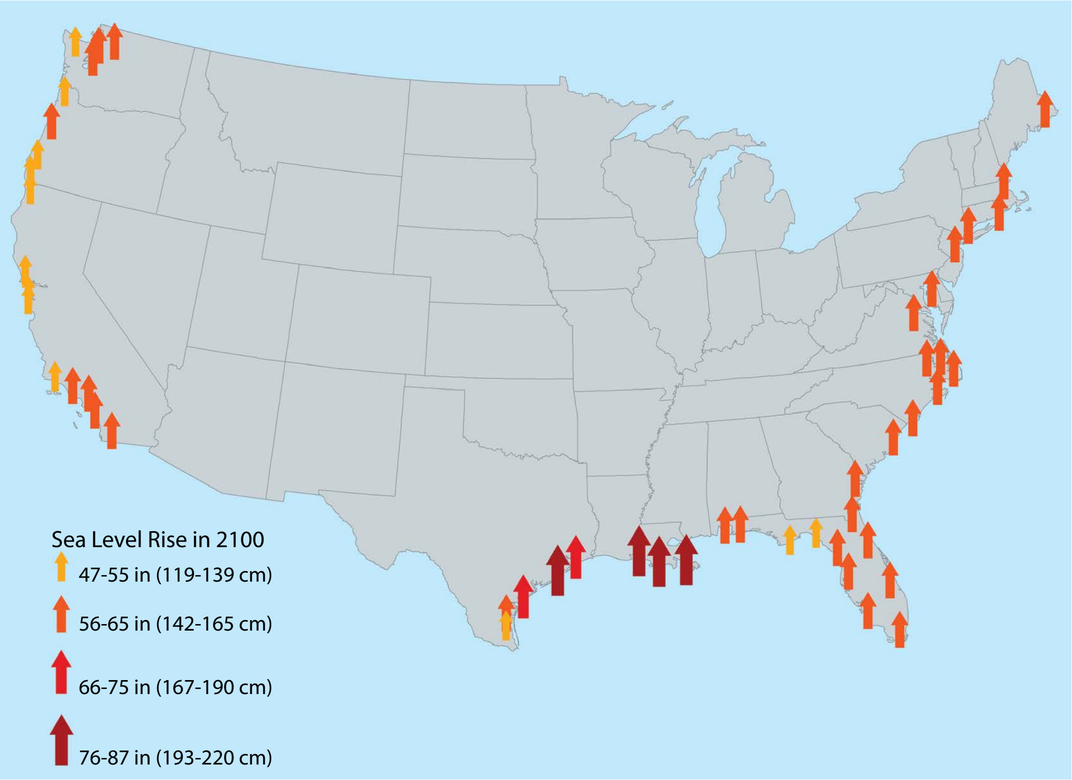


Sea Level Rise in the U.S.

Figure 2 shows projected relative sea level rise under the Reference scenario for select areas along the U.S. coast in 2100. For each coastal area, global rates of sea level change under the two scenarios were adjusted to account for vertical land movement (e.g., subsidence or uplift) using tide gauge data.[28] Areas located along the Gulf of Mexico and Atlantic Coast are projected to experience greater sea level rise, due to compounding effects of land subsidence, while areas along the West Coast are estimated to experience relatively lower levels of rise.

Figure 2. Projected Sea Level Rise along the Contiguous U.S. Coastline in 2100

Map shows projected relative (to land) sea level rise under the Reference scenario for select coastal counties in the contiguous U.S. Projections are based on global mean sea level rise in 2100 (56 inches), adjusted for local subsidence and uplift.[29]



Levels of Certainty

The CIRA modeling project was designed to investigate the relative importance of four key sources of uncertainty inherent to projecting future climate:

Future GHG emissions: Future emissions will be driven by population growth, economic growth, technology advancements, and decisions regarding climate and energy policy. Sensitivity analyses explore the uncertainty associated with varying levels of future GHG emissions under different policy scenarios.

Climate sensitivity: Future climate change depends on the response of the global climate system to rising GHG concentrations (i.e., how much temperatures will rise in response to a given increase in atmospheric CO_2). This response is complicated by a series of feedbacks within Earth's climate system that act to amplify or diminish an initial change.[30] Climate sensitivity is typically reported as the change in global mean temperature resulting from a doubling in atmospheric CO_2 concentration.

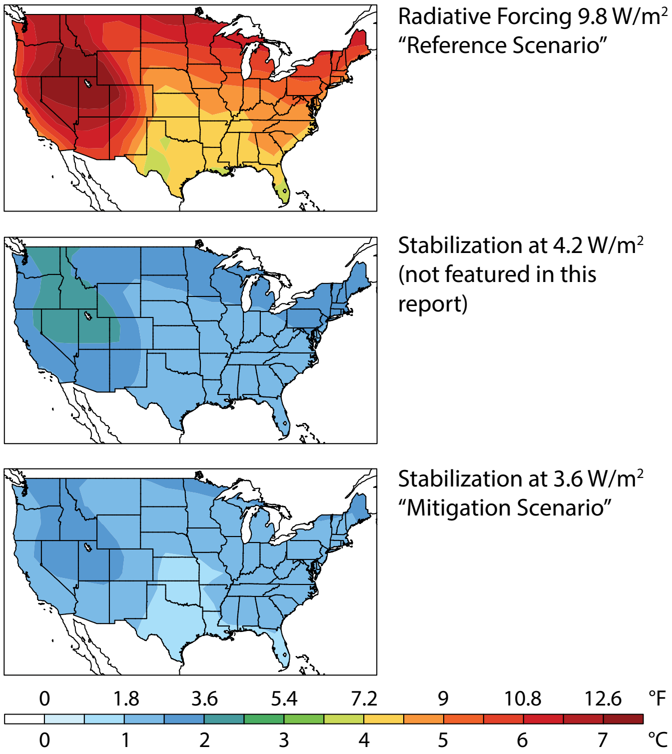
Natural variability: Natural, small- to medium-scale variations within Earth's climate system, such as El Niño events and other recurring patterns of ocean-atmosphere interactions, can drive increases or →

Emissions Scenarios

The CIRA framework includes scenarios with different levels of GHG emissions: a business-as-usual scenario with unconstrained emissions ("Reference") and a total radiative forcing of 9.8 W/m^2 by 2100 (8.6 W/m^2 using the IPCC method for calculating radiative forcing); a stabilization scenario reflecting global-scale reductions in GHG emissions, with a total radiative forcing of 4.2 W/m^2 by 2100 (3.8 W/m^2 using IPCC method; this scenario is not featured in this report); and a more stringent stabilization scenario with greater emissions reductions ("Mitigation") and a total radiative forcing of 3.6 W/m^2 by 2100 (3.2 W/m^2 using IPCC method).[34] Results using the Reference and Mitigation scenarios are the focus of this report.

Figure 1. Temperature Change in 2100 Relative to Present Day for the CIRA Emissions Scenarios

Changes in surface air temperature in 2100 (2091-2110 mean) relative to present-day (1991-2010 mean).[35]



Radiative Forcing 9.8 W/m^2
"Reference Scenario"

Stabilization at 4.2 W/m^2
(not featured in this report)

Stabilization at 3.6 W/m^2
"Mitigation Scenario"

Climate Sensitivity

The four climate sensitivity values considered are 2, 3, 4.5, and 6°C, which represent, respectively, the lower bound (CS 2°C), best estimate (CS 3°C), and upper bound (CS 4.5°C) of likely climate sensitivity based on the IPCC Fourth Assessment Report (AR4),[36] and a low-probability/high-risk climate sensitivity (CS 6°C).[37] Results using a climate sensitivity of 3°C are the focus of this report.

Figure 2. Influence of Climate Sensitivity on Global Temperature Change Relative to Present Day

Temperature change relative to the historic baseline (mean 1980-2009) under the Reference and Mitigation scenarios. The bold lines represent the results using a climate sensitivity of 3°C, and the shaded areas represent the range of temperature anomaly outcomes when using climate sensitivities of 2°C and 6°C.

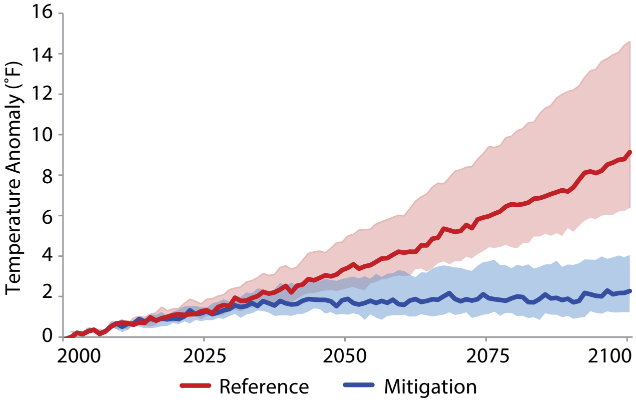
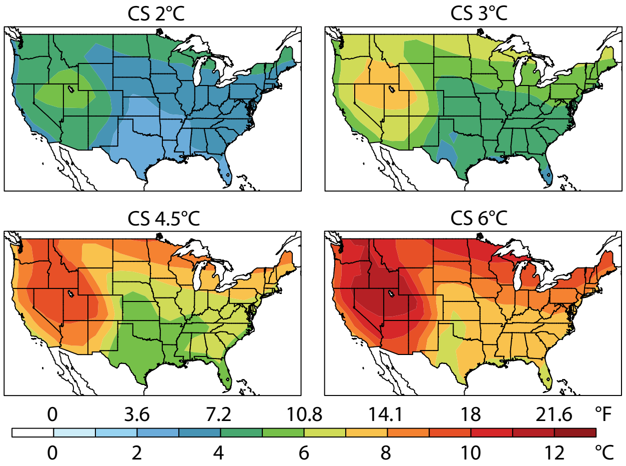


Figure 3. Future Temperature Change under Different Climate Sensitivities

Increases in surface air temperature in 2100 (2091-2110 mean) under the Reference scenario relative to present-day (1991-2010 mean).[38]



decreases in global or regional temperatures, as well as affect precipitation and drought patterns around the world. These types of natural variability cause uncertainty in temperature and precipitation patterns over timescales ranging from months up to a decade or more, but have a smaller effect on Earth's climate system over longer periods of time.[31]

Climate model: Different types of global-scale physical and statistical models are used to study aspects of past climate and develop projections of future change. The climate is very complex and is influenced by many uncertain factors; as a result, each model is different and produces different results. These complex models provide useful information both individually, by allowing the exploration of potential futures, and collectively, by providing insight on the level of agreement across models.

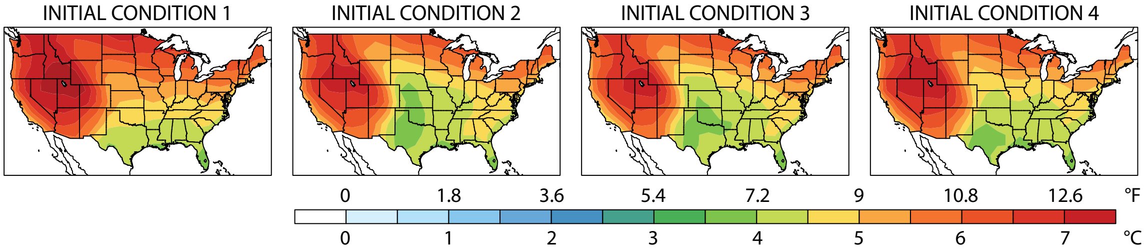
The CIRA uncertainty framework, described in detail in Monier et al. (2014),[32] explores these four major sources of uncertainty, including the influence that each could have on future temperature or precipitation in the U.S. While the effects of each source of uncertainty are not described for each sectoral impact discussed in this report, some of the impacts described in the Sectors section explore the potential influence of these factors. Maps presented in this section are adapted from Monier et al. (2014).[33]

Natural Variability

For each emissions scenario and climate sensitivity combination, the IGSM-CAM was simulated five times with slightly different initial conditions ("initializations") to account for uncertainty due to natural variability. Some sectors in the report use the average result of the five initializations.

Figure 4. The Effect of Natural Variability on Future Climate Projections

Increases in surface air temperature in 2100 (2091-2110 mean) relative to present-day (1991-2010 mean) for each of the IGSM-CAM initializations.[39]



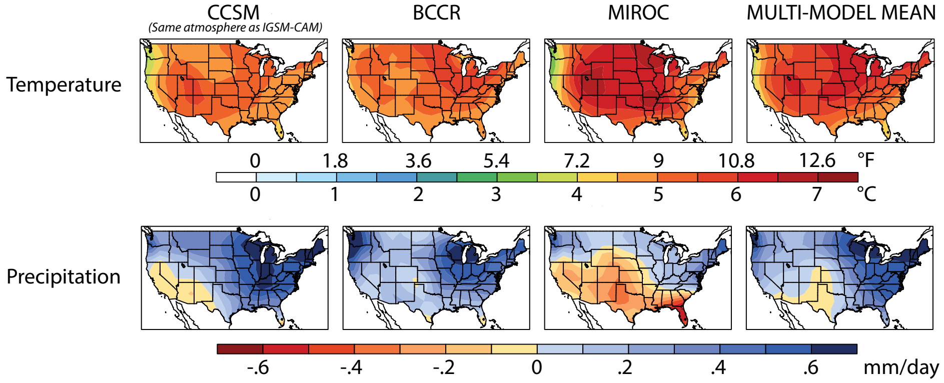
Climate Model

The results presented in this report rely primarily upon climate projections from the IGSM-CAM. To analyze the implications of a broader set of climate model outputs, the CIRA framework uses a pattern scaling method in the IGSM[40] for three additional climate models, plus a multi-model ensemble mean from the IPCC AR4 archive. As shown in Figure 5, there is better agreement across climate models with regard to temperature projections, and higher variability with regard to precipitation projections.[41]

- The NCAR Community Climate System Model version 3 (CCSM3.0) was chosen to compare with the IGSM- CAM model. Both have the same atmospheric and land components and similar biases over land.
- Bjerknes Centre for Climate Research Bergen Climate Model version 2.0 (BBCR_BCM2.0) was chosen because this model projects the largest increases in precipitation over the contiguous U.S.
- Model for Interdisciplinary Research on Climate version 3.2 medium resolution (MIROC3.2_medres) was chosen because this model projects decreases in precipitation over much of the contiguous U.S. Results using this "drier" pattern are shown in several sections of this report to provide comparison to the "wetter" IGSM-CAM simulations, which generally show increases in precipitation for much of the country (excluding the West). This comparison helps to bound uncertainty in future changes in precipitation for the contiguous U.S.

Figure 5. Climate Model Uncertainty for Future Projections

Changes in temperature and precipitation in 2100 (2091-2110 mean) relative to present-day (1991-2010 mean) for different climate models. Values assume a climate sensitivity of 3°C under the Reference scenario.



Future Climate Change Across Uncertainty Sources

Investigation of the relative contribution of the four sources of uncertainty described in this section reveals that temperature change is most influenced by decisions regarding whether to reduce GHG emissions and the value of climate sensitivity used (GHG emissions scenario being the dominant contributor). The contributions from different climate models and natural variability for temperature change are small in comparison. It is worth noting that the GHG emissions scenario is the only source of uncertainty that society has control over. 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.[42]

Boundaries of Analysis

The design of the CIRA project allows the results to be interpreted as the potential benefits (avoided impacts) to many economically important sectors of the U.S. due to global-scale actions to mitigate GHG emissions. The analytical approach offers a number of advantages, including consistency in the use of socio-economic and climate change scenarios across a wide range of sectoral impact and damage models, and exploration of the changes in impacts and damages across key sources of uncertainty.

As with any study, there are some analytical boundaries of the CIRA project and its underlying analyses that are important to consider, several of which are described below.[43] Future work to address these limitations will strengthen the estimates presented in this report, including the broader use of ranges and confidence intervals. Limitations specific to the individual sectoral analyses are described in the Sectors section of this report, as well as in the scientific literature underlying the analyses.

Emission and Climate Scenarios

With the goal of presenting a consistent and straightforward set of climate change impact analyses across sectors, this report primarily presents results for the Reference and Mitigation scenarios under a single simulation (initialization) of the IGSM-CAM climate model and assumes a climate sensitivity of 3°C. As described in the Levels of Certainty section, a large number of emissions and climate scenarios were developed under the CIRA project, reflecting various combinations of emissions scenarios, climate models, climate sensitivity, and climate model initializations. However, only some of these emissions and climate scenarios have been simulated across all sectoral analyses, primarily due to the level of effort necessary to run each scenario through the large number of sectoral models of the CIRA project. Analyzing results under the full set of scenarios would further characterize the range and potential likelihood of future risks.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Coverage of Sectors and Impacts

The analyses presented in this report cover a broad range of potential climate change impacts in the U.S., but there are many important impacts that have not yet been modeled in CIRA. Examples of these impacts include changes in vector-borne disease, morbidity from poor air quality, impacts on specialty crops and livestock, and a large number of effects on ecosystems and species. Without information on these impacts, this report provides only partial insight into the potential risks of climate change, and therefore does not account for all potential benefits of mitigation.

In addition, it is important to note that impacts are only partially valued economically in some sectors. For example, the Wildfire section presents estimated response and fuel management costs, but not other damages (e.g., health effects from decreased air quality, and property damages). A more complete valuation approach would likely increase the damages described in this report.

Finally, this 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.[44] 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 and the potential for GHG mitigation to reduce or avoid these changes.

Variability Across Climate Models

The choice of climate model in an impact analysis can influence patterns of future climate change. Within a number of the CIRA analyses, this uncertainty was evaluated through the use of "pattern scaling," a method by which the average change produced by running a climate model is combined with the specific geographic pattern of change calculated from a different model in order to approximate the result that would be produced by the second model. In this report, analyses that are sensitive to changes in precipitation are presented using both the IGSM-CAM (relatively wetter for the contiguous U.S.) and MIROC (relatively drier) climate models. However, not all sectoral impact models used pattern scaling in addition to the IGSM-CAM simulations, particularly for those impacts primarily driven by temperature, where there is generally more agreement across climate models. Finally, we note the limitation that pattern scaling is not a perfect representation of alternate models.[45]

Sectoral Impacts Modeling

With the exception of the electricity demand and supply sections of this report, the impact estimates presented were developed using a single sectoral impact model. While these models are complex analytical tools, the structure of the model, and how it may compare to the design of similar applications, can create important uncertainties that affect the estimation of impacts.[46] The use of additional models for each sector would help improve the understanding of potential impacts in the future. The results presented in this report were developed with little or no interactions among the impact sectors. As a result, the estimated impacts may omit important and potentially unforeseen effects. For example, the wildfire projections presented in this report will likely generate meaningful increases in air pollution, a potentially important linkage for the air quality analysis. Similarly, there are numerous connections among the agriculture, water, and electricity sectors that affect the impacts estimates in each.[47] 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 CIRA sectoral analyses. Improved connectivity between CIRA sectoral models will aid in gaining a more complete understanding of climate change impacts across sectors in the U.S.

Variability in Societal Characteristics

The impacts of climate change will not affect Americans equally. In addition to regional differences in impacts, socioeconomic factors (e.g., income, education) affect adaptive capacity and can make some communities more vulnerable to impacts. These issues are explored in the Coastal Property section, but the rest of the sectors do not analyze impacts across different levels of social vulnerability.

Feedbacks

The CIRA project uses a linear path from changes in socioeconomics and the climate system to impacts (with consistent inputs across multiple models). The socioeconomic scenarios that drive the CIRA modeling analyses do not incorporate potential feedbacks from climate change impacts to the climate system (e.g., GHG emissions from forest fires) and from sectoral damages to the economy (e.g., significant expenditures on "climate defensive" adaptation would likely reduce available financial capital to the economy for productive uses, or increase the cost of financing capital expenditures).

Geographic Coverage

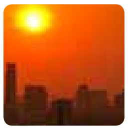
The report does not examine impacts and damages occurring outside of U.S. borders. Aside from their own relevance for policy-making, these impacts could affect the U.S. through, for example, changes in world food production, migration, and concerns for national security.

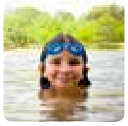
In addition, the primary geographic focus of this report is on the contiguous U.S., with most of the sectoral analyses excluding Hawaii, Alaska, and the U.S. territories. This omission is particularly important given the unique climate change vulnerabilities of these high-latitude and/or island locales. Finally, several sectoral analyses assess impacts in a limited set of major U.S. cities, and incorporation of additional locales would gain a more comprehensive understanding of likely impacts.

Use of Point Estimates

Results in this report are primarily presented as point estimates. For some sectors, ranges are provided based on the design of the underlying modeling analysis (i.e., the approach yields confidence intervals) or because of the scenarios used in that sector. Regarding the latter, the use of wetter and drier climate projections for sectors sensitive to changes in precipitation provides ranges of estimates bounding this uncertainty source. The uncertainties and limitations described in this section, along with others detailed throughout this report and in the underlying CIRA literature, signify that the estimates described in this report should not be interpreted as definitive predictions of future impacts at a particular place and time. The further exploration of these uncertainties, including the development of ranges for all impact projections, will further strengthen the CIRA results.

Sectors





ABOUT THE RESULTS

Unless otherwise noted, results presented in this section were developed using the following:

Emissions scenarios: The results are presented for the CIRA Reference and Mitigation scenarios.

Climate models: The results primarily rely upon climate projections from the IGSM-CAM. For sectors sensitive to changes in precipitation, results are also presented for the drier MIROC climate model.

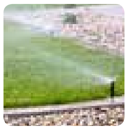
Climate sensitivity: The results assume a climate sensitivity of 3.0°C.

Accounting for inflation: The results are presented in constant 2014 dollars.[1]

Discounting: To estimate present value, annual time series of costs are discounted at a 3% annual rate, with a base year of 2015.[2] Annual estimates (i.e., costs in a given year) are not discounted.

Reporting of estimates: For consistency, results are reported with two significant figures.

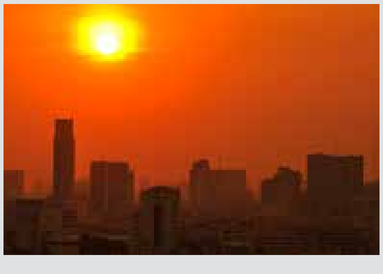

AREA
CLOSED
FLOODING



Health

SUBSECTORS

Air Quality



Extreme Temperature

Weather and climate play a significant role in our health and well-being. As a society, we have structured our day-to-day behaviors and activities around historical and current climate conditions. Increasing GHGs in the atmosphere are changing the climate faster than any time in recent history.[3] As a result, the conditions we are accustomed to and the environment in which we live will change in ways that affect human health. In addition to creating new problems, changes in the climate can exacerbate existing human health stressors, such as air pollution and disease. Many of the adverse effects brought on by climate change may be compounded by how our society is changing, including population growth, an aging population, and migration patterns that are concentrating development in urban and coastal areas.

HOW ARE PEOPLE VULNERABLE TO CLIMATE CHANGE?

Climate change is projected to harm human health in a variety of ways through increases in extreme temperature, increases in extreme weather events, decreases in air quality, and other factors.[4] Extreme heat events can cause illnesses and death due to heat stroke, cardiovascular disease, respiratory disease, and other conditions. Increased ground-level ozone is associated with a variety of health problems, including reduced lung function, increased frequency of asthma attacks, and even premature mortality.[5] Higher temperatures and changes in the timing, intensity, and duration of precipitation affect water quality, with impacts on the surface water we use. There are a variety of other impacts driven by climate change that are expected to pose significant health hazards, including increases in wildfire activity (see the Wildfire section of this report).[6]

WHAT DOES CIRA COVER?

CIRA analyzes the potential impacts of climate change on human health by focusing on air quality, extreme temperature mortality, labor, and water quality. Analyses of many other important health effects are not included in CIRA; these include, for example, impacts from increased extreme weather events (e.g., injury or death from changes in tropical storms), air pollution from wildfires, and vector-borne disease (e.g., Lyme disease and West Nile virus).

Labor

Water Quality

Air Quality

KEY FINDINGS

1. Unmitigated climate change is projected to worsen air quality across large regions of the U.S., especially in eastern, midwestern, and southern states. Impacts on ozone and fine particulate matter pollution are projected to be especially significant for densely-populated areas. The analysis holds emissions of traditional air pollutants constant at current levels to isolate the climate change related impact on air quality.

2. Global GHG mitigation is projected to reduce the impact of climate change on air quality and the corresponding adverse health effects related to air pollution. Mitigation is estimated to result in significant public health benefits in the U.S., such as avoiding 13,000 premature deaths in 2050 and 57,000 premature deaths in 2100. Economic benefits to the U.S. of avoided premature deaths are estimated at $160 billion in 2050, and $930 billion in 2100.

Climate Change and Air Quality Health Effects

Changes in climate are projected to affect air quality across the U.S. In already polluted areas, warmer temperatures are anticipated to increase ground-level ozone (O_3), a component of smog, and increase the number of days with poor air quality.[7] Changes in weather patterns may also affect concentrations of fine particulate matter ($PM_{2.5}$), a mixture of particles smaller than 2.5 micrograms per cubic meter ($\mu g\ m^{-3}$), emitted from power plants, vehicles, and wildfires. Inhaling ozone and fine particulate matter can lead to a broad range of adverse health effects, including premature mortality and aggravation of cardiovascular and respiratory disease.[8, 9]

Risks of Inaction

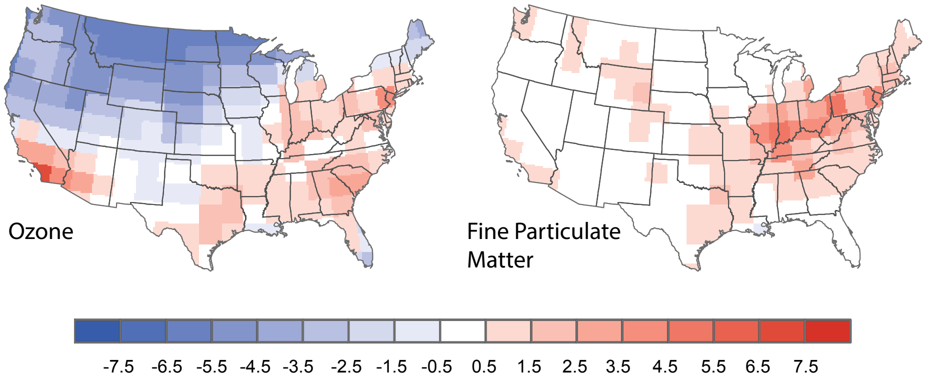
Without global GHG mitigation, climate change is projected to have a substantial effect on air quality across the contiguous U.S., with important regional differences (Figure 1). Ozone concentrations are projected to increase in the Reference scenario in more densely-populated regions, such as the East, Midwest, and South, while some less densely-populated areas experience decreases in ozone concentrations.[10] Although the national annual average ozone concentration is projected to decrease slightly (1.3 ppb +/- 0.2) by 2100, human exposure to ozone is projected to increase, driven by increasing concentrations in densely-populated areas. Climate-driven ozone increases are especially substantial during summer months. By 2100, the U.S.-average 8-hour-maximum ozone concentration in June-August is projected to increase 4.7 ppb (95% confidence interval ± 0.5).[11]

Unmitigated climate change is projected to exacerbate fine particulate matter pollution, especially in the Midwest and East. The annual U.S.-average $PM_{2.5}$ concentrations are projected to increase by 0.3 $\mu g\ m^{-3}$ (± 0.1) in 2050 and 0.7 $\mu g\ m^{-3}$ (± 0.1) in 2100 in the Reference scenario.[12]

Projections that climate change will lead to increased ozone in polluted regions are consistent with the assessment literature. There is less agreement regarding the magnitude of climate change effects on particulate matter, with the exception of increasing wildfire activity on particulates.[13] The results presented in this report add to this emerging area of research.

Figure 1. Projected Impacts of Unmitigated Climate Change on Air Pollution in the U.S.

Estimated change in annual-average ground-level hourly ozone (O_3, ppb) and fine particulate matter ($PM_{2.5}$, $\mu g\ m^{-3}$) from 2000 to 2100 under the Reference scenario.



Reducing Impacts through GHG Mitigation

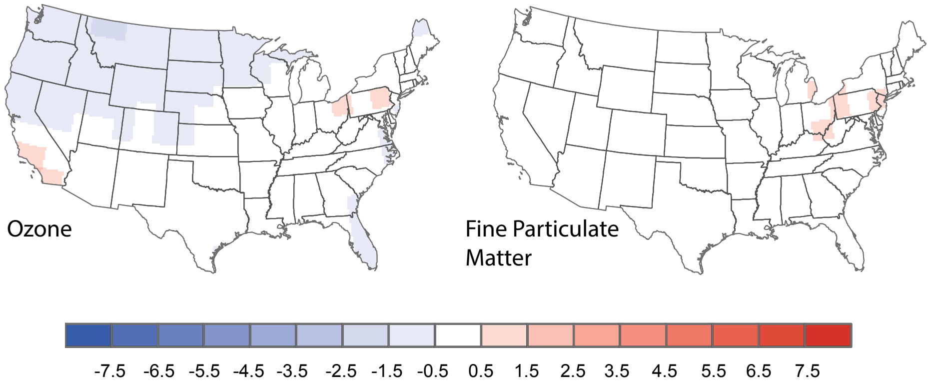
Global GHG mitigation is projected to avoid significant adverse impacts to air quality that would occur under the Reference scenario in densely-populated areas. Figure 2 shows air quality changes in the Mitigation scenario, which are much smaller than those under the Reference (Figure 1). Despite smaller reductions in ozone in some less densely-populated areas, global GHG mitigation is projected to reduce the increase in the annual-average, 8-hour-maximum, population-weighted ozone concentration by approximately 2.6 ppb (95% confidence interval ± 0.3) that would occur in the Reference in the U.S.

Global GHG mitigation is also projected to lessen the adverse effects of climate change on fine particulate matter pollution in the U.S. In 2100, the increase in the annual-average population-weighted PM$_{2.5}$ concentration under the Reference is reduced by approximately 1.2 µg m^{-3} (± 0.1) under the Mitigation scenario.

Reducing the impacts of climate change on air quality through global GHG mitigation is projected to result in significant health benefits across the U.S. For example, the Mitigation scenario is estimated to prevent an estimated 13,000 premature deaths in 2050 (95% confidence interval of 4,800-22,000) and 57,000 premature deaths in 2100 (95% confidence interval of 21,000-95,000) compared to the Reference.[14] Economic benefits to the U.S. of these avoided deaths are estimated at $160 billion and $930 billion in 2050 and 2100, respectively. In addition to reducing premature mortality, global GHG mitigation would result in other health benefits not presented here, including reduced respiratory- and cardiovascular-related hospital admissions.[15, 16]

Figure 2. Projected Impacts on Air Pollution in the U.S. with Global GHG Mitigation

Estimated change in annual-average ground-level hourly ozone (O$_3$, ppb) and fine particulate matter (PM$_{2.5}$, µg m^{-3}) from 2000 to 2100 under the Mitigation scenario.



Treatment of Co-Benefits

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 (both are emitted from many of the same sources). Incorporating these "co-benefits," which recent analyses[17] and assessments[18] indicate could provide large, near-term benefits to human health, would result in a more comprehensive understanding of air quality and climate interactions.

APPROACH

The CIRA analysis assesses the impact of climate change on air quality across the contiguous U.S. through changes in ground-level ozone and fine particulate matter (PM$_{2.5}$) concentrations.[19] Future concentrations of these pollutants are simulated in an atmospheric chemistry model, driven by weather patterns from the CIRA climate projections. The analysis projects future concentrations for five initializations of the IGSM-CAM climate model under the Reference and Mitigation scenarios in 30-year periods centered on 2050 and 2100 (with 95% confidence intervals based on the difference in mean across the initializations). Despite assumptions about growth in GHG emissions in the Reference and Mitigation scenarios, emissions of the traditional air pollutants are kept fixed at present-day levels to isolate the climate change-related impact on air quality. Changes in pollution due to projected increases in wildfires and changes in sea salt and dust are not considered. Pollutant concentrations are used to estimate changes in air pollution exposure in people. The Environmental Benefits Mapping and Analysis Program (BenMAP) is applied to estimate health effects (with 95% confidence interval based on concentration response functions in BenMAP).[20] To monetize the effects of changing mortality, a value of statistical life (VSL) of $9.45 million for 2010 (2014$) is used, adjusted to future years by assuming an elasticity of VSL to gross domestic product (GDP) per capita of 0.4.[21]

For more information on the approach, models used, and results for the air quality sector, please refer to Garcia-Menendez et al. (2015).[22]

Extreme Temperature

KEY FINDINGS

1. Without global GHG mitigation, the average number of extremely hot days in the U.S. is projected to more than triple from 2050 to 2100. The projected reduction in deaths from extremely cold days is more than offset by the projected increase in deaths from extremely hot days. This result holds for all reported future years, indicating that unmitigated climate change clearly poses an increasing health risk from extreme temperatures.

2. Global GHG mitigation is projected to result in approximately 12,000 fewer deaths from extreme temperature in the 49 modeled cities in 2100. Inclusion of the entire U.S. population would greatly increase the number of avoided deaths, but accounting for adaptation could decrease the number.

Climate Change and Extreme Temperature Mortality

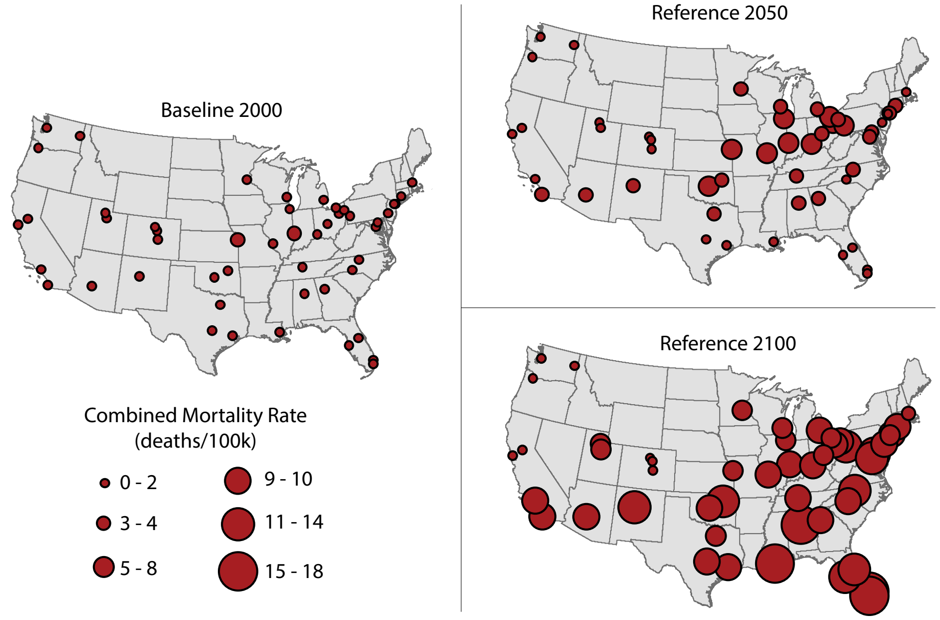
Climate change will alter the weather conditions that we are accustomed to. Extreme temperatures are projected to rise in many areas across the U.S., bringing more frequent and intense heat waves and increasing the number of heat-related illnesses and deaths.[23] Exposure to extreme heat can overwhelm the body's ability to regulate its internal temperatures, resulting in heat exhaustion and/or heat stroke, and can also exacerbate existing medical problems, such as heart and lung diseases.[24] During a 1995 heat wave in Chicago, an estimated 700 individuals died as a result of the extreme heat.[25] Warmer temperatures are also expected to result in fewer extremely cold days, which may also reduce deaths associated with extreme cold.[26]

Risks of Inaction

Climate change poses a significant risk to human health as more days with extreme heat are projected to cause more deaths over time. Without global GHG mitigation, the average number of extremely hot days is projected to more than triple from 2050 to 2100, while the number of extremely cold days is projected to decrease. 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, a finding that is consistent with the conclusions of the assessment literature.[27] Under the Reference, the net increase in projected deaths from more extremely hot days and fewer extremely cold days in 49 cities is approximately 2,600 deaths in 2050, and 13,000 deaths in 2100, but accounting for adaptation could decrease these numbers. Figure 1 shows the net mortality rate from extreme hot and cold temperatures by city in the Reference scenario.

Figure 1. Projected Extreme Temperature Mortality in Select Cities Due to Unmitigated Climate Change

Estimated net mortality rate from extremely hot and cold days (number of deaths per 100,000 residents) under the Reference scenario for 49 cities in 2050 and 2100. Red circles indicate cities included in the analysis; cities without circles should not be interpreted as having no extreme temperature impact.

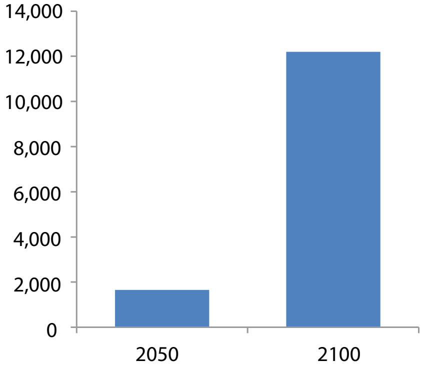


Reducing Impacts through GHG Mitigation

As shown in Figure 2, the projected mortality rates under the Mitigation scenario show small changes through 2100, unlike in the Reference where rates increase substantially. As a result, the net benefits associated with GHG mitigation increase over time. As shown in Figure 3, global GHG mitigation is estimated to result in significant public health benefits across the U.S. by substantially reducing the risk of extreme temperature-related deaths that would occur under the Reference. Under the Mitigation scenario, extreme temperature mortality is reduced by 64% in 2050 and by 93% in 2100[28] compared to the Reference. For the 49 cities analyzed, global GHG mitigation is projected to save approximately 1,700 U.S. lives in 2050, and approximately 12,000 U.S. lives in 2100 (Figure 3).

In 2050, the economic benefits of GHG mitigation are estimated at $21 billion, increasing to $200 billion in 2100 (see the Approach section for more information). It is important to note that these projections reflect only the results for the 49 cities included in this study; corresponding national benefits would be much larger.

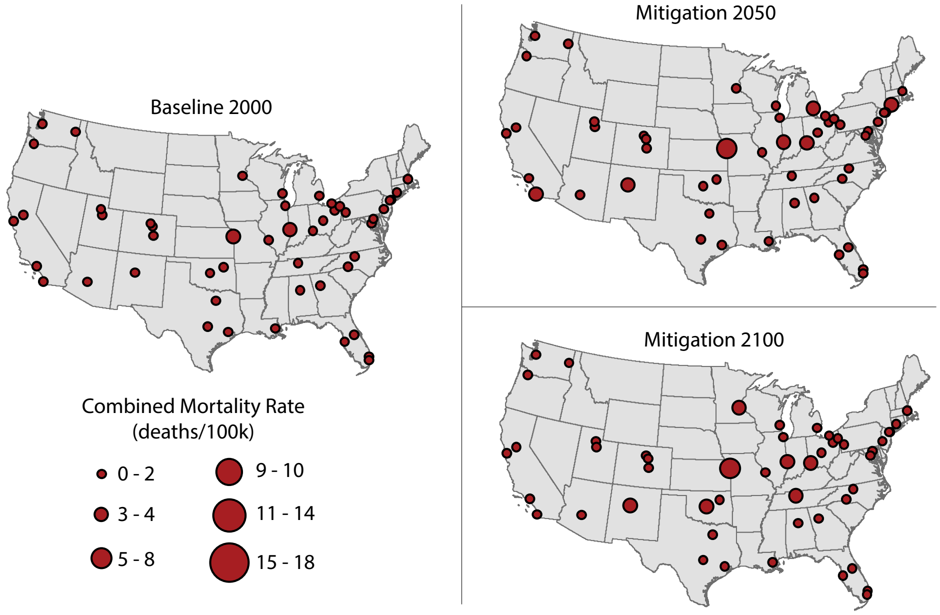
Figure 3. Avoided Extreme Temperature Mortality in 49 U.S. Cities Due to Global GHG Mitigation



The analysis also examines the implications of adjusting temperature thresholds to account for potential adaptation of the human body to warmer temperatures. Specifically, the analysis assumes that the human health response to extreme temperatures in all 49 cities was equal to that of Dallas. Using this approach, results show that mitigation would still save a projected 5,500 lives in 2100 compared to the Reference.

Figure 2. Projected Extreme Temperature Mortality in Select Cities with Global GHG Mitigation

Estimated net mortality rate from extremely hot and cold days (number of deaths per 100,000 residents) under the Mitigation scenario for 49 cities in 2050 and 2100. Red circles indicate cities included in the analysis; cities without circles should not be interpreted as having no extreme temperature impact.



APPROACH

The CIRA 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 (of all causes) and extreme temperatures are combined with the IGSM-CAM projections of extremely hot and cold days using city-specific extreme temperature thresholds to estimate future deaths from heat and cold in the Reference and Mitigation scenarios. Extremely hot days are defined as those with a daily minimum temperature warmer than 99 percent of the days in the period 1989-2000. Extremely cold days are defined as those with a daily maximum temperature colder than 99 percent of the days in the period 1989-2000. As a result, the study explicitly addresses the question of the net mortality impact of climate change on future extreme temperature days. The potential impact of future population change is accounted for using an EPA demographic model (ICLUS).[29] To monetize the effects of changing mortality, a baseline value of statistical life (VSL) of $9.45 million for 2010 (2014$) is used, adjusted to future years by assuming an elasticity of VSL to GDP per capita of 0.4.[30] The results presented in this section have been updated since Mills et al. (2014) to include additional cities and more recent mortality rate data.[31] Finally, this analysis did not estimate impacts across ages or socioeconomic status. As these demographics change, they could impact the results presented here.

For more information on the CIRA approach and results for the extreme temperature mortality sector, please refer to Mills et al. (2014).[32]

Labor

KEY FINDINGS

1. Without global GHG mitigation, labor hours in the U.S. are projected to decrease due to increases in extreme temperatures. Over 1.8 billion labor hours are projected to be lost in 2100, costing an estimated $170 billion in lost wages.

2. Global GHG mitigation is estimated to save 1.2 billion labor hours and $110 billion in wages in 2100 in the contiguous U.S. that would otherwise be lost due to unmitigated climate change.

Climate Change and Labor

Climate change may affect labor in a number of ways, but projections of hotter summer temperatures raise a particular concern. Extreme summer heat is increasing in the U.S. and will be more frequent and intense in the future.[33] Heat exposure can affect workers' health, safety and productivity.[34] When exposed to high temperatures, workers are at risk for heat-related illnesses and therefore may take more frequent breaks, or 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).[35]

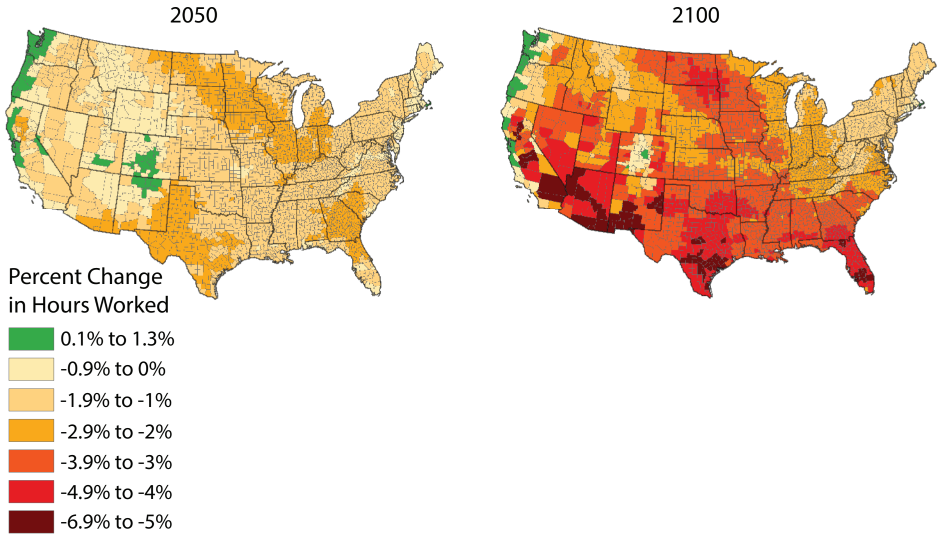
Risks of Inaction

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. In 2100, over 1.8 billion labor hours across the workforce are projected to be lost due to unsuitable working conditions (95% confidence interval of 1.2-2.4 billion). These lost hours would be very costly, totaling over $170 billion in lost wages in 2100 (95% confidence interval of $110-$220 billion).

As shown in Figure 1, the majority of the country is projected to experience decreases in labor hours due to extreme temperature effects. In 2100, parts of the Southwest and Florida are estimated to experience a decrease in hours worked for high-risk industries ranging from -5% to -7%. Although the impacts vary by region, only a limited number of counties are projected to experience increases in labor hours.

Figure 1. Impacts of Unmitigated Climate Change on Labor in the U.S.

Estimated percent change in hours worked from 2005 to 2050 and 2100 under the Reference scenario. Estimates represent change in hours worked at the county level for high-risk industries only, and are normalized by the high-risk working population in each county.



Reducing Impacts through GHG Mitigation

At the national level, impacts to labor under the Mitigation scenario (Figure 2) are substantially smaller compared to the Reference (Figure 1). Counties in the Southwest, Texas, and Florida that are estimated to lose up to 7% of high-risk labor hours under the Reference in 2100 do not experience such losses under the Mitigation scenario.

When comparing the two scenarios (Figure 3), global GHG mitigation is projected to prevent the loss of approximately 360 million labor hours across the workforce in 2050, saving nearly $18 billion in wages. In 2100, the avoided loss of labor hours more than triples, and losses are substantially reduced over a majority of the contiguous U.S. Specifically, mitigation is estimated to prevent the loss of nearly 1.2 billion labor hours and $110 billion in wages in 2100 compared to the Reference.

Figure 2. Labor Impacts in the U.S. with Global GHG Mitigation

Estimated percent change in hours worked from 2005 to 2050 and 2100 under the Mitigation scenario. Estimates represent change in hours worked at the county level for high-risk industries only, and are normalized by the high-risk working population in each county.

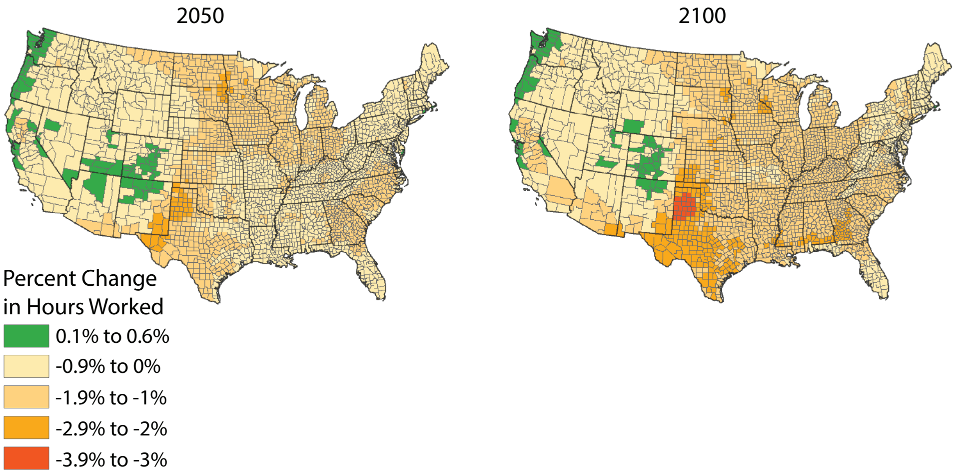
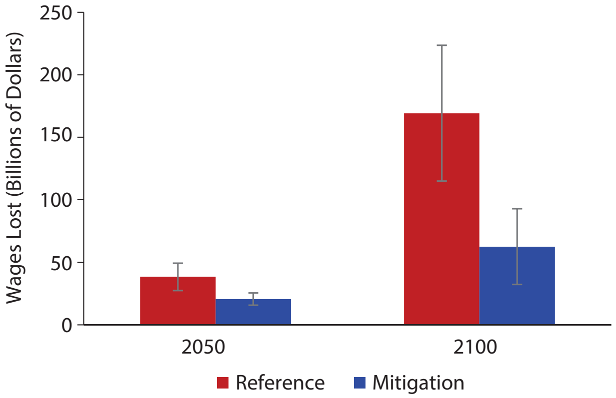


Figure 3. Economic Impacts to Labor with and without Global GHG Mitigation

Estimated wages lost under the Reference and Mitigation scenarios for all labor categories in the contiguous U.S. (billions 2014$). Error bars represent lower- and upper-95% confidence intervals of the dose-response function (see the Approach section for more information).

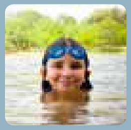


APPROACH

The CIRA analysis focuses on the impact of changes in extreme temperatures on labor supply[36] 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).[37] Mean maximum temperatures from the IGSM-CAM are projected for two future periods (2050 and 2100, 5-year averages centered on those years) at the county level in the CIRA Reference and Mitigation scenarios. 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 the CIRA county-level population projections from the ICLUS model.[38] 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.[39] A range of estimates for the dose-response function are assessed and used to calculate confidence intervals to show the sensitivity of the results. 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, or technological advancements to reduce exposure.

The analysis estimates the cost of the projected losses in labor hours based on the Bureau of Labor Statistics' estimated average wage in 2005 ($23.02 per hour in a 35 hour work week),[40] adjusted to 2100 based on the projected change in GDP per capita.

For more information on the CIRA approach for the labor sector, please refer to Graff Zivin and Neidell (2014)[41] and Section G of the Technical Appendix for this report.



Water Quality

KEY FINDINGS

1. Unmitigated climate change is projected to have negative impacts on water quality in the U.S., particularly in the Southwest and parts of Texas.

2. Global GHG mitigation is projected to prevent many of the water quality damages estimated under the Reference scenario, primarily by reducing the warming of water bodies across the country.

3. Under the Mitigation scenario, costs associated with decreased water quality are reduced approximately 82% in 2100 compared to the Reference, corresponding to cost savings of approximately $2.6-$3.0 billion.

Climate Change and Water Quality

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. These physical impacts on water quality will also have potentially substantial economic impacts, since water quality is valued for drinking water and recreational and commercial activities such as boating, swimming, and fishing.[42,43] The analysis presented in this section estimates changes in water quality, but does not quantify the resulting health effects.

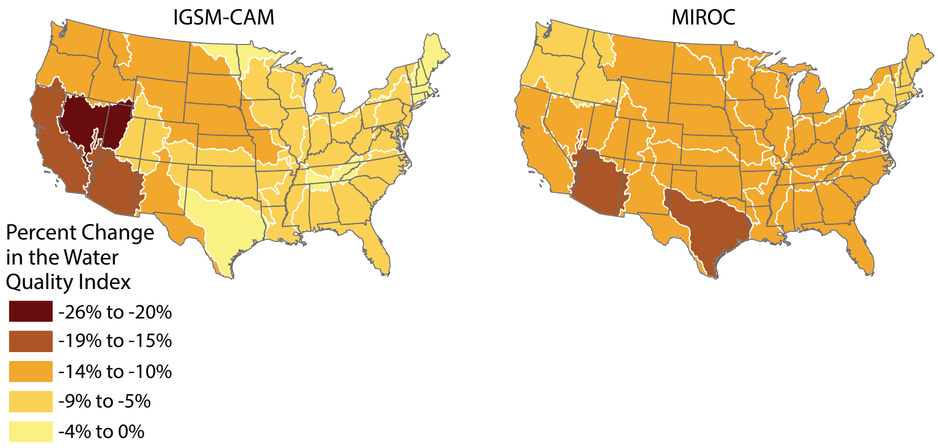
Risks of Inaction

Unmitigated climate change is projected to decrease water quality in the U.S. compared to a future with no climate change. The Water Quality Index (WQI) calculated in the CIRA analysis includes several key water quality constituents, including temperature, dissolved oxygen, total nitrogen, and total phosphorus.[44] The WQI serves as a measure of water quality; the higher the WQI, the higher the water quality.

As shown in Figure 1, the WQI across the U.S. is projected to decline in the Reference scenario in 2100 using both the IGSM-CAM and MIROC climate models. Parts of Texas and the Southwest, in particular, are estimated to experience substantial WQI declines of 15-26% in 2100. Projections that climate change will decrease river and lake water quality are consistent with the findings of the assessment literature.[45]

Figure 1. Effects of Unmitigated Climate Change on U.S. Water Quality in 2100

Percent change in the Water Quality Index in 2100 under the Reference scenario compared to the Control (to isolate the effects of climate change). The WQI is calculated for the 2,119 8-digit hydrologic unit codes (HUCs) of the contiguous U.S., and aggregated to the 18 Water Resource Regions (2-digit HUCs).



Reducing Impacts through GHG Mitigation

Global GHG mitigation is projected to reduce the increase in water temperature that is estimated to occur under the Reference, with corresponding water quality benefits (i.e., avoided degradation) primarily due to better oxygenation. The effects of mitigation on total nitrogen and total phosphorus concentrations vary by region, but the increase in total nitrogen is reduced by up to 80% in some areas of the western U.S. compared to the Reference scenario.

Figure 2 presents the projected change in water quality damages in 2050 and 2100 under the Reference and Mitigation scenarios for the IGSM-CAM and MIROC climate models. As shown in the figure, increases in damages are projected in both scenarios, but most notably in the Reference, where damages are estimated to increase by approximately $3.2-$3.7 billion in 2100. Under the Mitigation scenario, damages are reduced by approximately 82% compared to the Reference in 2100, corresponding to approximately $2.6-$3.0 billion in avoided costs.

Figure 3 presents the avoided water quality damages in 2100 under the Mitigation scenario compared to the Reference using the IGSM-CAM and MIROC climate models. As shown in the figure, global GHG mitigation is projected to result in economic benefits relative to the Reference across the entire contiguous U.S. California is projected to experience the greatest benefits of mitigation in 2100, ranging from approximately $750 million to $1.0 billion.

Figure 2. Change in U.S. Water Quality Damages with and without Global GHG Mitigation

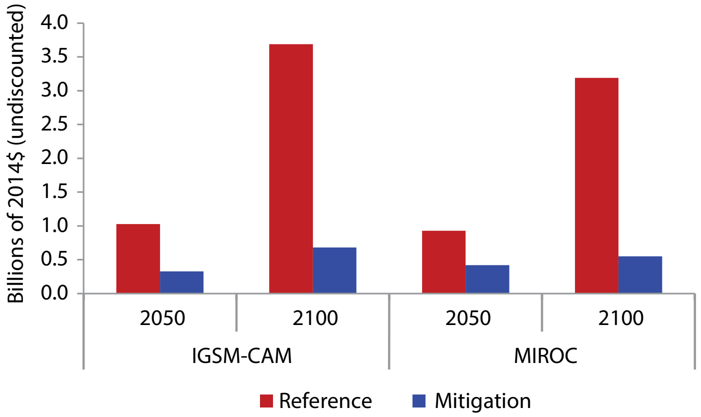
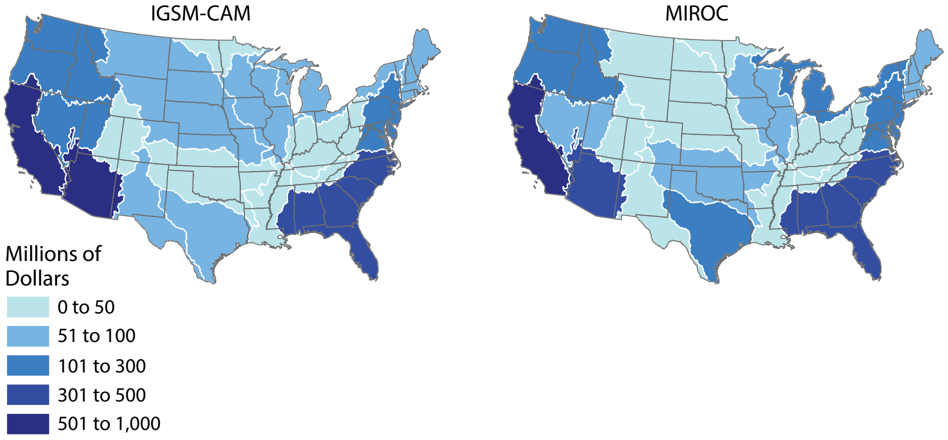


Figure 3. Benefits of Global GHG Mitigation for U.S. Water Quality in 2100

Avoided damages under the Mitigation scenario compared to the Reference in 2100 (millions 2014$). Damages are calculated for the 2,119 8-digit HUCs of the contiguous U.S., and aggregated to the 18 Water Resource Regions (2-digit HUCs).



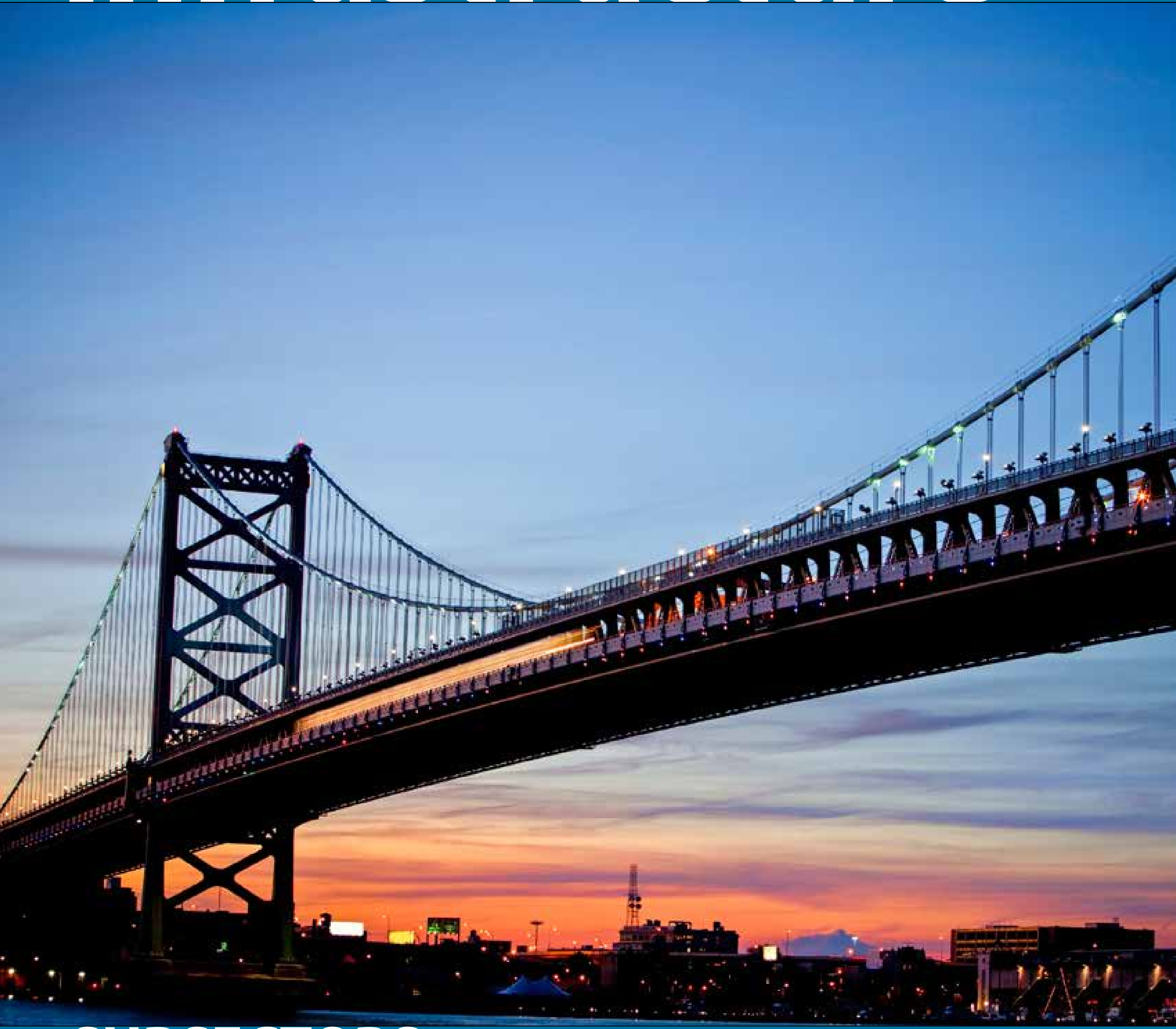
APPROACH

The CIRA analysis uses a series of linked models to evaluate the impacts of climate change on water quality in futures with and without global GHG mitigation. The analysis relies upon climate projections from two climate models: IGSM-CAM, which projects a relatively wetter future for most of the U.S., and the drier MIROC model. The CIRA temperature and precipitation projections inform a rainfall-runoff model (CLIRUN-II) that estimates river flow.[46] A water demand model projects water requirements of the municipal and industrial (M&I), agriculture, and other sectors. The runoff and demand projections inform a water supply and demand model that estimates reservoir storage and release, and in turn produces a time series of water allocations for the various demands. After this allocation step, the analysis relies on the QUALIDAD water quality model to simulate a number of water quality constituents in rivers and reservoirs.[47] Changes in overall water quality are estimated using changes in the Water Quality Index (WQI), a commonly used metric that combines multiple pollutant and water quality measures. Finally, a relationship between changes in the WQI and changes in the willingness to pay for improving water quality is used to estimate the economic implications of projected water quality changes.

Results for the CIRA scenarios are compared to a Control to isolate the effect of climate change. See the Water Resources section of this report for information on projected changes in the Inland Flooding, Drought, and Water Supply and Demand sectors. Decreases in water quality due to climate change will likely have an adverse effect on human health due to, for example, the increased risk of harmful aquatic blooms and impacts on sources of drinking water. Human health effects due to decreased water quality are not estimated, but are important considerations to fully understand climate change impacts in this sector. Inclusion of these effects would likely increase the benefits of GHG mitigation.

For more information on the CIRA approach and results for the water quality sector, please refer to Boehlert et al. (2015).[48]

Infrastructure



SUBSECTORS

Bridges

Roads

Infrastructure makes up the basic physical and organizational structure of our society and is by design interdependent and interconnected. Built infrastructure includes urban buildings; systems for energy, transportation, water, wastewater, drainage, and communication; industrial structures; and other products of human design and construction.[1] U.S. infrastructure has enormous value, both directly as a capital asset and indirectly to support human well-being and a productive economy.

Total public spending on transportation and water infrastructure exceeds $300 billion annually; roughly 25 percent of that total is spent at the federal level and accounts for three percent of total federal spending.[2] Recent analyses point to large gaps between existing capital and maintenance spending and the level of expenditure necessary to maintain current levels of services.[3]

HOW IS INFRASTRUCTURE VULNERABLE TO CLIMATE CHANGE?

Experience over the past decade provides compelling evidence of how vulnerable infrastructure can be to climate change effects, including sea level rise, storm surge, and extreme weather events.[4] Climate change will put added stress on the nation's aging infrastructure to varying degrees over time. Sea level rise and storm surge, in combination with the pattern of heavy development in coastal areas, are already resulting in damage to infrastructure such as roads, buildings, ports, and energy facilities. Floods along the nation's rivers, inside cities, and on lakes following heavy downpours, prolonged rains, and rapid melting of snowpack are damaging infrastructure in towns and cities, on farmlands, and in a variety of other places across the nation. In addition, extreme heat is damaging transportation infrastructure such as roads, rails, and airport runways.

WHAT DOES CIRA COVER?

CIRA analyzes potential climate change impacts and damages to four types of infrastructure in the U.S.: roads, bridges, urban drainage, and coastal property. Analyses of several important types of infrastructure are not included in CIRA, particularly telecommunications and energy transmission networks, and the Urban Drainage analysis only analyzes impacts in 50 cities of the contiguous U.S. Further, some analyses in this sector assume that adaptation measures will be well-timed. This likely results in conservative estimates of future damages, as history has shown that infrastructure investment and maintenance are often not implemented in optimal, well-timed ways.

Urban Drainage

Coastal Property

Bridges

KEY FINDINGS

1. Without reductions in global GHG emissions, an estimated 190,000 inland bridges across the nation will be structurally vulnerable because of climate change by the end of the century. In some areas, more than 50% of bridges are projected to be vulnerable as a result of unmitigated climate change. This analysis estimates the damages of climate change in terms of increased costs to maintain current levels of service (i.e. adaptation costs). Without adaptation, climate change could render many bridges unusable, leading to large economic damages.

2. Global GHG mitigation is estimated to substantially reduce the number of bridges across the U.S. that become vulnerable in the 21st century by reducing the projected increase in peak river flows under the Reference scenario.

3. Global GHG mitigation is projected to reduce adaptation costs that would be incurred under the Reference scenario. The benefits of global GHG mitigation are estimated at $3.4-$42 billion from 2010-2050 and $10-$15 billion from 2051-2100 (discounted at 3%).

Climate Change and Bridges

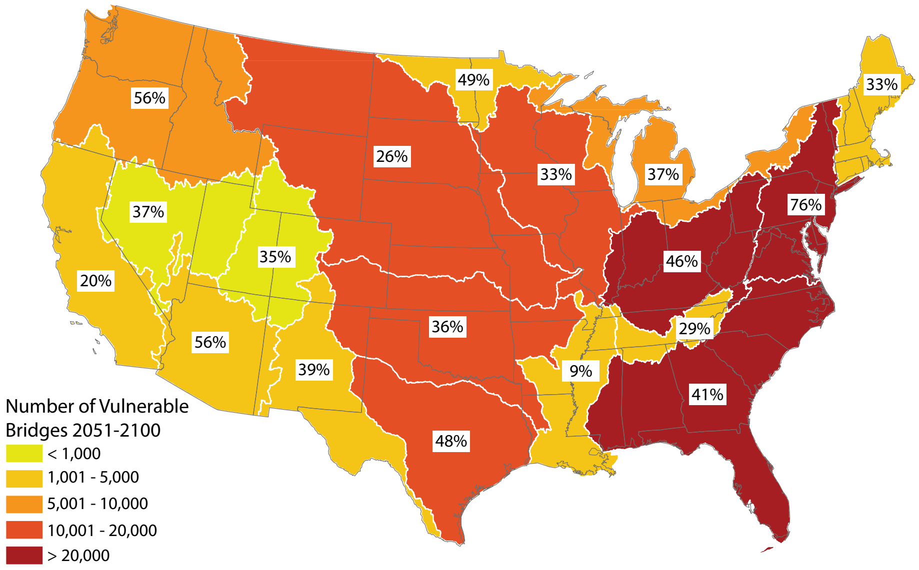
Road bridges are a central component of the U.S. transportation system. With the average U.S. bridge now over 40 years old, however, more than 250 million vehicles cross structurally deficient bridges on a daily basis.[5] Similar to other transportation infrastructure, bridges are vulnerable to a range of threats from climate change.[6] Currently, most bridge failures are caused by scour, where swiftly moving water removes sediment from around bridge structural supports, weakening or destroying their foundations. 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.

Risks of Inaction

Increased inland flooding caused by climate change threatens bridges across the U.S. and risks a net increase in maintenance costs. Figure 1 shows the number and percent of bridges in each hydrologic region of the contiguous U.S. identified as vulnerable to climate change in the late 21st century under the Reference scenario using the IGSM-CAM climate model. In total, approximately 190,000 bridges are identified as vulnerable. In addition, the costs of adapting bridges to climate change under the Reference scenario are estimated at $170 billion for the period from 2010 to 2050, and $24 billion for the period from 2051 to 2100 (discounted at 3%). The higher costs during the first half of the century are primarily due to the large number of vulnerable bridges that require strengthening in the near term in the face of increasing peak river flows due to climate change. These findings regarding near-term bridge vulnerability and adaptation costs due to unmitigated climate change are consistent with the findings of the assessment literature.[7]

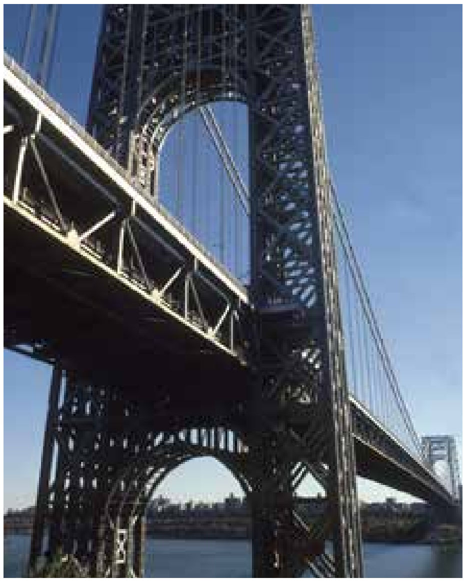
Figure 1. Bridges Identified as Vulnerable in the Second Half of the 21st Century Due to Unmitigated Climate Change

Estimated number of vulnerable bridges in each of the 2-digit hydrologic unit codes (HUCs) of the contiguous U.S. in the period from 2051-2100 under the Reference scenario using the IGSM-CAM climate model. The map also shows the percentage of inland bridges in each HUC that are vulnerable due to climate change.



Reducing Impacts through GHG Mitigation

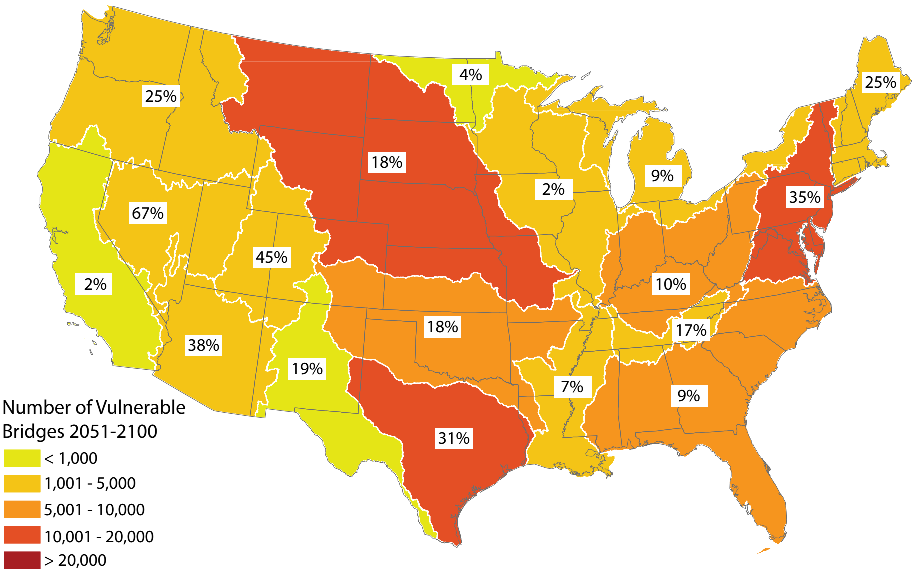
As shown in Figure 2, global GHG mitigation is projected to substantially reduce the number of vulnerable bridges in many areas of the contiguous U.S. compared to the Reference scenario (Figure 1). For example, the percentage of vulnerable bridges in the Northwest region, which includes Washington and parts of Oregon and Idaho, is reduced from 56% under the Reference to 25% under the Mitigation scenario. At the national scale, the total number of vulnerable bridges is reduced by roughly 40,000 through 2050 compared to the Reference scenario, and by over 110,000 in the second half of the century.



In addition, the analysis estimates that global GHG mitigation reduces the costs of adaptation substantially relative to the Reference scenario. In the period from 2010 to 2050, costs under the Mitigation scenario are approximately $42 billion lower than under the Reference (discounted at 3%). Although adaptation costs are lower in the second half of the century, costs under the Mitigation scenario are nearly 60% lower than they are under the Reference scenario, with savings estimated at $15 billion (discounted at 3%). These results rely upon climate projections using the IGSM-CAM, which projects a relatively wetter future for most of the U.S. compared to the MIROC climate model (see the Levels of Certainty section of this report for more information). The projected benefits of global GHG mitigation are lower with the drier MIROC model (not shown) for the 2010-2050 period, at approximately $3.4 billion, but are higher in the 2051-2100 period, at approximately $10 billion (discounted at 3%).

Figure 2. Bridges Identified as Vulnerable in the Second Half of the 21st Century with Global GHG Mitigation

Estimated number of vulnerable bridges in each of the 2-digit HUCs of the contiguous U.S. in the period from 2051-2100 under the Mitigation scenario using the IGSM-CAM climate model. The map also shows the percentage of inland bridges in each HUC that are vulnerable due to climate change.



APPROACH

The CIRA analysis identifies inland bridges in the contiguous U.S. that may be vulnerable to increased peak river flows due to climate change and estimates the costs to adapt the at-risk infrastructure.[8] The analysis relies upon climate projections from two climate models: IGSM-CAM, which projects a relatively wetter future for most of the U.S., and the drier MIROC model. Bridge performance and vulnerability are determined using the National Bridge Inventory database and are based on the following four elements:

- substructure condition;
- channel and channel protection condition;
- waterway adequacy; and
- vulnerability to scour.

The analysis estimates the timing of bridge vulnerability (based on the 100-year, 24-hour storm event), and the adaptation costs of maintaining the current condition and level of service of the at-risk bridges. Two types of bridge fortification and the costs of their implementation are analyzed: the use of riprap (large rocks and rubble) to stabilize bridge foundations and the use of additional concrete to strengthen bridge piers and abutments. Although there will likely be significant changes to the nation's bridges over the course of the century—some bridges will be strengthened, some will deteriorate, some will be removed, and new bridges will be built—this analysis estimates the costs of adapting the nation's existing bridge infrastructure to different future climates based on its current state (i.e., the additional costs due to climate change are isolated).[9,10]

For more information on the CIRA approach and results for the bridges sector, please refer to Neumann et al. (2014)[11] and Wright et al. (2012).[12]

Roads

KEY FINDINGS

1. Climate change is projected to increase the cost of maintaining road infrastructure. This analysis estimates the damages of climate change in terms of increased costs to maintain current levels of service (i.e. adaptation costs). Without adaptation, climate change could render many roadways unusable, leading to large economic damages.

2. In all regions, adaptation costs associated with the effects of higher temperatures on paved roadways are estimated to increase over time. In the central regions of the country, in particular, changes in precipitation patterns are projected to increase costs associated with re-grading unpaved roadways.

3. Without global GHG mitigation, adaptation costs in 2100 in the U.S. roads sector are estimated to range from $5.8-$10 billion.

4. Global GHG mitigation is projected to avoid an estimated $4.2-$7.4 billion of the damages under the Reference scenario in 2100.

Climate Change and Roads

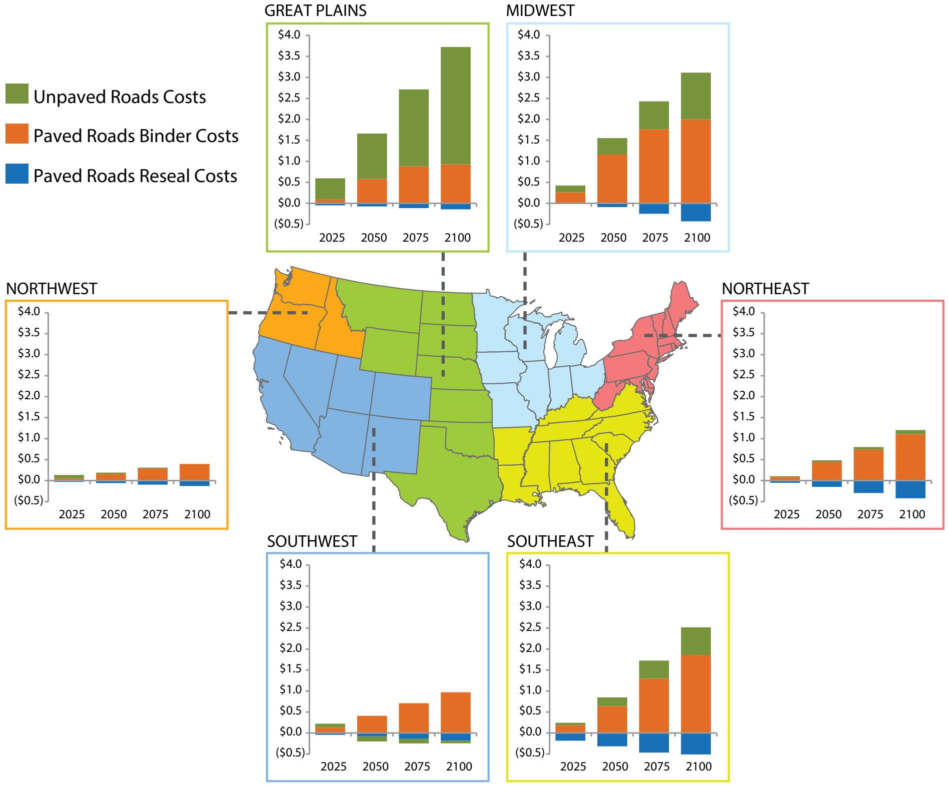
The U.S. road network is one of the nation's most important capital assets. Climate stress on roads will likely change in the future, with various potential impacts and adaptation costs.[13] For example, roads may experience more frequent buckling due to increased temperatures, more frequent washouts of unpaved surfaces from increases in intense precipitation, and changes in freeze-thaw cycles that cause cracking.[14]

Risks of Inaction

Without reductions in global GHG emissions, the costs of maintaining, repairing, and replacing pavement are projected to increase, which is consistent with the findings of the assessment literature regarding adaptation costs for road infrastructure.[15] Figure 1 presents the estimated regional damages (in the form of adaptation costs) to the U.S. road network under the Reference scenario using the ISGM-CAM climate model. The greatest impacts are projected to occur in the Great Plains region, where costs are mainly due to erosion of unpaved roads associated with increased precipitation. Costs associated with the use of different pavement binders to avoid cracking of paved roads are also high, particularly in the Midwest and Southeast regions, and they increase over time in all regions due to the projected rise in temperature. Costs of resealing roads after freeze-thaw events decrease over time as the climate changes, but the magnitude of the decrease does not offset the projected increase in other costs.

Figure 1. Projected Impacts of Unmitigated Climate Change on U.S. Road Infrastructure

Adaptation costs (billions 2014$, undiscounted) under the Reference scenario using the IGSM-CAM climate model. Results are presented for the six regions used in the Third National Climate Assessment.



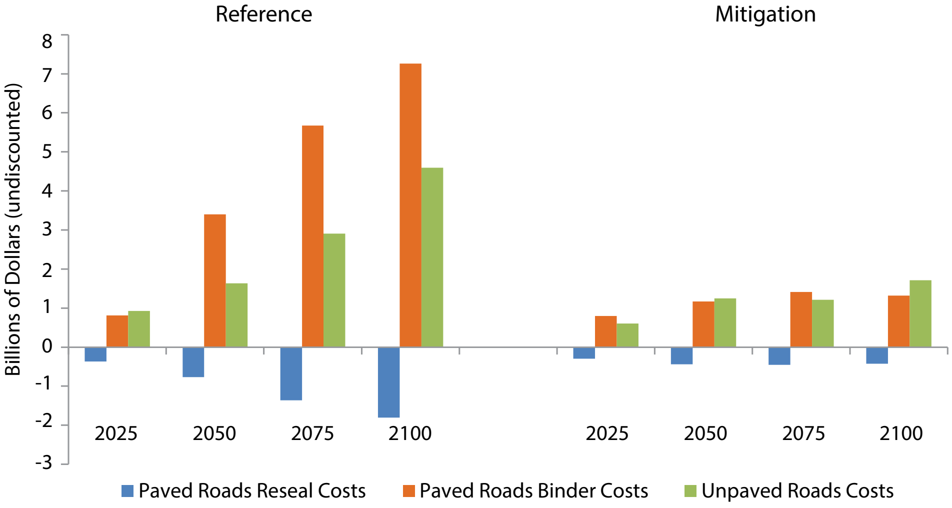
Reducing Impacts through GHG Mitigation

Adaptation costs for the U.S. road network are substantially reduced with global GHG mitigation compared to the Reference scenario (Figure 2). These reductions are due in large part to the effect of lower temperatures under the Mitigation scenario on maintenance needs for paved roads. Specifically, costs associated with asphalt binders account for a large share of the adaptation costs nationally under the Reference, and these costs are significantly lower with mitigation. Costs associated with adaptation for unpaved roads are also substantially lower under the Mitigation scenario, as heavy precipitation events are projected to be less severe compared to the Reference. Costs of resealing roads after freeze-thaw cycles are projected to decrease under both scenarios, but the magnitude of the decrease does not offset the projected increase in other costs.

By 2050, the adaptation costs under the Reference scenario are substantially higher, illustrating the benefits that accrue over time with GHG mitigation. In addition, although the costs of adaptation increase over the course of the century under both scenarios, they do so at a much faster rate under the Reference. Under the Reference, adaptation costs are estimated at approximately $10 billion in 2100, whereas under the Mitigation scenario costs are estimated at $2.6 billion. As a result, global GHG mitigation is projected to avoid over $7 billion in damages in 2100. These results rely upon climate projections from the IGSM-CAM, which projects a relatively wetter future for most of the U.S. compared to the MIROC climate model (see the Levels of Certainty section of this report for more information). The projected benefits of global GHG mitigation are lower with the drier MIROC model (not shown), at $4.2 billion in 2100, reflecting the reduced impact of precipitation on unpaved roads under both scenarios.[16]

Figure 2. Projected Impacts on U.S. Road Infrastructure with and without Global GHG Mitigation

Costs of adaptation for the Reference and Mitigation scenarios using the IGSM-CAM climate model (billions 2014$). The reduction in adaptation costs under the Mitigation scenario relative to the Reference reflects the benefits of global GHG mitigation.



APPROACH

The CIRA approach assesses four risks to road infrastructure associated with climate change:

- rutting of paved roads from precipitation;
- rutting of paved roads caused by freeze-thaw cycles;
- cracking of paved roads due to high temperatures; and
- erosion of unpaved roads from precipitation.

The CIRA analysis examines the implications of changes in climate over time for the U.S. road network based on stressor-response functions for each of the above effects. The analysis considers the effects of temperature and precipitation, but does not include impacts due to sea level rise and storm surge, which would likely increase damages to roads. The analysis relies upon climate projections from two climate models: IGSM-CAM, which projects a relatively wetter future for most of the U.S., and the drier MIROC model.

The costs of adaptation to effectively counteract the climate change impacts and maintain roads at their current levels of service are estimated for each of the CIRA scenarios. As there will be continued maintenance needs over time, this analysis focuses on the additional costs due to climate change. The response measures include more frequent resealing to avoid rutting; use of different pavement binders during resurfacing to avoid cracking of asphalt-paved roads; and more frequent re-grading of unpaved roads to minimize erosion impacts. This analysis assumes well-timed adaptation to maintain service levels, a potentially overly optimistic assumption given that infrastructure investments are oftentimes delayed.

For more information on the CIRA approach and results for the roads sector, please refer to Neumann et al. (2014)[17] and Chinowsky et al. (2013).[18]

Urban Drainage

KEY FINDINGS

1. Climate change is projected to result in increased adaptation costs for urban drainage systems in cities across the U.S., particularly in the Great Plains region.
2. Without global GHG mitigation, adaptation costs in 2100 associated with the 50-year, 24-hour storm in 50 major U.S. cities are projected to range from $1.1-$12 billion.
3. Global GHG mitigation is projected to result in cost savings for urban drainage systems in these cities ranging from $50 million to $6.4 billion in 2100 for the 50-year, 24-hour storm, depending on the climate model used. Inclusion of all U.S. cities would likely increase the cost savings by a substantial amount.

Climate Change and Drainage

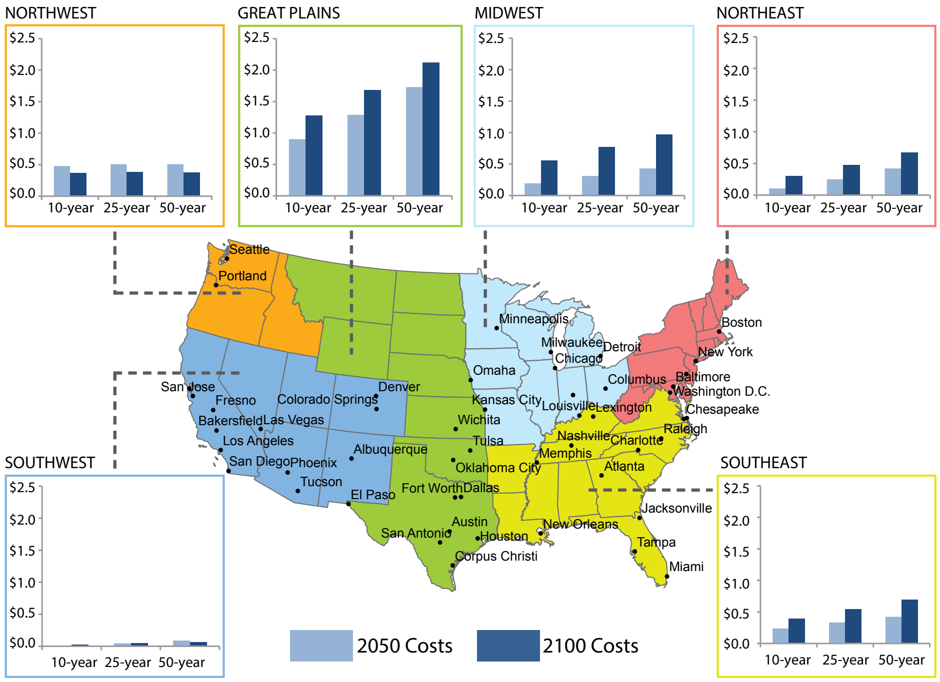
Urban drainage systems capture and treat stormwater runoff and prevent urban flooding. During storm events, the volume of runoff flowing into drainage systems and the ability of these systems to manage runoff depend on a variety of site-specific factors, such as the imperviousness of the land area in 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.[19] In areas where precipitation intensity increases significantly, adaptation investments may be necessary to prevent runoff volumes from exceeding system capacity.

Risks of Inaction

Without global GHG mitigation, climate change is projected to result in increased adaptation costs for urban drainage infrastructure, a finding that is consistent with the conclusions of the assessment literature.[20] Figure 1 presents the projected costs for the 50 modeled cities in 2050 and 2100 under the Reference scenario using the IGSM-CAM climate model for the three categories of storm events modeled (24-hour events with precipitation intensities occurring every 10, 25, and 50 years).[21] The average per-square-mile costs are projected to be highest in the Great Plains region in both 2050 and 2100 due to the projected increase in heavy precipitation in that region. Adaptation costs are estimated to be relatively low in the Southwest due to the projected reduction in precipitation in that region.

Figure 1. Projected Impacts of Unmitigated Climate Change on U.S. Urban Drainage Systems

Weighted average per-square-mile adaptation costs (millions 2014$, undiscounted) in 2050 and 2100 for the 10-, 25-, and 50-year storms under the Reference scenario using the IGSM-CAM climate model. Costs for each of the 50 modeled cities (shown) are aggregated to the six regions used in the Third National Climate Assessment.

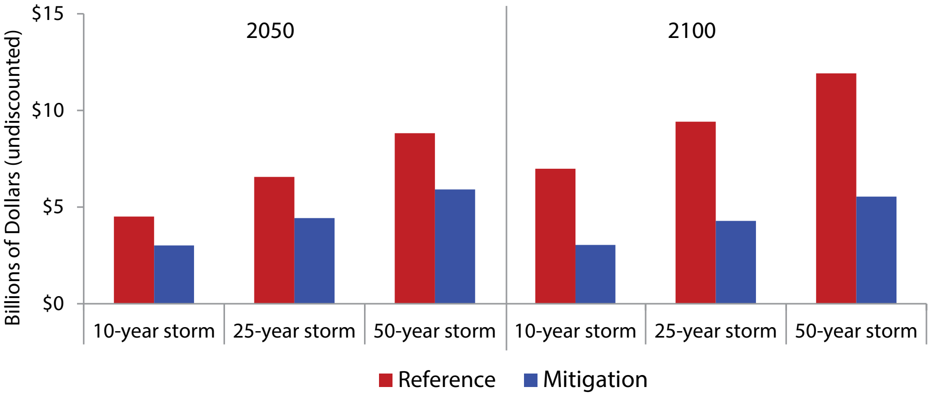


Reducing Impacts through GHG Mitigation

Global GHG mitigation is projected to result in substantial adaptation cost savings for urban drainage systems in the 50 modeled cities (Figure 2). Overall, cost savings are projected to be higher in 2100 than in 2050, and increase according to the intensity of the storm modeled, with the greatest savings occurring for the 50-year, 24-hour storm. For this particular storm event, total adaptation costs for the modeled cities are projected to be $12 billion in 2100 under the Reference. Under the Mitigation scenario, these costs are reduced to approximately $5.5 billion, which represents a cost savings of approximately $6.4 billion. Cost savings for the 10- and 25-year storms under the Mitigation scenario are approximately $3.9 billion and $5.1 billion, respectively, in 2100. Looking across the contiguous U.S., the Great Plains region is projected to experience the largest reductions in adaptation costs as a result of global GHG mitigation. These results rely upon climate projections from the IGSM-CAM, which projects a relatively wetter future for most of the U.S. compared to the MIROC climate model (see the Levels of Certainty section of this report for more information). Using the drier MIROC model, projected benefits of GHG mitigation for the modeled cities associated with the 50-year, 24-hour storm event are estimated at $50 million.

Figure 2. Projected Impacts on Urban Drainage Systems in 50 U.S. Cities with and without Global GHG Mitigation

Projected adaptation costs in 2050 and 2100 for the Reference and Mitigation scenarios using the IGSM-CAM climate model (billions 2014$). The values of the red bars represent the sum of all adaptation costs shown in Figure 1 for the years 2050 and 2100.



APPROACH

The CIRA analysis estimates the costs of adapting urban drainage systems to meet future demands of increased runoff associated with more intense rainfall under climate change. The analysis relies upon climate projections from two climate models: IGSM-CAM, which projects a relatively wetter future for most of the U.S., and the drier MIROC model. Adaptive actions focus on the use of best management practices to limit the quantity of runoff entering stormwater systems. While many site-specific factors influence the effect of climate change on a given drainage system, the CIRA analysis uses a streamlined approach that allows for the assessment of potential impacts in multiple U.S. cities under the CIRA scenarios.[22] Specifically, the analysis uses a reduced-form approach for projecting changes in flood depth and the associated costs of flood prevention, based on an approach derived from EPA's Storm Water Management Model (SWMM).

The simplified approach yields impact estimates in units of average adaptation costs per square mile for a total of 50 cities across the contiguous U.S. (see Figure 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 four future time periods (2025, 2050, 2075, and 2100). The analysis 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 under climate change.

For more information on the CIRA approach and results for the urban drainage sector, please refer to Neumann et al. (2014)[23] and Price et al. (2014).[24,25]

Coastal Property

KEY FINDINGS

1. A large area of U.S. coastal land and property is at risk of inundation from global 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.

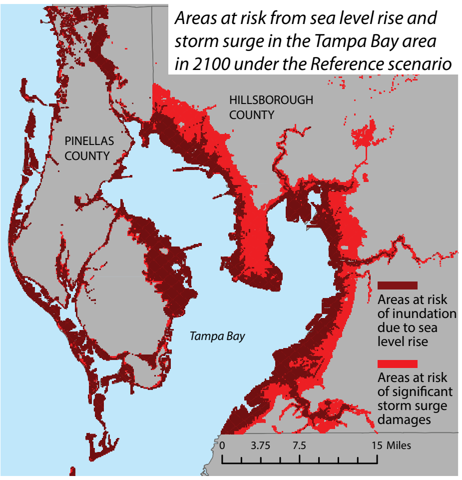
2. Without adaptation, unmitigated climate change is projected to result in $5.0 trillion in damages for coastal property in the contiguous U.S. through 2100 (discounted at 3%). Protective coastal adaptation measures significantly reduce total costs to an estimated $810 billion.

3. Global GHG mitigation reduces adaptation costs for coastal areas, but the majority of benefits occur late in the century.

4. Areas of higher social vulnerability are more likely to be abandoned than protected in response to unmitigated sea level rise and storm surge. GHG mitigation decreases this risk.

Climate Change and Coastal Property

Coastal areas in the U.S. are some of the most densely populated, developed areas in the nation, and they contain a wealth of natural and economic resources. Rising temperatures are causing ice sheets and glaciers to melt and ocean waters to expand, contributing to global sea level rise at increasing rates. 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. The combined effects of sea level rise and other climate change factors, such as increased intensity of coastal storms, may cause rapid and irreversible change.[26]



Areas at risk from sea level rise and storm surge in the Tampa Bay area in 2100 under the Reference scenario

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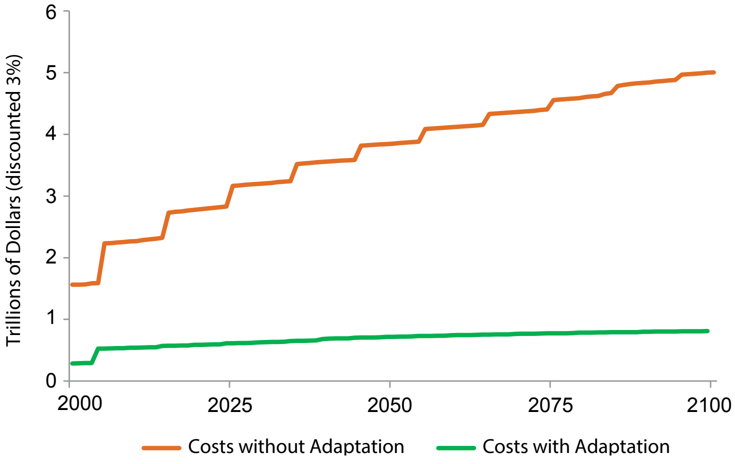
Risks of Inaction

Sea level rise and storm surge pose increasingly large risks to coastal property, including costs associated with property abandonment, residual storm damages, and protective adaptation measures (e.g., elevating properties and armoring shorelines). As shown in Figure 1, the analysis estimates that under the Reference scenario the cumulative damages to coastal property across the contiguous U.S. will be $5.0 trillion through 2100 (discounted at 3%) if no adaptation measures are implemented. If adaptation measures are taken, these damages are reduced to $810 billion. Projections of increasing risks of sea level rise and storm surge for coastal property, and of the potential for adaptation to reduce overall costs, are consistent with the findings of the assessment literature.[27] The graphic above illustrates the importance of these potential impacts at a local scale by identifying at-risk land in the Tampa Bay, FL area. In this locale, approximately 83,000 acres are projected to be at risk of inundation due to sea level rise by 2100, and an additional 51,000 acres are projected to be at risk of significant storm surge. The total area at risk (130,000 acres) is approximately one and a half times the size of the City of Tampa.

Figure 1. Costs of Sea Level Rise and Storm Surge to Coastal Property with and without Adaptation under the Reference Scenario

The step-wise nature of the graph is due to the fact that storm surge risks are evaluated every ten years, beginning in 2005. Costs with adaptation include the value of abandoned property, residual storm damages, and costs of protective adaptation measures (trillions 2014$).



Reducing Impacts through GHG Mitigation

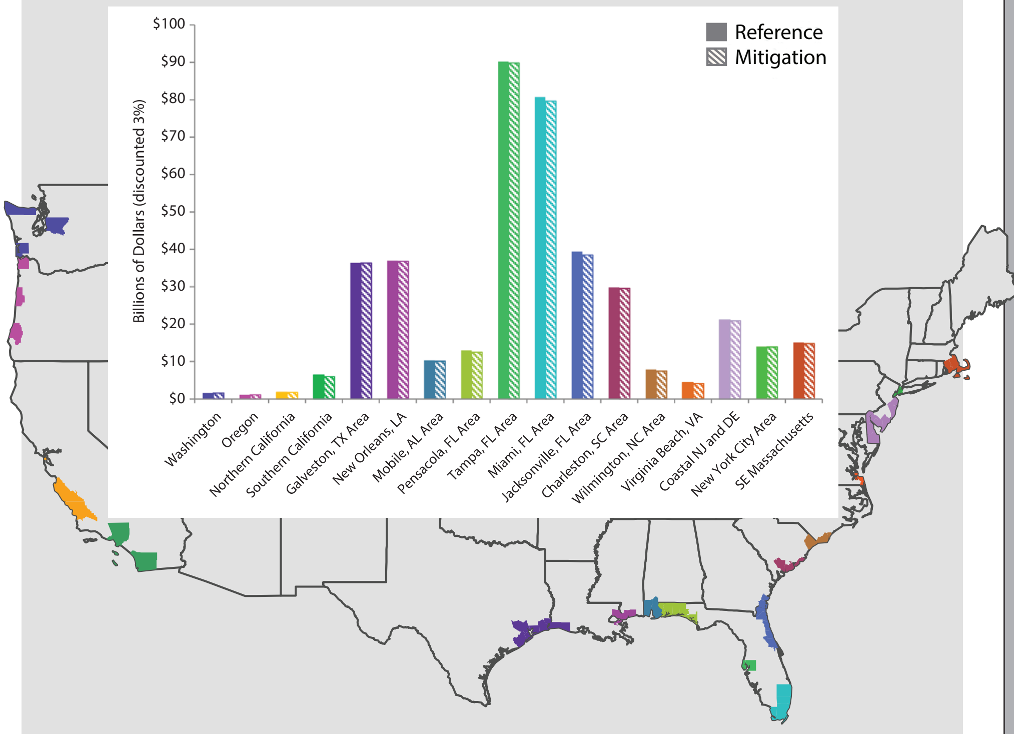
Under the Mitigation scenario, total costs (i.e., property damages and protective investments) across the contiguous U.S. are estimated at $790 billion through 2100 (discounted at 3%), about 3% less than the Reference scenario.[28] The effect of global GHG mitigation in reducing adaptation costs is modest and is likely underestimated in this analysis for several reasons. First, as described in the CIRA Framework section, global sea level rise is similar under the Reference and Mitigation scenarios through mid-century. It is not until the second half of the century when the benefits of reduced sea level rise under the Mitigation scenario become apparent. Further, the proportional effect of global GHG mitigation in reducing the rate of sea level rise is smaller under the CIRA scenarios compared to other scenarios in the literature.[29]

Second, when considering the present value total cost under the Reference and Mitigation scenarios, avoided adaptation costs accrued in later years are more heavily affected by discounting.[30] Third, the analysis assumes that coastal areas will implement cost-efficient and well-timed adaptation measures in response to the risks under both the Reference and Mitigation scenarios. Since many parts of the coastline are not sufficiently protected today, and because adaptation measures that are taken are oftentimes not well-timed, the CIRA estimates for this sector likely underestimate damages. For comparison purposes, the benefits of global GHG mitigation increase by a factor of ten if adaptation measures are not implemented.

Figure 2 shows the costs of adaptation for coastal properties (including the value of properties that are abandoned due to the severity of sea level rise or storm surge damages) for 17 key sites under the Reference and Mitigation scenarios. As shown, costs are only modestly lower under the Mitigation scenario. 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.

Figure 2. Costs to Coastal Property of Sea Level Rise and Storm Surge through 2100

Costs are shown for 17 multi-county coastal areas that were modeled for sea level rise and storm surge impacts and potential adaptation response (billions 2014$).



APPROACH

The CIRA analysis identifies at-risk coastal property across the contiguous U.S. and estimates the costs that would be incurred due to climate change, with and without adaptation. Importantly, impacts to other coastal assets (e.g., roads and ecological resources) are not estimated in this analysis. The analysis relies upon sea level rise projections through 2100[31] that account for dynamic ice-sheet melting based on a semi-empirical model,[32] and are adjusted for regional land movement using local tide gauge data.[33] The analysis then uses a tropical cyclone simulator[34] and a storm surge model[35] 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.[36]

Using EPA's National Coastal Property Model, the CIRA analysis estimates 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). The approach uses four primary responses to protect coastal land and property: beach nourishment; property elevation; shoreline armoring; and 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. 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. The analysis also explores the potential impact of climate change on socially disadvantaged populations (see the Environmental Justice section of this report).

For more information on the CIRA approach and results for the coastal property sector, please refer to Neumann et al. (2014a)[37] and Neumann et al. (2014b).[38]

Environmental Justice

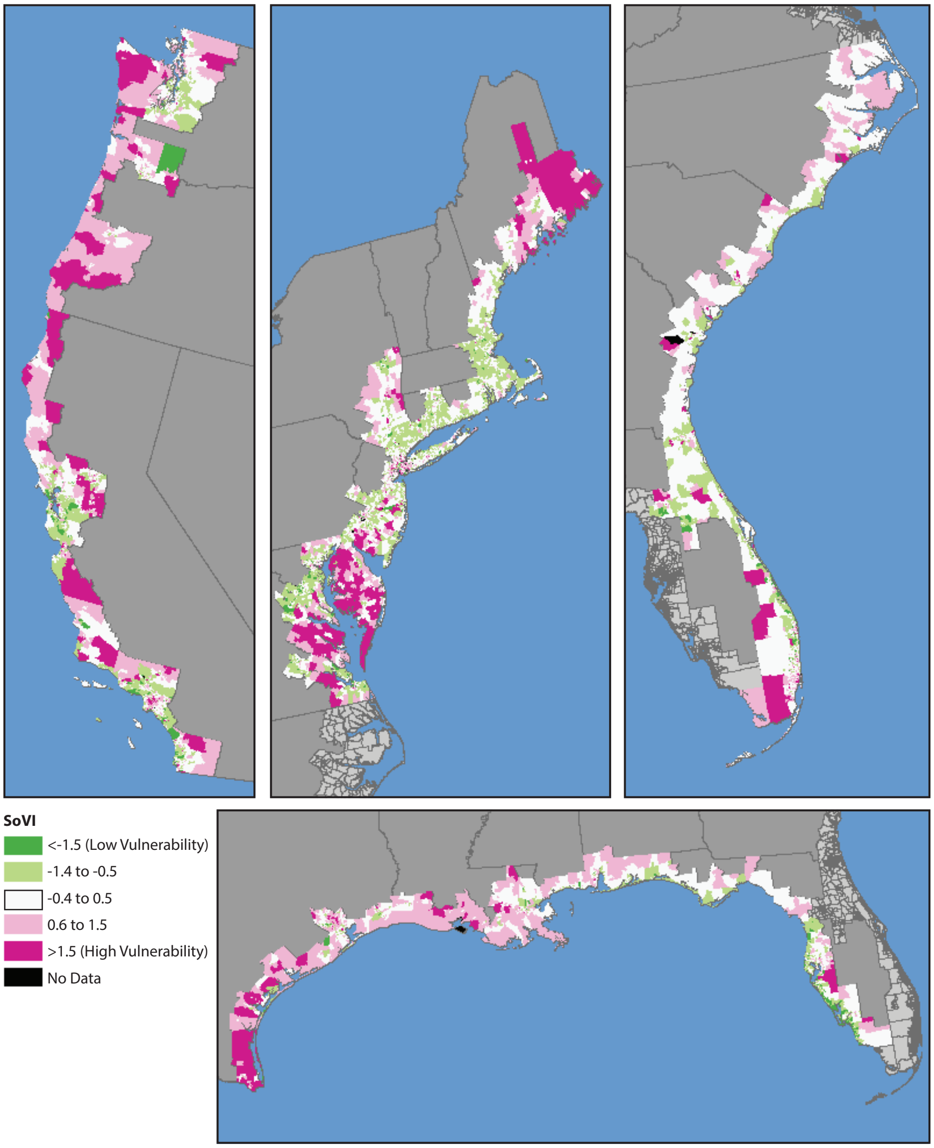
Building on the coastal property impacts described in the previous section, this analysis examines the environmental justice implications of projected sea level rise and storm surge in the contiguous U.S. Specifically, the approach quantifies how sea level rise and storm surge risks are distributed across different socioeconomic populations along the U.S. coastline; how these populations are likely to respond; and what adaptation costs (i.e., property damage and protection investments) will potentially be incurred.

The Social Vulnerability Index

The CIRA analysis uses the Social Vulnerability Index (SoVI) to identify socially vulnerable coastal communities in the U.S.[39] SoVI was developed to quantify social vulnerability using county-level (and later Census tract-level) socioeconomic and demographic data. The index is a well-vetted tool, and does not include any environmental risk factors, thereby eliminating the risk of double counting climate risk when socioeconomic and demographic data are combined with sea level rise and storm surge vulnerability.[40] The CIRA analysis uses Census tract-level SoVI values based on 2000 Census data for 26 demographic variables, capturing information on wealth, gender, age, race, and employment. Figure 1 shows the SoVI index values for the four coastal regions used in the analysis: Pacific (California through Washington), North Atlantic (Maine through Virginia), South Atlantic (North Carolina through Monroe County, Florida), and Gulf (Collier County, Florida through Texas).

Figure 1. Social Vulnerability Index for the Coastal U.S.

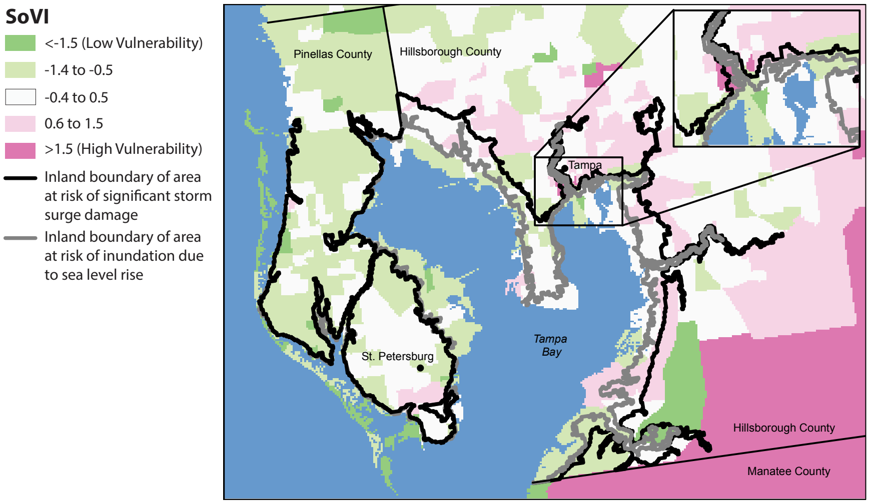
Census tract-level SoVI values are regionally normalized to allow for comparisons of the SoVI scores within each area. Areas with low SoVI scores (i.e., people with lower social vulnerability) are shaded in green and areas with higher SoVI scores (i.e., people with greater social vulnerability) are shaded in pink.



Case Study: Tampa Bay Area

EPA's National Coastal Property Model identifies areas along the contiguous U.S. coastline that are likely to be at risk from sea level rise and storm surge through 2100.[41, 42] By layering these projections on top of the SoVI results, following the approach described in Martinich et al. (2013),[43] the analysis assesses the potential impact of sea level rise and storm surge on socially disadvantaged populations in coastal areas. Figure 2 presents a case study of the Tampa Bay, Florida area (Pinellas and Hillsborough Counties). The area from the water to the gray lines represents the projected area at risk of inundation due to sea level rise, while the area from the water to the black lines represents projected areas at risk from significant storm surge damage in 2100.[44] As shown, there are areas with higher socially vulnerable populations (pink shading) near the city of Tampa, in particular, that are projected to be at risk of significant storm surge damages.

Figure 2. Social Vulnerability of Areas at Risk from Sea Level Rise and Storm Surge in the Tampa Bay Area by 2100 under the Reference Scenario



National Results

Figure 3 compares the number of people in the 17 multi-county coastal areas (see previous section for locations) identified as at risk due to climate change under the Reference and Mitigation scenarios, by SoVI category. As shown, the Mitigation scenario reduces the number of at-risk people compared to the Reference scenario for all SoVI categories. The benefits of global GHG mitigation are particularly high for the population identified by the SoVI as most socially vulnerable; for this population, the number of at-risk people is reduced by 23% under the Mitigation scenario compared to the Reference.

The CIRA analysis also projects adaptation responses based on sea level rise, storm surge height, property value, and costs of adaptation.[45] The model estimates whether people living in coastal areas are likely to respond to climate threats by: 1) protecting property through beach nourishment, property elevation, or shoreline armoring; 2) abandoning property, or 3) incurring storm surge damages without adapting. Figure 4 presents the adaptation results, by area, for the five SoVI categories in the Reference. More area is likely to be abandoned than protected across all social vulnerability categories. However, in the most vulnerable SoVI categories (0.6-1.5 and greater than 1.5), a relatively larger proportion of the area inhabited is likely to be abandoned (89% and 86%, respectively) rather than protected through adaptation measures (8% and 10%, respectively).

Figure 3. Social Vulnerability of Populations at Risk from Sea Level Rise and Storm Surge through 2100 with and without Global GHG Mitigation

Vulnerability estimated in 17 multi-county coastal areas in the contiguous U.S., along with the estimated percent changes from Reference to Mitigation.

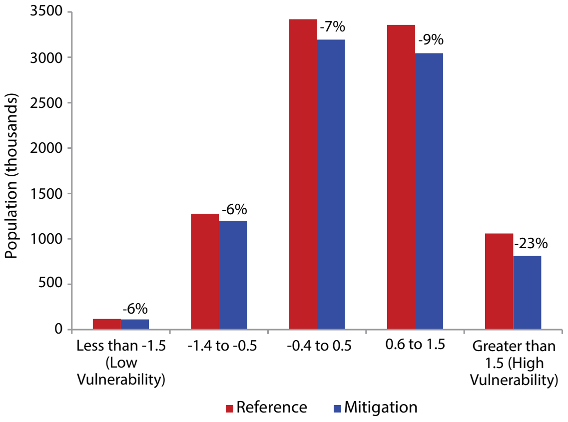
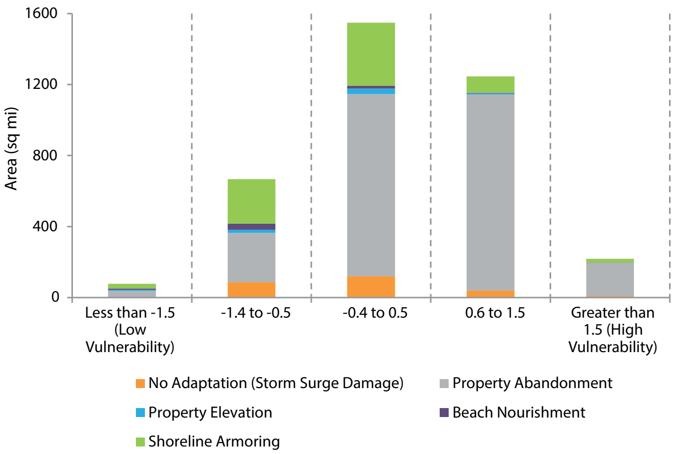


Figure 4. Adaptation Measures by SoVI Category under the Reference Scenario



Electricity

SUBSECTORS

Electricity Demand

Electricity is an essential element of modern life. It lights and cools our homes, powers our computers, 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% of U.S. greenhouse gas emissions.[1]

HOW IS THE ELECTRICITY SECTOR VULNERABLE TO CLIMATE CHANGE?

Climate change has implications for electricity production, distribution, and use.[2] For example, coastal electricity infrastructure, such as power plants and substations, are vulnerable to storm surge and wind damage. Elevated temperatures diminish thermal power plant efficiency and capacity, and can reduce the capacity of transmission lines. In addition, effects on water supply alter the quantity and temperature of cooling water available for thermoelectric generation.[3] On the demand side, warmer winters decrease the demand for heating. However, this reduction is smaller than the increase in electricity demand for cooling due to higher summer temperatures. Across the U.S., higher minimum temperatures increase the number of days in a year when air conditioning is needed, and higher maximum temperatures increase the peak electricity demand, further stressing our aging power grid.

WHAT DOES CIRA COVER?

Numerous studies highlight the potential for emission reductions in the electricity sector, yet fewer studies have explored the physical, operational, and economic impacts of a changing climate on this sector. CIRA assesses the impacts of rising temperatures on electricity demand, system costs, and the generation mix needed to meet increasing demand across the contiguous U.S. through 2050.[4] Importantly, impacts to the demand and supply of other energy sources (e.g., fuel for transportation) are not estimated. Also, the electricity supply analysis does not include the effects of climate change on hydropower and water availability for thermoelectric power generation. Additional work is necessary to further evaluate climate change impacts on electricity supply, particularly the effects of extreme heat events and storm damage on capacity and reliability. Finally, future work to improve connectivity between the CIRA electricity, water, and agriculture analyses will aid in better understanding potential cross-sector impacts.

Electricity Supply

Electricity Demand

KEY FINDINGS

1. Without global GHG mitigation, rising temperatures will likely result in higher electricity demand across the country, as the increased need for air conditioning outweighs decreases in electric heating requirements. The estimated percent increase in electricity demand for air conditioning is highest in the Northeast and Northwest regions.

2. Global GHG mitigation, which lessens the rise in temperature, is projected to lead to lower electricity demand across all regions of the country relative to the Reference scenario.

Climate Change and Electricity Demand

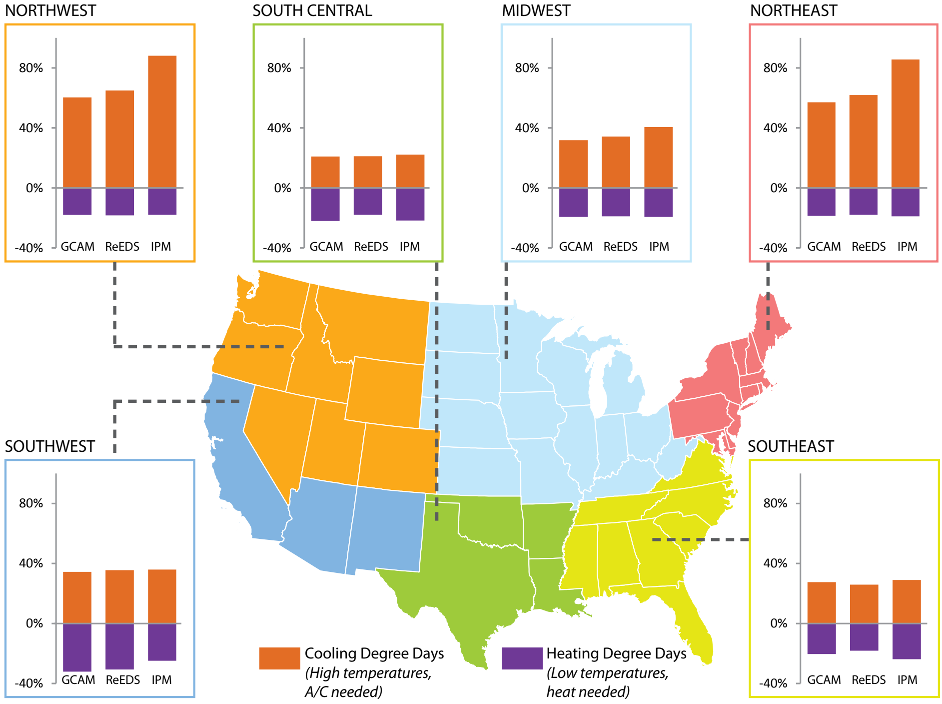
As air temperatures rise due to climate change, electricity demands for cooling are expected to increase in every U.S. region.[5] Higher summer temperatures, particularly during heat waves, will likely increase peak electricity demand, placing more stress on the electricity grid and increasing electricity costs. Although the majority of U.S. residential and commercial cooling demand is met with electricity, less than 9% of heating demand is met with electricity.[6, 7] Therefore, although higher average temperatures are expected to reduce electricity demands for heating, net electricity use is projected to increase under climate change. This section presents estimated impacts on electricity demand, but does not consider impacts on demand for other fuel sources used in residential cooling or heating.

Risks of Inaction

Rising temperatures are projected to increase electricity demands for cooling. Figure 1 shows the percent change in regional heating and cooling degree days (HDDs/CDDs, see Approach for definitions) from 2005 to 2050 in the Reference scenario. Results are presented for the three models used in the analysis (GCAM, ReEDS, and IPM), which exhibit similar trends of falling HDDs (shown in purple) and rising CDDs (shown in orange). These trends are consistent with projections described in the assessment literature.[8] Across the U.S., HDDs decrease between 18%-29% on average, with greater decreases occurring in the South due in part to already-high temperatures. The increase in CDDs is highest in the Northeast and Northwest (68% and 71% on average, respectively). The projected changes in HDDs and CDDs have implications for regional electricity demand. Average U.S. electricity demand is projected to increase under the Reference by 1.5%-6.5% by 2050, compared to a Control with no temperature change. Across the regions and models shown in Figure 2, electricity demand is projected to increase by 0.5%-9.0%, with the exception of the ReEDS model in the Northwest, which projects a decrease of 0.5%.[9]

Figure 1. Projected Impact of Unmitigated Climate Change on Regional Heating and Cooling Degree Days from 2005 to 2050

Percent change in HDDs and CDDs from 2005 to 2050 under the Reference compared to a Control with no temperature change. Results are presented for six regions and for the three models used in the analysis.

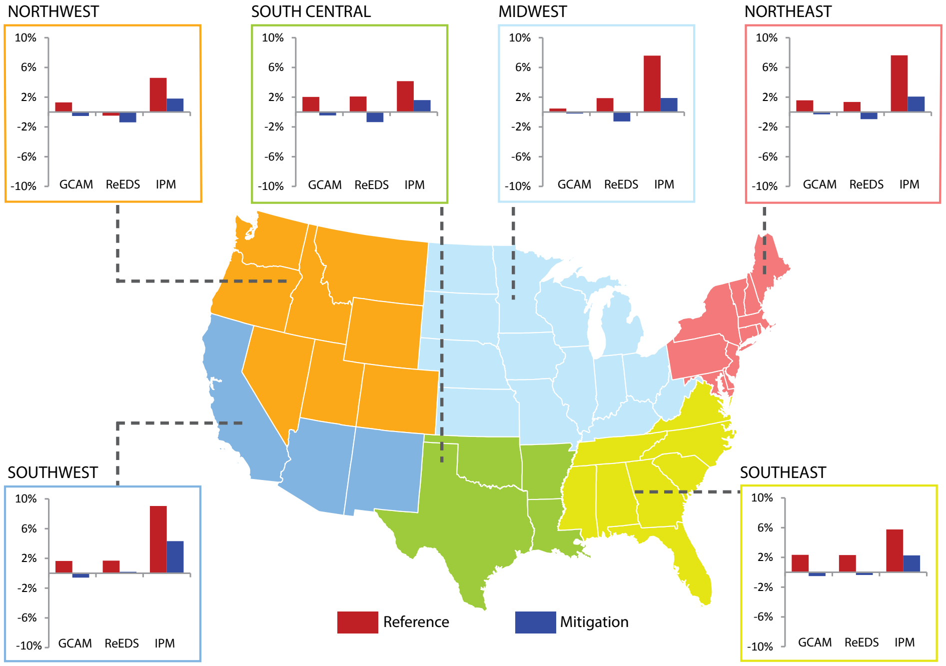


Reducing Impacts through GHG Mitigation

Global GHG emissions reductions under the Mitigation scenario result in smaller increases in temperatures compared to the Reference, thereby reducing cooling demand across the country. Figure 2 illustrates this effect, presenting the change in regional energy demand in 2050 in the Reference and Mitigation scenarios relative to a Control with no temperature change. As shown, the change in demand in the Mitigation scenario is consistently lower than in the Reference across all of the models. This decrease in demand is due in large part to lower temperatures under the Mitigation scenario compared to the Reference, and in the GCAM and ReEDS models the lower demand is also due to an increase in electricity costs associated with reducing GHG emissions. The impact of GHG mitigation on electricity supply is discussed in greater detail in the Electricity Supply section of this report.

Figure 2. Change in Regional Electricity Demand in 2050 with and without Global GHG Mitigation

Change in regional electricity demand for the Reference and Mitigation scenarios relative to a Control (no temperature change). Results are presented for six regions and for each of the three models used in the analysis (GCAM, ReEDS, and IPM).



APPROACH

The CIRA analysis examines how rising temperatures under climate change will affect electricity demand. It applies a common set of temperature projections from IGSM-CAM to three models of the U.S. electric power sector:

- Global Change Assessment Model (GCAM-USA): a detailed, service-based building energy model for the 50 U.S. states;[10, 11]
- 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.;[12] and
- Integrated Planning Model (IPM®): a dispatch and capacity planning model used by the public and private sectors to inform business and policy decisions.[13]

The models project changes in electricity demand as functions of changes in heating and cooling degree-days (HDDs/CDDs). 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 analysis compares the results across the CIRA scenarios, while also accounting for non-climate changes in electricity demand (e.g., population and economic growth). To assess the effect of rising temperatures in the Reference and Mitigation scenarios, changes in heating and cooling degree days and electricity demand are compared to a Control that assumes temperatures do not change over time.

For more information on the CIRA approach and results for the electricity demand sector, please refer to McFarland et al. (2015).[14]

Electricity Supply

KEY FINDINGS

① Projected electricity supply is higher in all three electric power sector models under the Reference scenario, reflecting a higher demand for cooling, and lower under the Mitigation scenario as a result of lower temperatures and the demand response to GHG mitigation.

② The relative magnitude of costs to the electric power system are similar under the Reference and Mitigation scenarios, highlighting that the costs associated with rising temperatures in the Reference are comparable to the costs associated with reducing GHG emissions in the Mitigation scenario. Specifically, the higher demands under the Reference scenario increase system costs by 1.7%-8.3% above the Control. Under the Mitigation scenario, system costs increase by 2.3%-10% above the Control, or 0.6%-5.5% above Reference scenario costs.

Climate Change and Electricity Supply

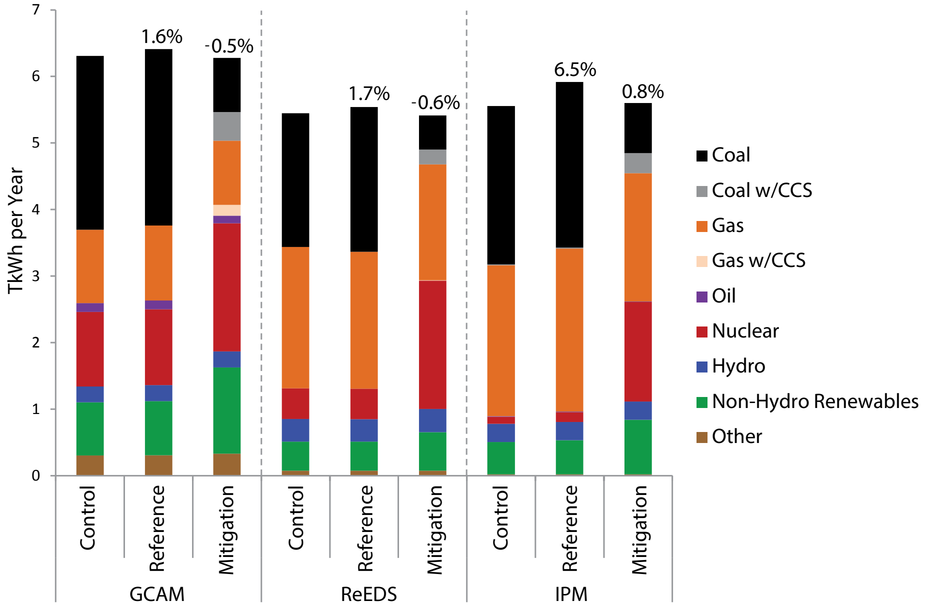
As described in the Electricity Demand section, warmer air temperatures under climate change are expected to result in higher demand for electricity, leading to the need for increased capacity in the power system to meet this demand. At the same time, higher temperatures reduce the capacity of both thermal power plants and transmission lines.

The power sector accounts for the largest share of GHG emissions in the U.S.,[15] and is also considered the most cost-effective source of emission reductions under mitigation policies.[16] A variety of impacts and changes are therefore expected to occur in this sector, including changes in sector emissions, system costs, and generation mix (i.e., the assortment of fuels used to generate electricity).

Effects on Electricity Generation

In the CIRA analyses, a large amount of CO_2 reductions in the U.S. under the Mitigation scenario occur in the electricity sector.[17] As a result, the generation capacity and mix of energy sources used to produce electricity is projected to change over time. Figure 1 shows the projected change in generation mix in 2050 from the three electric power sector models under the CIRA scenarios. Projected electricity supply is higher in all three models under the Reference, reflecting a higher demand for cooling, and lower under the Mitigation scenario as a result of lower temperatures and the costs of reducing GHG emissions. For any given model, the supply mix in the Reference does not differ substantially from the Control, which accounts for future population and economic growth, but no temperature change. However, all three models under the Mitigation scenario project substantial reductions in coal generation and expanded generation from nuclear and renewables.

Figure 1. Electricity Generation by Technology and Scenario in 2050 with Percent Change in Generation from Control[18]

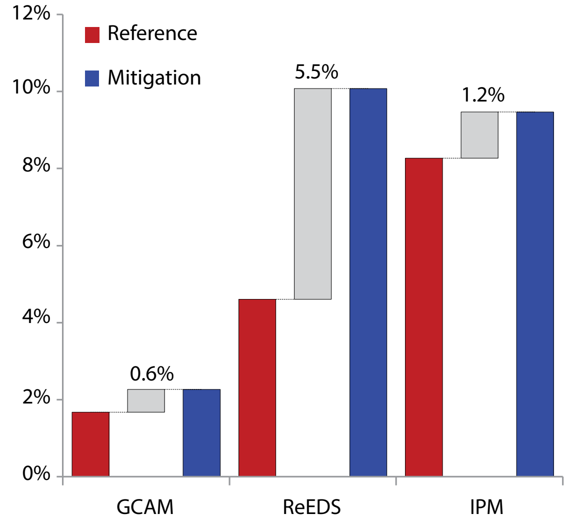


Change in System Costs

Rising temperatures under both scenarios, especially under the Reference, result in higher demands for electricity and increased power system costs to expand capacity. At the same time, altering the generation mix to reduce GHG emissions imposes costs on the power system. Figure 2 presents the percent change in cumulative system costs under the Reference and Mitigation scenarios compared to a Control with no temperature change (2015-2050, discounted at 3%). The costs increase by 1.7%-8.3% under the Reference and by 2.3%-10% under the Mitigation scenario. The incremental system costs of the Mitigation scenario above the Reference are 0.6%-5.5%, highlighting that the costs to the electric power sector associated with rising temperatures in the Reference are comparable to the costs associated with reducing GHG emissions in the Mitigation scenario. It is important to note, however, that this does not account for benefits of GHG mitigation outside of the electricity sector, nor does it examine other effects of climate change on electricity supply, such as changes in cooling water availability or extreme weather events.

Figure 2. Percent Change in Cumulative System Costs (2015-2050) in the Reference and Mitigation Scenarios Compared to the Control

Grey bars represent the difference between the Reference and Mitigation scenarios.



APPROACH

The CIRA analysis assesses impacts on the U.S. electricity sector's supply side using the same three models described in the Electricity Demand section. The models project changes in the generation mix needed to meet increasing demand due to future warming and socioeconomic changes (e.g., population and economic growth) under the CIRA scenarios. The three models also estimate the corresponding system costs—comprised of capital, operations and maintenance, and fuel costs—and the changes in CO_2 emissions over time. This analysis is unique compared to the other sectoral analyses of this report in that the costs of GHG mitigation in the electric power sector are estimated alongside the benefits. The three electric power sector models simulate these costs over time, and the rationale for presenting them here is to provide a comparison between the increase in power system costs due to mean temperature increases under the two scenarios and the costs associated with reducing GHG emissions from electric power generation. It is important to note that the effect of temperature change on generation accounts for only a small portion of the total effects of climate change on electricity supply. Other important effects, such as changes in hydropower generation or the availability of cooling water for thermoelectric combustion, are not included. Inclusion of these impacts on the electricity supply system would likely increase the benefits of mitigation to this sector.

For more information on the CIRA approach and results for the electricity supply sector, please refer to McFarland et al. (2015).[19]

Water Resources

SUBSECTORS

Inland Flooding

Drought

Water, a resource that sustains life across the globe, is a vital component of a productive economy, providing a critical input to production in a number of key economic sectors.[1] In the U.S., water is used in many ways, including for human consumption, agricultural irrigation, power plant cooling, and hydropower generation. In addition, rivers, lakes, and oceans allow for navigation, fishing, and recreation activities. Water also plays an array of vital roles in ecosystems, which in turn provide crucial services that support human life. Analyzing the effects of climate change on water resources can be particularly challenging as climate variables affect both the supply and demand of water in different ways, and the impacts vary over space and time.

HOW IS WATER VULNERABLE TO CLIMATE CHANGE?

The water cycle is inextricably linked to climate, and climate change has a profound impact on water availability at global, regional, and local levels. As temperatures rise, the rate of evaporation increases, which makes more water available in the air for precipitation but also contributes to drying over some areas.[2] Further, climate change will result in increased intensity of precipitation events, leading to heavier downpours. Therefore, as climate change progresses, many areas are likely to see increased precipitation and flooding, while others will experience less precipitation and increased risk of drought. Some areas may experience both increased flooding and drought. Many of these meteorological changes, along with their associated impacts, are already being observed across the U.S. These changes, combined with demographic, socioeconomic, land use, and other changes, affect the availability, quality, and management of water resources in the U.S.[3]

WHAT DOES CIRA COVER?

The CIRA analyses estimate impacts and damages from three water resource-related models addressing flooding, drought, and water supply and demand (see the Health section of this report for water quality impacts). The models differ in the component of the water sector assessed and geographic scale, but together provide a quantitative characterization of water sector effects that no single model can capture. As the water cycle is sensitive to changes in precipitation, the analyses use a range of projections for future precipitation (see the CIRA Framework section for more information). Finally, future work to improve connectivity between the CIRA electricity, water, and agriculture analyses will aid in better understanding potential impacts to these sectors.

Water Supply and Demand

Inland Flooding

KEY FINDINGS

① Warmer temperatures under climate change are projected to increase precipitation intensity in some regions of the contiguous U.S., raising the risk of damaging floods.

② The effect of global GHG mitigation on flooding damages is sensitive to projected changes in precipitation. The flooding analysis using the IGSM-CAM climate model, which projects relatively wet conditions for most of the U.S., estimates that mitigation will result in a reduction in flood damages of approximately $2.9 billion in 2100 compared to the Reference. Using the drier MIROC model, the analysis projects that mitigation will result in disbenefits of approximately $38 million in 2100.

Climate Change and Inland Flooding

Extreme precipitation events have intensified in recent decades across most of the U.S., and this trend is projected to continue.[4] Heavier downpours can result in more extreme flooding and increase the risk of costly damages.[5] Flooding affects human safety and health, property, infrastructure, and natural resources.[6] In the U.S., non-coastal floods caused over 4,500 deaths from 1959 to 2005 and flood-related property and crop damages averaged nearly $8 billion per year[7] from 1981 to 2011.[8] 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 expanded development in floodplains, urbanization, and land-use changes.[9]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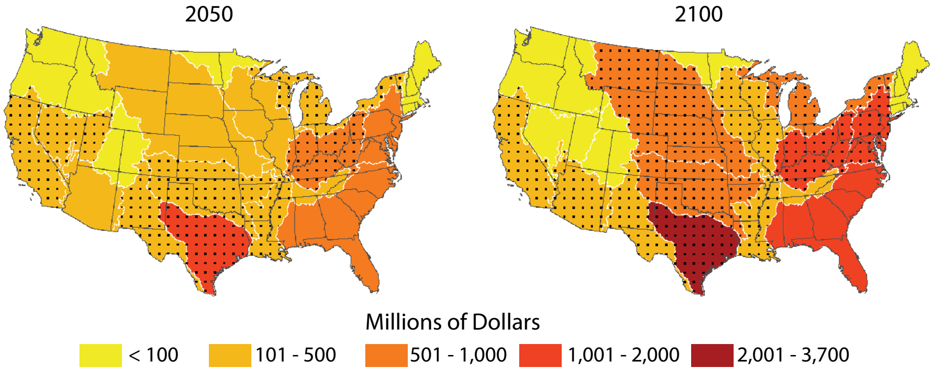
Risks of Inaction

Without GHG mitigation, climate change under the IGSM-CAM projections is estimated to increase monetary damages associated with inland flooding across most of the contiguous U.S. Figure 1 presents the projected flood damages in 2050 and 2100 under the Reference scenario. As shown, substantial damages are projected to occur in more regions over time. By 2100, damages are projected to be significantly different from the historic period (at a 90% confidence interval) in 11 of the 18 large watersheds (2-digit hydrologic unit codes). The greatest damages are projected to occur in the eastern U.S. and Texas, with damages in these regions ranging from $1.0-$3.7 billion in 2100.[10] Projections of increased flood damages across most of the U.S. are consistent with the findings of the assessment literature.[11]

Figure 1. Estimated Flood Damages Due to Unmitigated Climate Change

Estimated flood damages under the Reference scenario in 2050 and 2100 for the IGSM-CAM climate model (millions 2014$). Results are presented for the 18 2-digit hydrologic unit codes (HUCs) of the contiguous U.S. Stippled areas indicate regions where the projected damages are significantly different from the historic period (at a 90% confidence interval).



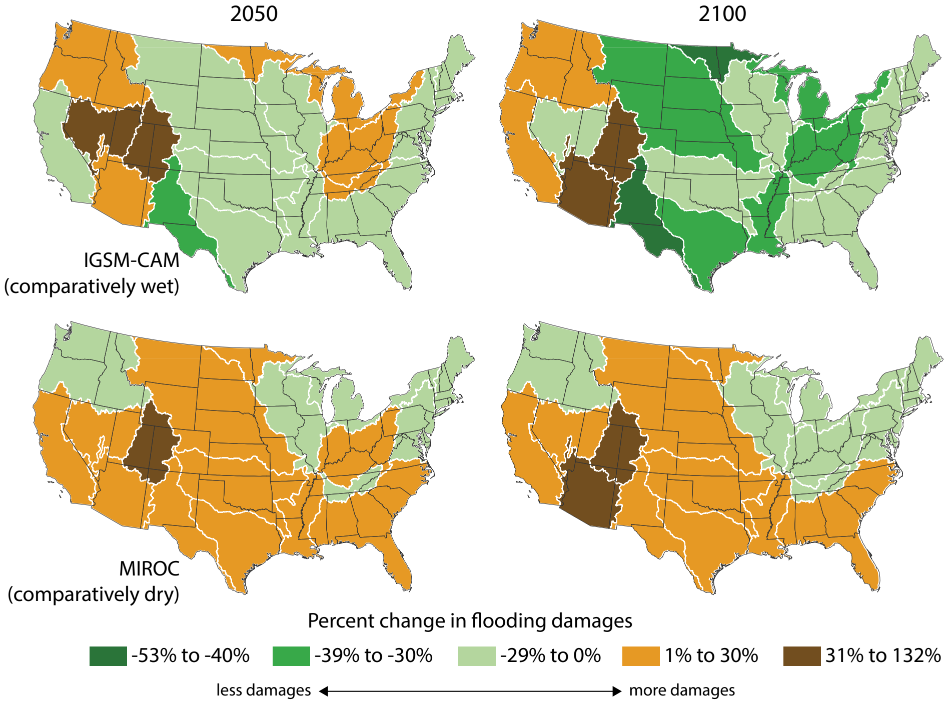
Reducing Impacts through GHG Mitigation

Under the relatively wetter IGSM-CAM climate projections, global GHG mitigation is projected to result in increased flooding damages compared to today, but decreased damages compared to the Reference scenario in most regions of the contiguous U.S. As shown in Figure 2, damages are reduced in 10 out of 18 regions in 2050 and in 14 out of 18 regions in 2100, with particularly pronounced differences between the scenarios in 2100. In 2100, the modeled reduction in damages is approximately $2.9 billion. By the end of the century, substantial benefits are projected over much of the Great Plains and Midwest regions, where damages are estimated to be reduced between 30% and 40% in many states. The four regions not showing benefits of GHG mitigation under the IGSM-CAM projections are located in the western part of the U.S., which also faces the highest risk of drought, as described in the Drought section of this report.

Figure 2 also presents results using the MIROC climate model, which projects a drier future compared to the IGSM-CAM model. Under the MIROC projections, flooding damages are generally reduced under both the Reference and Mitigation scenarios and, as a result, there are modest disbenefits of mitigation across most of the contiguous U.S. in 2050 and 2100. In 2100, damages are projected to increase nationally by $38 million under the Mitigation scenario compared to the Reference.

Figure 2. Change in Flooding Damages Due to Global GHG Mitigation

Percent change in flooding damages for the Mitigation scenario compared to the Reference. Results are presented for the 18 2-digit HUCs of the contiguous U.S. Negative values, shown in green, reflect reductions in flooding damages from global GHG mitigation.



APPROACH

The CIRA analysis quantifies how climate change could affect inland flooding damages in the contiguous U.S. Given the complexities inherent in projecting national flood damages, including the need for small watershed-scale hydrologic modeling, the results presented in this section should be considered first-order estimates. The analysis estimates changes in inland (non-coastal) flood damages following the approach described in Wobus et al. (2013).[12] Specifically, the analysis applies statistical relationships between historical precipitation and observed flood damages in each region of the U.S. to estimate the probability of damaging events occurring in a given year for the baseline period (1983-2008). Flood probabilities are then updated based on precipitation projections for specific events (i.e., 1-, 3-, 5-, and 7-day precipitation totals) under the Reference and Mitigation scenarios to estimate future flood damages. The analysis relies upon climate projections from two climate models: IGSM-CAM, which projects a relatively wetter future for most of the U.S., and the drier MIROC model. Damages are aggregated to the 18 U.S. Geological Survey National Water Resource Regions (WRRs) for two future periods (2050 and 2100), and are then statistically compared to modeled damages for the historic period. Importantly, the estimated damages do not include impacts on human health or economic disruption. The approach assumes that the distribution of monetary damages from flooding, including the effects of non-climate risk factors, will not change in the future.[13] Finally, the value of damages occurring in the future is scaled to account for changes in wealth using projected increases in per capita income in the two CIRA scenarios.

For more information on the CIRA approach and results for flooding damages, please refer to Strzepek et al. (2014)[14] and Wobus et al. (2013).[15]

Drought

KEY FINDINGS

① In the absence of global GHG mitigation, climate change is projected to result in a pronounced increase in the number of droughts in the southwestern U.S.

② Global GHG mitigation leads to a substantial reduction in the number of drought months in the southwestern U.S. in both climate models analyzed. The effect of GHG mitigation in other regions is highly sensitive to projected changes in precipitation.

③ The reduction in drought associated with GHG mitigation provides economic benefits to the crop-based agriculture sector ranging from $9.3-$34 billion through 2100 (discounted at 3%).

Climate Change and Drought Risk

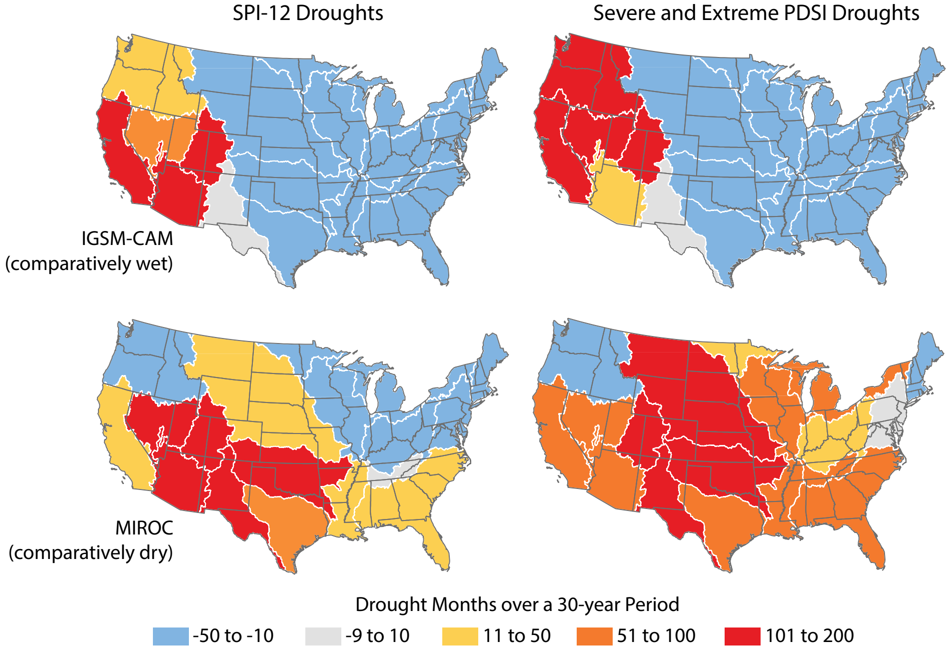
Climate change-related impacts on temperature and precipitation are expected to alter the location, frequency, and intensity of droughts in the U.S., with potentially devastating socioeconomic and ecological consequences.[16] Already, many U.S. regions face increasing water management challenges associated with drought, such as disruptions in navigation and water shortages for irrigation. In recent decades, recurring droughts across the West and Southeast have had significant socioeconomic and ecological impacts.[17]

Risks of Inaction

Without global GHG mitigation, climate change threatens to increase the number of droughts in certain regions of the U.S. The CIRA analysis uses multiple climate projections, each with unique patterns of regional change, to estimate the change in the number of SPI and PDSI droughts (see Approach for descriptions).[18] As discussed in the CIRA Framework section of this report, the IGSM-CAM projects a relatively wetter future for most of the contiguous U.S., while the MIROC model projects a drier future. Figure 1 shows that, although the climate models estimate different outcomes with respect to drought risk for the central and eastern U.S., they both project that the Southwest will experience pronounced increases in both SPI and PDSI drought months. Some areas of the country that are projected to experience increases in drought by 2100 are also projected to experience higher flooding damages (see the Inland Flooding section). This finding should not be interpreted as a conflicting result, and is consistent with the conclusions of the assessment literature,[19] which describe the drivers of these changes as more intense yet less frequent precipitation, and increases in evaporation due to higher temperatures.[20]

Figure 1. Effects of Unmitigated Climate Change on Drought Risk by 2100

Projected change in number of SPI and PSDI drought months under the Reference scenario over a 30-year period centered on 2100. Results are presented for the 18 2-digit hydrologic unit codes (HUCs) of the contiguous U.S. Changes occurring in the grey-shaded areas should be interpreted as having no substantial change between the historic and future periods.



Reducing Impacts through GHG Mitigation

Global GHG mitigation leads to a substantial reduction in drought risk for many parts of the country (Figures 2 and 3). Under the IGSM-CAM climate projections, GHG mitigation substantially reduces drought occurrence across the western U.S., while under the MIROC model, drought is reduced over a majority of the country. Both climate models project reductions in drought in the Southwest, where the risks of increased droughts were highest under the Reference.

The overall decrease in the number of droughts under the Mitigation scenario, particularly in the West, results in substantial benefits to the crop-based agriculture sector. Through 2100, the present value benefits of GHG mitigation in the agricultural sector reach $9.3 billion (discounted at 3%) using the IGSM-CAM climate projections, compared to the Reference. Using the drier MIROC climate model, the Mitigation scenario provides benefits to the agriculture sector of approximately $34 billion (discounted at 3%). Projections from both climate models estimate higher economic benefits of GHG mitigation in the southwestern U.S., where drought frequency is projected to increase most dramatically in the absence of GHG mitigation.

Figure 2. Percentage Change in Number of Severe and Extreme Drought Months with and without GHG Mitigation

Change in number of PDSI drought months under the Reference and Mitigation scenarios over a 30-year period centered on 2100 in the contiguous U.S. Under both climate models, GHG mitigation results in fewer drought months compared to the Reference.

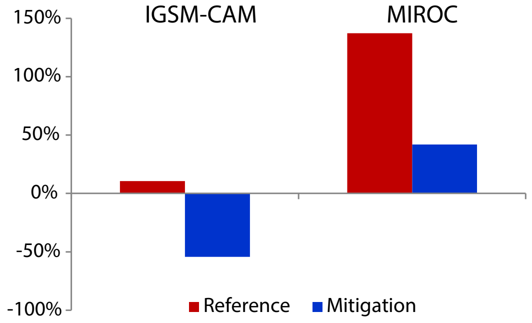
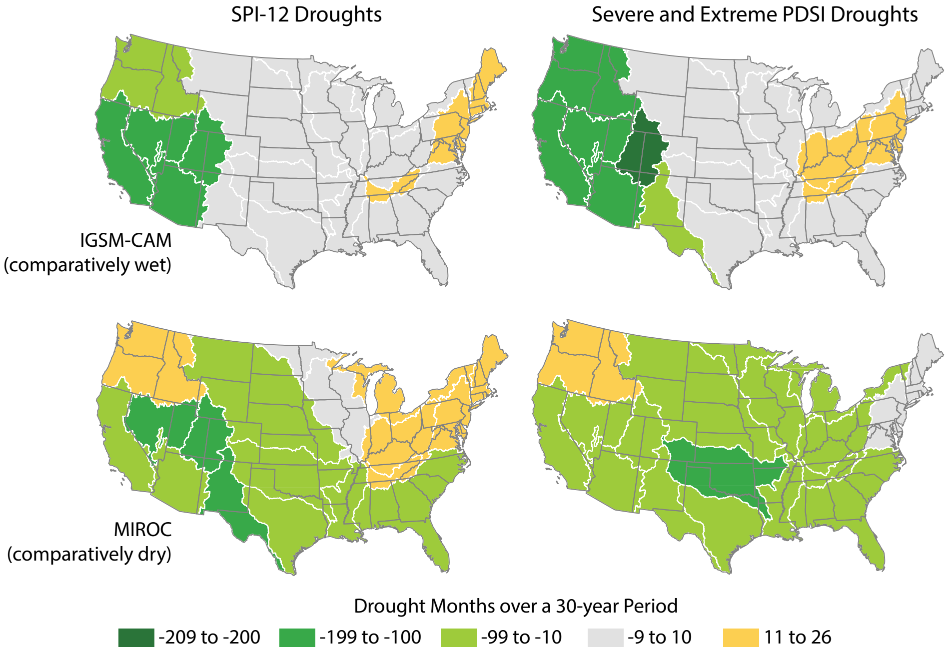


Figure 3. Effect of Global GHG Mitigation on Drought Risk by 2100

Estimated change in number of SPI and PDSI drought months under the Mitigation scenario compared to the Reference over a 30-year period centered on 2100. Results are presented for the 18 2-digit HUCs of the contiguous U.S. Shades of green represent reductions in the number of drought months due to GHG mitigation. Changes occurring in the grey-shaded areas should be interpreted as having no substantial change between the historic and future periods.



APPROACH

The CIRA analysis estimates the effect of climate change on the frequency and intensity of droughts across the contiguous U.S. The approach is based on the methodology from Strzepek et al. (2010).[21] It relies on two drought indices for both the historical and two 21st century time periods. The drought indices account for changes in key climate variables: the Standardized Precipitation Indices (SPI-5 and SPI-12) measure meteorological drought based on change in precipitation from the historical median, and the Palmer Drought Severity Index (PDSI) uses precipitation and temperature data to estimate the relative changes in a particular region's soil moisture. Drought risk is calculated for 99 sub-basins or watersheds in the contiguous U.S. and aggregated to 18 2-digit HUC regions.

The analysis then estimates the effect on crop-based agriculture of the change in frequency and intensity of droughts under the CIRA climate projections. This approach projects impacts using a sectoral model that relates historical drought occurrence with impacts on crop outputs.[22] The resulting relationships are then applied to climate projections under the CIRA Reference and Mitigation scenarios using the IGSM-CAM and MIROC climate models to estimate the economic impacts of climate change and effects of GHG mitigation.[23] This analysis only monetizes the impacts of drought on crop-based agriculture, and does not include other damages (e.g., decreased water availability, ecosystem disruption). Therefore the results estimated here likely underestimate the benefits of GHG mitigation for this sector.

For more information on the CIRA approach and results for the drought sector, please refer to Strzepek et al. (2014)[24] and Boehlert et al. (2015).[25]

Water Supply & Demand

KEY FINDINGS

① Unmitigated climate change is projected to have profound impacts on both water availability and demand in the U.S., compounding challenges from changes in demographics, land use, energy generation, and socioeconomic factors.

② Without global GHG mitigation, damages associated with the supply and demand of water across the U.S. are estimated to range from approximately $7.7-$190 billion in 2100. The spread of this range indicates that the effect of climate change on water supply and demand is highly sensitive to projected changes in runoff and evaporation, both of which vary greatly across future climate projections and by U.S. region.

③ Global GHG mitigation is estimated to substantially decrease damages compared to the Reference. Projected benefits under the Mitigation scenario range from $11-$180 billion in 2100, depending on projected future climate. Importantly, global GHG mitigation is projected to preserve water supply and demand conditions more similar to those experienced today.

Climate Change and Water Supply and Demand

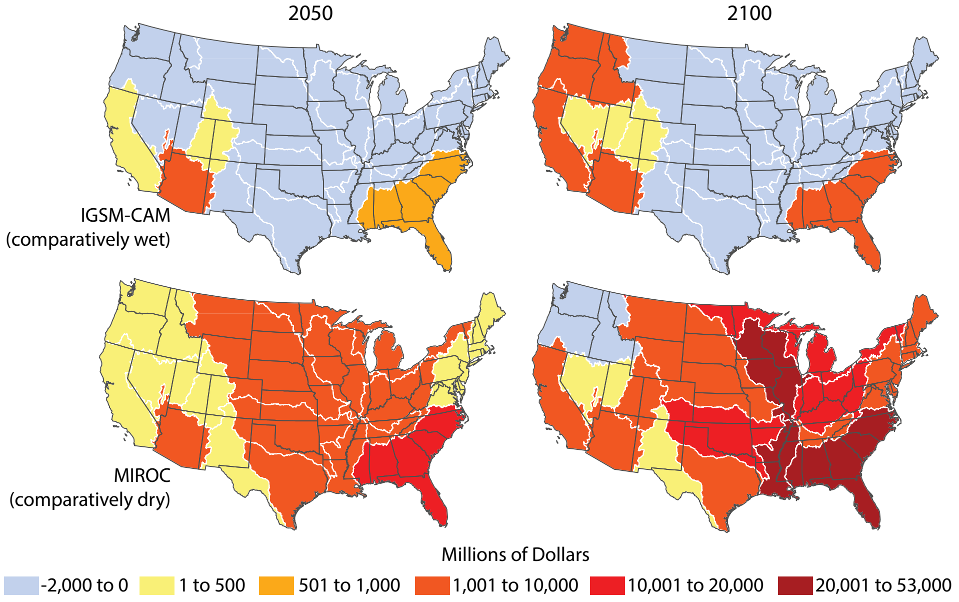
Water management in the U.S. is characterized by the struggle to balance growing demand from multiple sectors of the economy with increasingly limited supplies in many areas. Unmitigated climate change is projected to have profound impacts on both water availability and demand in the U.S., compounding challenges from changes in demographics, land use, energy generation, and socioeconomic factors. As temperatures rise and precipitation patterns become more variable, changes in regional water demand and surface and groundwater supplies are expected to increase the likelihood of water shortage for many areas and uses.[26]

Risks of Inaction

The effect of climate change on water supply and demand is highly sensitive to projected changes in runoff and evaporation, both of which vary across future climate projections and by U.S. region (Figure 1). Despite these variations, increased damages of unmitigated climate change are projected in the Southwest and Southeast regions under both climate models, and these damages increase over time. These projections are consistent with the findings of the assessment literature.[27] Using climate projections from the IGSM-CAM model, the analysis estimates damages at $7.7 billion in 2100. Despite the majority of U.S. regions showing modest increases in welfare (economic well-being) in 2100, the damages in the Southwest and Southeast are much larger in magnitude, and therefore drive the national total. Highlighting the sensitivity of this sector to the climate model used, the drier MIROC model estimates that net damages could be substantially larger, at approximately $190 billion in 2100.

Figure 1. Projected Impacts of Unmitigated Climate Change on Water Supply and Demand

Estimated change in economic damages under the Reference scenario in 2050 and 2100 compared to the historic baseline for the IGSM-CAM and MIROC climate models (millions 2014$). Results are presented for the 18 2-digit hydrologic unit codes (HUCs) of the contiguous U.S. Yellow, orange, and red areas indicate increased damages, while blue areas indicate decreased damages.



Reducing Impacts through GHG Mitigation

Global GHG mitigation is projected to substantially reduce damages compared to the Reference (Figures 2 and 3), and importantly, preserve water supply and demand conditions more similar to those experienced today. The IGSM-CAM model estimates that damages are \$7.7 billion under the Reference scenario in 2100, while the Mitigation scenario results in an increase in welfare (collective economic well-being of the population) of \$3.4 billion. Therefore, mitigation is estimated to result in a total increase in welfare of \$11 billion in 2100 compared to the Reference. Using the drier MIROC model, the Mitigation scenario yields damages of approximately \$19 billion in 2100; however, this represents avoided damages of approximately \$180 billion compared to the Reference scenario (numbers do not sum due to rounding).

Figure 2. Economic Damages Associated with Impacts on Water Supply and Demand with and without Global GHG Mitigation

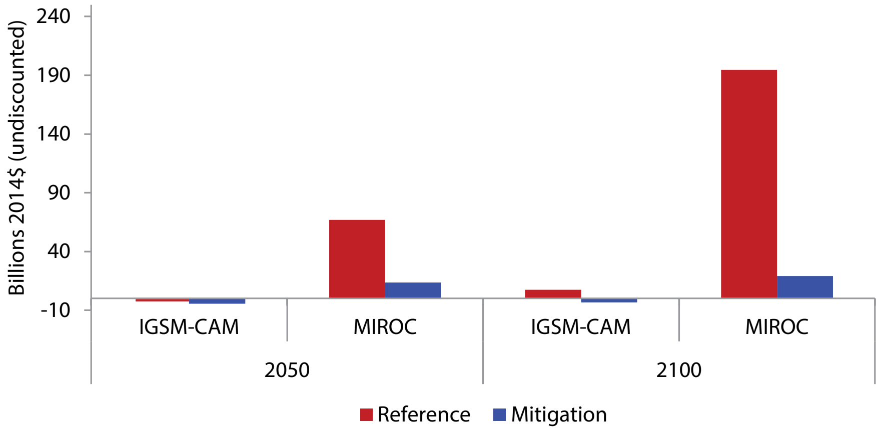
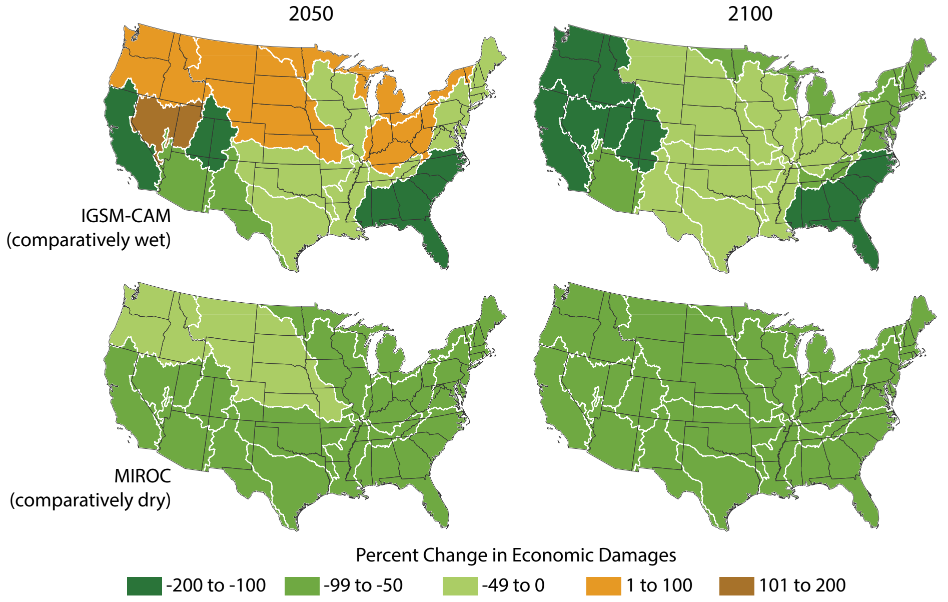


Figure 3. Projected Impacts of GHG Mitigation on Water Supply and Demand

Estimated percent change in economic damages under the Mitigation scenario in 2050 and 2100 relative to the Reference. Results are presented for the 18 2-digit HUCs of the contiguous U.S. Negative values (shown in green) indicate decreases in damages, or positive economic benefits, due to global GHG mitigation.



APPROACH

The CIRA analysis estimates the economic impacts associated with changes in the supply and demand of water, based on a national-scale optimization model developed by Henderson et al. (2013).[28] The model simulates changes in supply and demand in 99 sub-regions or watersheds of the contiguous U.S. based on changes in runoff and evaporation, population, irrigation demand, and other inputs that vary over time. Economic impact functions are applied for a range of water uses including irrigated agriculture, municipal and domestic water use, commercial and industrial water use, hydroelectric power generation, and in-stream flows.[29] The benefits from water use are maximized according to a wide range of constraints, such as storage and conveyance capacities, historic irrigated acreage, and renewable recharge capacity for groundwater. Economic damages are incurred in the model when any one of the water uses specified above does not receive sufficient volume to sustain the baseline activity level. Impacts are summed across all uses in each sub-region and reported as changes in economic welfare. Finally, the optimization model is driven by climate projections from the IGSM-CAM, as well as the MIROC climate model, which projects a relatively drier future for the contiguous U.S. compared to other climate models.[30]

For more information on the CIRA approach and results for the water supply and demand analysis, please refer to Strzepek et al. (2014)[31] and Henderson et al. (2013).[32]

Agriculture and

SUBSECTORS

Crop and Forest Yields

Forestry

The U.S. has a robust agriculture sector that produces nearly $330 billion per year in agricultural commodities.[1] The sector ensures a reliable food supply and supports job growth and economic development.[2] 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.[3]

U.S. forests provide a number of important goods and services, including timber and other forest products, recreational opportunities, cultural resources, and habitat for wildlife. Forests also provide opportunities to reduce future climate change by capturing and storing carbon, and by providing resources for bioenergy production.[4]

HOW ARE AGRICULTURE AND FORESTRY VULNERABLE TO CLIMATE CHANGE?

U.S. agricultural and forest production are sensitive to changes in climate, including changes in temperature and precipitation, more frequent and severe extreme weather events, and increased stress from pests and diseases.[5] At the same time, climate change poses an added risk to many forests due to ecosystem disturbance and tree mortality through wildfire, insect infestations, drought, and disease outbreaks.[6] Climate change has the potential to both positively and negatively affect the location, timing, and productivity of agricultural and forest systems, with economic consequences for and effects on food security and timber production both in the U.S. and globally.[7,8] Adaptation measures, such as changes in crop selection, field and forest management operations, and use of technological innovations, have the potential to delay and reduce some of the negative impacts of climate change, and could create new opportunities that benefit the sector.

WHAT DOES CIRA COVER?

The CIRA analysis estimates climate change impacts on the agriculture and forestry sectors using both biophysical and economic models. The agriculture analyses demonstrate effects on the yield and productivity of major crops, such as corn, soybean, and wheat, but do not include specialty crops, such as tree fruits, or livestock. Further, the analysis does not explicitly model impacts on biofuel production or include technological advances in agricultural management practices. The analyses include yield and productivity impacts, but do not simulate the effects of changes in wildfire, pests, disease, and ozone. Future work to improve the multiple interactions among the CIRA energy, water, and agriculture analyses will aid in better understanding potential impacts to these sectors.

Market Impacts

KEY FINDINGS

1. Unmitigated climate change is projected to result in substantial decreases in yields for most major agricultural crops.

2. Global GHG mitigation is projected to substantially benefit U.S. crop yields compared to the Reference scenario.

3. Without considering the influence of wildfires, the effect of GHG mitigation on forest productivity is less substantial compared to the response for crops. The direction of the effect depends strongly upon climate model and forest type (hardwood vs. softwood).

Risks of Inaction

Without significant global GHG mitigation, climate change is projected to have a large negative impact on the U.S. agriculture sector. Table 1 presents the projected percent change in national crop yields in 2100 due to unmitigated climate change under the Reference scenario. For all major irrigated crops, with the exception of hay, climate projections from both the IGSM-CAM and MIROC models result in decreased yields, with very substantial declines projected for soybeans, sorghum, and potatoes. For rainfed crops, climate projections using the drier MIROC climate model result in substantial declines for all crops, particularly cotton, sorghum, hay, wheat, and barley. Rainfed yields using the wetter IGSM-CAM climate model are more varied, ranging from a substantial decrease in hay yields to moderate gains in cotton, sorghum, and wheat yields.[9] Projected declines in crop productivity resulting from unmitigated climate change over the longer term are consistent with the findings of the assessment literature.[10]

As shown in Figure 1, the effect of unmitigated climate change on forest productivity in the U.S. varies over time and depends on the climate model used. Using the IGSM-CAM projections, hardwood yields increase by 2100, while the change in softwood yields is very small. Projections using the drier MIROC climate model result in increased hardwood and softwood yields by the end of the century, though the gains are smaller than those projected under the Mitigation scenario.

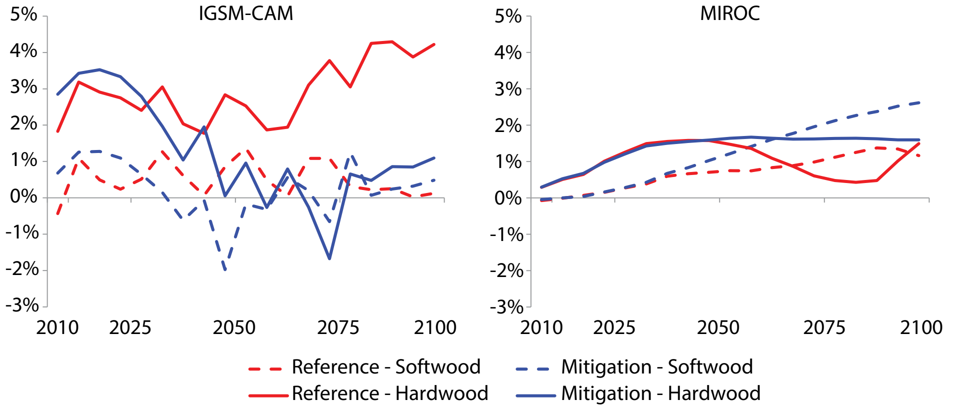
Table 1. Projected Percent Change in U.S. Crop Yields in 2100 without Global GHG Mitigation

Estimates in this table assume no technological improvements in yields over time such that crop productivity in future periods relative to a scenario with no climate change is based purely on differences in climatic conditions. This assumption allows the analysis to isolate and evaluate climate change impacts on crops without confluence with other factors. Results do not include effects from changes in ozone, pests, and disease. Rice and potatoes are simulated under irrigated management only.[11]

CROP	IGSM-CAM		MIROC	
	RAINFED	IRRIGATED	RAINFED	IRRIGATED
Cotton	17%	-11%	-27%	-17%
Corn	6%	-3%	-8%	-10%
Soybean	-5%	-20%	-19%	-23%
Sorghum	18%	-17%	-29%	-22%
Rice	n/a	-3%	n/a	-3%
Hay	-62%	29%	-65%	32%
Potato	n/a	-33%	n/a	-39%
Wheat	18%	-8%	-19%	-13%
Barley	-16%	-22%	-29%	-11%

Figure 1. Projected Change in Potential Forestry Yields with and without Global GHG Mitigation

Percent change in potential hardwood and softwood yields across the U.S. relative to the base period (1980-2009) under the Reference and Mitigation scenarios for the IGSM-CAM and MIROC climate models. Effects of wildfire, pest, and disease on yields are not included.



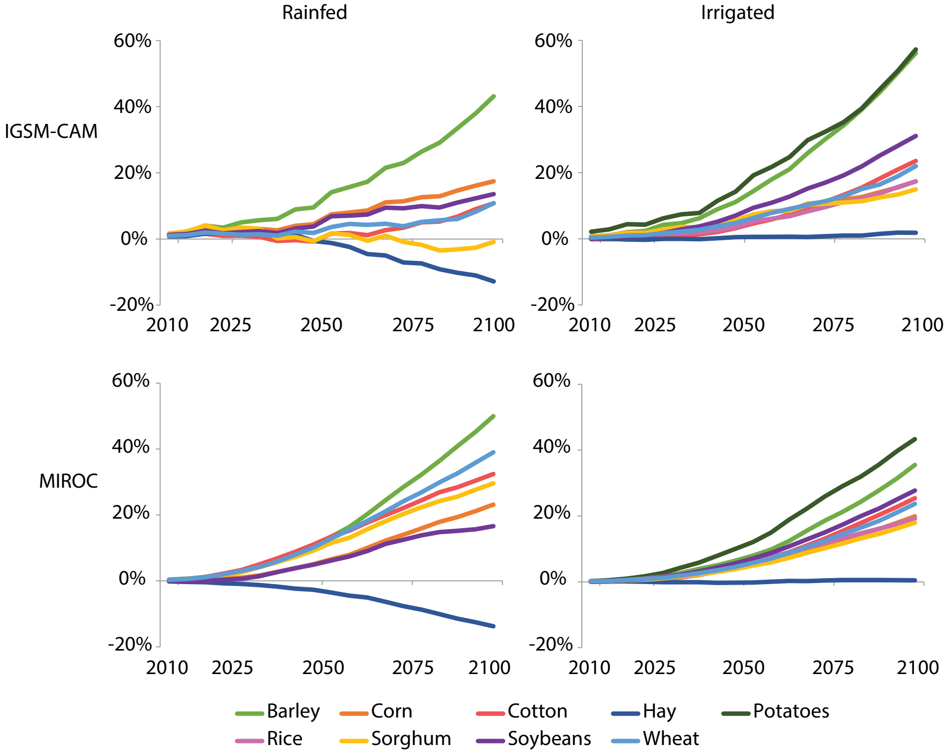
Reducing Impacts through GHG Mitigation

Global GHG mitigation is estimated to substantially benefit U.S. crop yields. Figure 2 presents the projected change in national crop yields for key crops under the Mitigation scenario compared to the Reference. The figure shows changes in rainfed and irrigated yields using projections from the IGSM-CAM climate model and the relatively drier MIROC model. In general, the benefits to crop yields of global GHG mitigation increase over the course of the century, with the exception of rainfed hay (for both climate models) and rainfed sorghum (for IGSM-CAM). Global GHG mitigation is projected to have a particularly positive effect on the future yields of irrigated soybeans, irrigated potatoes, and irrigated and rainfed barley.

The projected effect of GHG mitigation on forest productivity is less substantial compared to the response for crops. Figure 1 shows the estimated percent change in average national forest productivity (contiguous U.S.) under the Reference and Mitigation scenarios relative to the base period. Although forest productivity generally increases with climate change under both scenarios, projections using the relatively wetter IGSM-CAM climate model result in larger gains under the Reference scenario, particularly for hardwoods. Higher forest productivity under the IGSM-CAM Reference in the future is likely driven by the enhanced positive effects of CO_2 fertilization under the high-emission Reference, along with the response to increases in precipitation in many areas of the contiguous U.S. that are forested. The MIROC climate projections, on the other hand, result in slightly rising yields of both hardwoods and softwoods through 2100 under the Mitigation case. It is important to note that these yield estimates do not include the effects of wildfire, pests, or disease, which would likely decrease simulated productivity based on the findings of the assessment literature,[12] especially under the Reference scenario (See Wildfire section of this report).[13]

Figure 2. Projected Impacts of Global GHG Mitigation on Crop Yields

Percent change in crop yields from the EPIC model in the contiguous U.S. under the Mitigation scenario compared to the Reference for the IGSM-CAM and MIROC climate models.[14] Rice and potatoes are simulated under irrigated management only.



APPROACH

The analysis uses the Environmental Policy Integrated Climate (EPIC) model[15,16] to simulate the effects of climate change on crop yields in the contiguous U.S. The analysis examines agricultural crop productivity for multiple crops, including corn, soybean, wheat, alfalfa hay, sorghum, cotton, rice, barley, and potatoes. Yield potential is simulated for each crop for both rainfed and irrigated production with the exception of rice and potatoes, which are assumed to be irrigated.[17] Because production regions may change over time in response to climate change, EPIC simulates potential cultivation and production in areas within 100 km (62 miles) of historical production regions.

EPIC is driven by changes in future climate from both the IGSM-CAM[18] and MIROC climate models under the Reference and Mitigation scenarios. The results presented in this section include the effect of CO_2 fertilization on crop yields; Beach et al. provide a sensitivity analysis of the effect of CO_2 fertilization on the crop yield results from EPIC.

Changes in forest growth rates are simulated using the MC1 dynamic vegetation model, consistent with the approach described in Mills et al. (2014)[19] and the Wildfire and Carbon Storage sections of this report.[20] MC1 is also driven by the IGSM-CAM and MIROC models, and assumes full CO_2 fertilization effects.

The effects of changes in wildfires, pests, disease, and ozone are not captured in this analysis.[21] Inclusion of these effects on crop and forest yields would likely result in increased benefits of GHG mitigation compared to those presented in this section.

For more information on the CIRA approach and results for agriculture and forestry crop yields analysis, please refer to Beach et al.[22]

Market Impacts

KEY FINDINGS

1. Based on the projected changes in yields, global GHG mitigation is estimated to result in lower crop prices over the course of the 21st century compared to the Reference.

2. Changes in crop and forest productivity alter related market dynamics, land allocation, crop mix, and production practices, which in turn affect GHG emissions and carbon sequestration from the agriculture and forestry sectors. Global GHG mitigation has a large effect on emissions fluxes in managed forests: however, the magnitude and direction of the effect are sensitive to climate model projection.

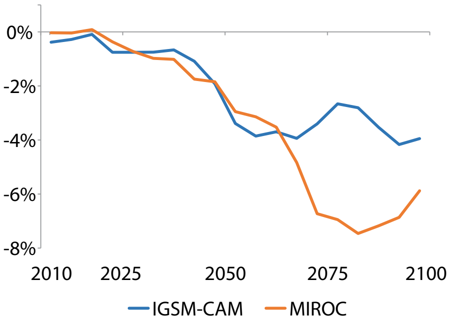
3. Under both climate model projections, global GHG mitigation increases total economic welfare in the agriculture and forestry sectors by $43-$59 billion (discounted at 3%) through 2100 compared to the Reference. The magnitude of estimated economic welfare impacts in the agricultural sector is much larger than in the forestry sector.

Changes in Crop Price

As described in the Crop and Forest Yields section of this report, global GHG mitigation is projected to result in generally higher crop yields in the U.S. relative to the Reference. As a result, mitigation is projected to result in less pressure on land resources and declining commodity prices. As shown in Figure 1, climate projections from both the IGSM-CAM and MIROC climate models show steep declines in a broad index of crop prices starting around 2040. Projections using the drier MIROC climate model result in greater declines in crop prices by the end of the century than those using the wetter IGSM-CAM model. Adverse effects of climate change on crop and food prices, which are largely avoided in the Mitigation scenario, are consistent with the findings of the assessment literature.[23]

Figure 1. Projected Change in National Crop Price Index Due to Global GHG Mitigation

Percent change in crop price index under the Mitigation scenario relative to the Reference for the IGSM-CAM and MIROC climate models.



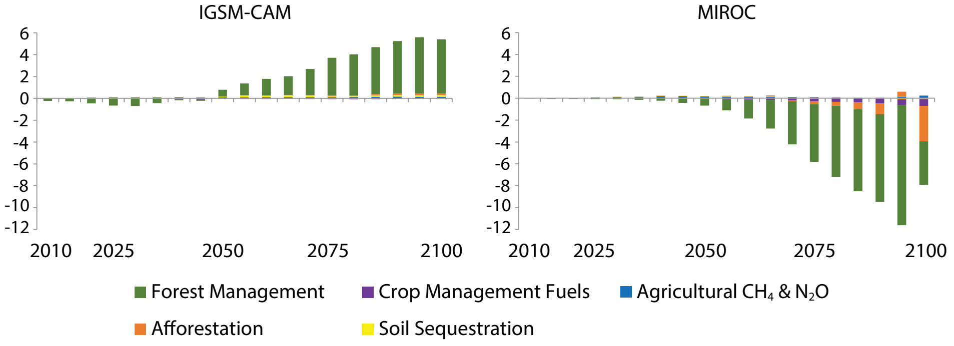
Changes in Emissions

Changes in land allocation, crop mix, and production practices in turn affect GHG emissions from agriculture and forestry practices. Figure 2 shows the estimated changes in cumulative GHG emissions under the Mitigation scenario compared to the Reference using projections from the IGSM-CAM and MIROC climate models. Under the IGSM-CAM projections, GHG mitigation is estimated to increase net GHG emissions from these sectors in the second half of the century. The increase is due in large part to the generally lower forest productivity that is projected to occur under the Mitigation scenario compared to the Reference, as the latter has higher productivity driven by the generally warmer and wetter future climate, as well as the enhanced positive effects of CO_2 fertilization (see the Crop and Forest Yields section). Thus, global GHG mitigation results in less forest carbon sequestration over time. Higher levels of carbon storage in forests under the generally warmer and wetter future of the IGSM-CAM Reference scenario are consistent with the findings presented in the Carbon Storage section of this report.

Under the MIROC climate projections, on the other hand, forest productivity is enhanced under the Mitigation scenario relative to the Reference, and forests take up and store more carbon. In addition, although emissions from livestock agriculture rise, GHG emissions related to crop production generally decline as less area is devoted to crops due to higher yields.

Figure 2. Projected Changes in Accumulated GHG Emissions in the Agriculture and Forestry Sectors Due to Global GHG Mitigation

Projected change in cumulative GHG emissions by type under the Mitigation scenario relative to the Reference for the IGSM-CAM and MIROC climate models (billion metric tons of CO_2 equivalent).



Changes in Consumer and Producer Surplus

The changes in crop prices and the level of production and consumption of agriculture and forestry products have important implications for the economic welfare of consumers and commodity producers. The analysis measures these effects through changes in consumer and producer surplus,[24] as summarized in Table 1. Using both climate model projections, global GHG mitigation increases total economic welfare (well-being) in the agriculture and forestry sectors by $43 to $59 billion (discounted at 3%) through 2100 compared to the Reference. Estimated consumer surplus is higher under the drier MIROC conditions than it is under the IGSM-CAM, primarily due to the larger crop yields under the Mitigation scenario compared to the Reference (see the Crop and Forest Yields section).

The effect of global GHG mitigation on producer surplus varies depending on the climate model used. The IGSM-CAM climate projections result in an increase in producer surplus, though not as substantial as the projected increase in consumer surplus. The drier MIROC projections result in a slight decrease in producer surplus due to the substantial increase in crop yields and resulting decrease in prices.

Table 1. Projected Effect of Global GHG Mitigation on Consumer and Producer Surplus in the Agriculture and Forestry Sectors

Change in cumulative consumer and producer surplus from 2015-2100 under the Mitigation scenario compared to the Reference (million 2014$, discounted at 3%). Results are rounded to two significant digits and therefore may not sum. In addition, the agriculture and forestry results do not sum to totals due to rounding, and because the table reflects independently calculated average values for agriculture, forestry, and combined totals.

	CONSUMER SURPLUS	PRODUCER SURPLUS	TOTAL
IGSM-CAM			
Agriculture	$29,000	$13,000	$43,000
Forestry	$67	$350	$420
TOTAL	$29,000	$14,000	$43,000
MIROC			
Agriculture	$62,000	-$3,300	$59,000
Forestry	-$160	$920	$750
TOTAL	$62,000	-$2,400	$59,000

APPROACH

The CIRA analysis uses the Forest and Agricultural Sector Optimization Model with Greenhouse Gases (FASOM-GHG)[25,26] to estimate changes in market outcomes associated with projected impacts of climate change on U.S. crop and forest yields. As described in the previous section, projected yields across regions and crop/forest types are generated by the EPIC and MC1 models. FASOM-GHG is driven by changes in potential yield from EPIC and MC1 for each of the five initializations of the IGSM-CAM climate model for both the Reference and Mitigation scenarios,[27] as well as the drier MIROC climate model.

FASOM-GHG simulates landowner decisions regarding crop mix and production practices, and projects the allocation of land over time to competing activities in both the forest and agricultural sectors and the associated impacts on commodity markets.[28] Given the changes in potential yields projected by EPIC and MC1, FASOM-GHG uses an optimization approach to maximize consumer and producer surplus over time.[29, 30] The model is constrained such that total production is equal to total consumption, total U.S. land use remains constant (with the potential movement of land from forest to agriculture and vice versa), and non-climate drivers in the agriculture and forestry sectors are consistent between the scenarios to isolate the effect of climate change. In addition, the analysis assumes no price incentives for avoiding GHG emissions or carbon sequestration in the agriculture and forestry sectors (i.e., the sectors do not participate in the global GHG mitigation policy). Finally, 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 supply/demand framework described in the Water Quality section of this report.[31]

For more information on the CIRA approach and results for the FASOM-GHG agriculture and forestry market impacts analysis, please refer to Beach et al.[32]

Ecosystems

SUBSECTORS

Coral Reefs

Shellfish

An ecosystem is a community of organisms interacting with each other and their environment. People, animals, plants, microbes, water, and soil are typical components of ecosystems. We constantly interact with the ecosystems around us to derive and maintain services that sustain us and contribute to our livelihoods. Clean air and water, habitat for species, and beautiful places for recreation are all examples of these goods and services. With the diversity of ecosystem types in the U.S. being so great—from the tidal marshes of the East Coast to the desert valleys of the Southwest to the temperate rainforests of the Pacific Northwest—climate change is likely to fundamentally alter our nation's landscape and natural resources.[1]

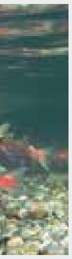
HOW ARE ECOSYSTEMS VULNERABLE TO CLIMATE CHANGE?

Ecosystems are held together by the interactions and connections among their components. Climate is a central connection in all ecosystems. Consequently, changes in climate will have far-reaching effects throughout Earth's ecosystems. Climate change can affect ecosystems and species in a variety of ways; for example, it can lead to changes in the timing of seasonal life-cycle events, such as migrations; habitat shifts; food chain disruptions; increases in pathogens, parasites, and diseases; and elevated risk of extinction for many species.[2]

Climate change directly affects ecosystems and species, but it also interacts with other human stressors on the environment. Although some stressors cause only modest impacts by themselves, the cumulative impact of climate and other changes can lead to dramatic ecological impacts. For example, coastal wetlands already in decline due to increasing development will face increased pressure from rising sea levels.

WHAT DOES CIRA COVER?

CIRA analyzes the potential benefits of global GHG mitigation on coral reefs and freshwater fisheries in the U.S., focusing on changes in recreational use of coral reefs and recreational fishing. This section also examines the projected impacts of ocean acidification on the U.S. shellfish market. Lastly, CIRA quantifies the physical and economic impacts of climate change on wildfires and terrestrial ecosystem carbon storage. Climate change will affect many species and ecosystems beyond what is explored in this report; consequently, CIRA captures only a glimpse of the potential benefits of GHG mitigation on this sector.



Freshwater Fish

Wildfire

Carbon Storage

Coral Reefs

KEY FINDINGS

1. Coral reefs are already disappearing due to climate change and other non-climate stressors. Temperature increases and ocean acidification are projected to further reduce coral cover in the future.
2. Without global GHG mitigation, extensive loss of shallow corals is projected by 2050 for major U.S. reef locations. Global GHG mitigation delays Hawaiian coral reef loss compared to the Reference scenario, but provides only minor benefits to coral cover in South Florida and Puerto Rico, as these reefs are already close to critical thresholds of ecosystem loss.
3. GHG mitigation results in approximately $22 billion (discounted at 3%) in recreational benefits through 2100 for all three regions, compared to a future without emission reductions.

Climate Change and Coral Reefs

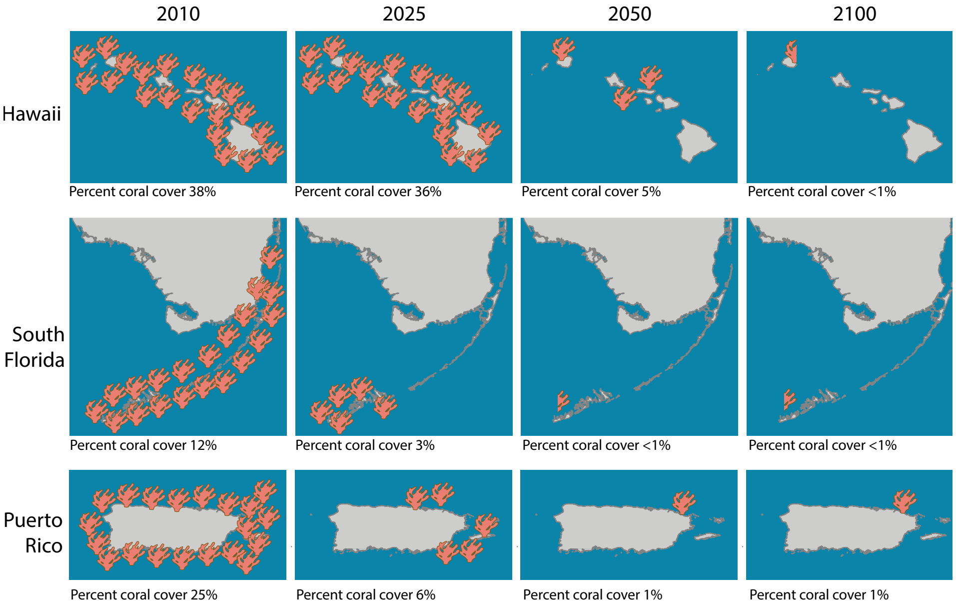
Coral reefs, including those found in Hawaii and the Caribbean, are unique ecosystems that are home to large numbers of marine plant and animal species. They also provide vital fish spawning habitat, protect shorelines, and are valuable for recreation and tourism. However, shallow-water coral reefs are highly vulnerable to climate change.[3] 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. In addition, ocean acidification (ocean chemistry changes due to elevated atmospheric CO_2) can reduce the availability of certain minerals in seawater that are needed to build and maintain coral skeletons.

Risks of Inaction

Without GHG mitigation, continued warming and ocean acidification will have very significant effects on coral reefs. For major U.S. reefs, projections under the Reference show extensive bleaching and dramatic loss of shallow coral cover occurring by 2050, and near complete loss by 2100. In Hawaii, coral cover is projected to decline from 38% (current coral cover) to approximately 5% by 2050, with further declines thereafter. In Florida and Puerto Rico, where present-day 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.[4] This drastic decline in coral reef cover, indicating the exceedance of an ecosystem threshold, could have significant ecological and economic consequences at regional levels. These projections of shallow coral loss for major U.S. reefs are consistent with the findings of the assessment literature.[5]

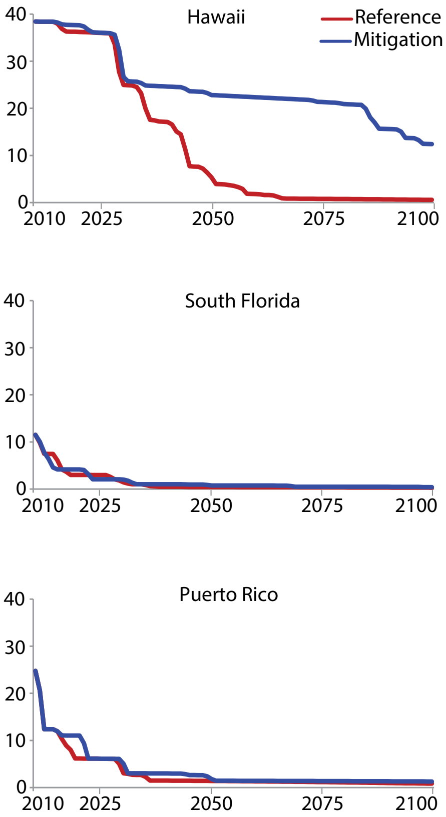
Figure 1. Projected Impact of Unmitigated Climate Change on Coral Reef Cover in the U.S.

Approximate reduction in coral cover at each location under the Reference scenario relative to the initial percent cover. Coral icons do not represent exact reef locations. Results for 2075 are omitted as there is very little change projected between 2050 and 2100.



Reducing Impacts through GHG Mitigation

Figure 2. Percent Change in Coral Reef Cover with and without Global GHG Mitigation at Major U.S. Reefs



Mitigating global GHG emissions can reduce only some of the projected biological and economic impacts of climate change on coral reefs in the U.S. Figure 2 shows projected coral reef cover over time in Hawaii, South Florida, and Puerto Rico under the Reference and Mitigation scenarios. In Hawaii, the decline in reef cover slows under the Mitigation scenario compared to the Reference, as some of the extensive bleaching episodes and effects of ocean acidification are avoided. But even under the Mitigation scenario, Hawaii is projected to eventually experience substantial reductions in coral cover. In South Florida and Puerto Rico, the projected GHG emission reductions associated with the Mitigation scenario are likely insufficient to avoid multiple bleaching and mortality events by 2025, and coral cover declines thereafter nearly as fast as in the Reference.

The delay in the projected decline of coral results in an estimated $22 billion in economic benefits for recreation across the three sites through 2100 (discounted at 3%). The majority of these recreational benefits are projected for Hawaii, with an average value through 2100 of approximately $20 billion (95% confidence interval of $10-$30 billion). In Florida, where coral reefs have already been heavily affected, recreational benefits are also positive, but notably lower at approximately $1.4 billion (95% confidence interval of $0.74-$2.1 billion). In Puerto Rico, benefits are estimated at $0.38 million (95% confidence interval of $0.20-$0.57 million), but only represent recreational benefits for permanent residents, and therefore are not directly comparable to the other locations where visits from nonresident tourists are also included. Including the economic value of other services provided by coral reefs, such as shoreline protection and fish-rearing habitat, would increase the benefits of mitigation.

CORAL COVERAGE | REPRESENTATIVE PHOTOS OF CORAL REEF DECLINE

HEALTHY REEF
40-75% live coral cover

SEVERELY DEGRADED REEF
10-25% live coral cover

NEARLY DEAD REEF
<10% live coral cover

APPROACH

The CIRA analysis examines the physical and economic impacts of climate change and ocean acidification on coral reefs in Hawaii, South Florida, and Puerto Rico. Using the COMBO (Coral Mortality and Bleaching Output) model,[6,7] the analysis first estimates declines in coral reef cover (a measure of coral reef health and density) using projections of future ocean temperature (from the IGSM-CAM) and chemistry under the CIRA Reference and Mitigation scenarios.[8] The effects of future bleaching events 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.[9] Projected impacts to recreation at each site are provided with confidence intervals based on the 95% interval for per-trip recreational values.

For more information on the CIRA approach and results for the coral reef sector, please refer to Lane et al. (2013)[10] and Lane et al. (2014).[11]

Shellfish

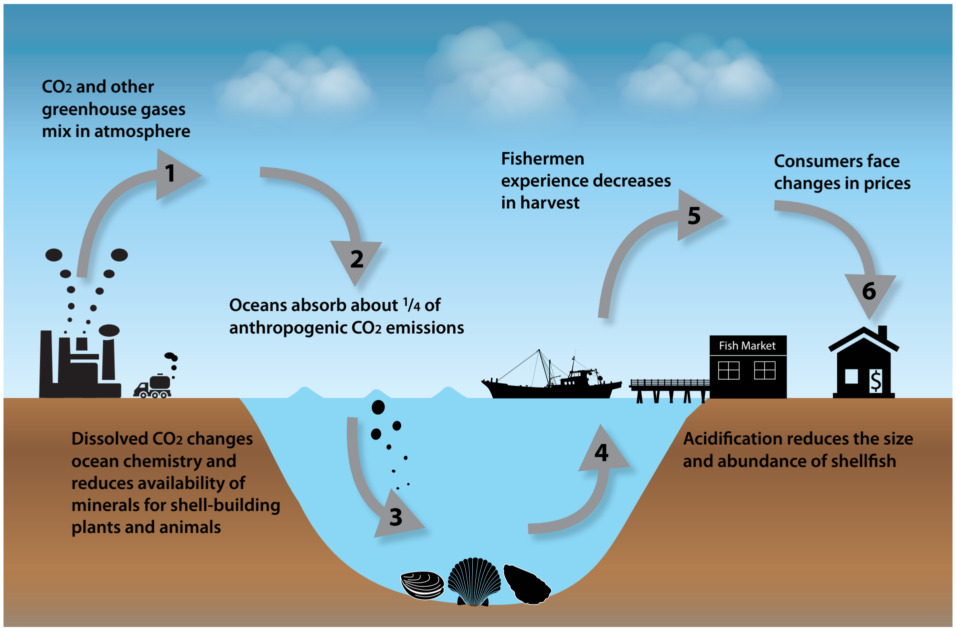
KEY FINDINGS

1. Without global GHG mitigation, the harvests of some shellfish in the U.S. are projected to decline by 32%-48% by the end of the century due to ocean acidification, though estimated impacts vary by species.
2. 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.
3. Global GHG mitigation is projected to avoid $380 million in consumer losses in 2100 compared to the Reference scenario by preventing most of the decreases in the supply of select shellfish and the resulting price increases.

Ocean Acidification and Shellfish

The ocean absorbs about one quarter of the CO_2 released into the atmosphere by human activities, primarily from the combustion of fossil fuels. 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 (Figure 1).[12] 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.[13] Some shellfish are highly vulnerable to ocean acidification[14] and any impacts to these species are expected to negatively affect the economy. Certain species have high commercial value; for example, each year in the U.S., oysters, clams, and scallops supply 170 million pounds of seafood valued at $400 million.[15]

Figure 1. Ocean Acidification Impact Pathway for Shellfish



Risks of Inaction


©Getty Images/John Burke

The pace of ocean acidification is accelerating. Since the Industrial Revolution, the average pH of surface ocean waters has fallen by 0.1, representing a nearly 30% increase in acidity.[16] Under the Reference scenario, ocean acidification is projected to cause pH to drop an additional 0.3, representing a 100% increase in acidity from pre-industrial times. Continued ocean acidification is estimated to reduce the supply of oysters, scallops, and clams in 2100 by 45% (13 million pounds per year), 48% (21 million pounds), and 32% (31 million pounds), respectively (Figure 2). These decreases in supply are projected to result in price increases by 2100 of approximately $2.20 (a 68% increase from 2010), $9.10 (140%), and $1.30 (123%) per pound, respectively, and lead to consumer losses of roughly $480 million per year by the end of the century. These projections are consistent with the findings of the assessment literature, which describe reduced growth and survival of U.S. shellfish stocks due to unmitigated ocean acidification.[17]

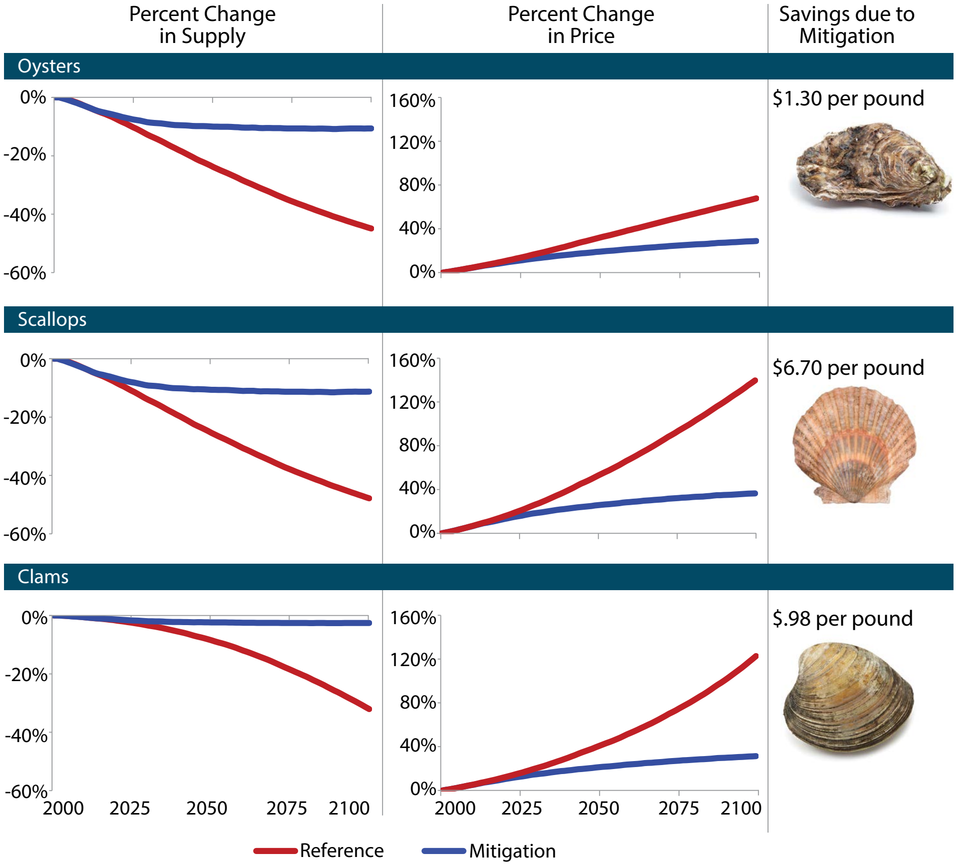
Reducing Impacts through GHG Mitigation

Reducing global GHG emissions can mitigate the ecological and economic impacts of ocean acidification. Figure 2 shows how the supplies of oysters, scallops, and clams are projected to fall with ocean acidification under the Reference and Mitigation scenarios. Although supplies are estimated to decrease under both scenarios relative to present-day supplies, the Mitigation scenario avoids a majority of the impacts, particularly for clams. In 2100, global GHG mitigation is projected to avoid the loss of 54 million pounds of oysters, scallops, and clams, or 34% of the present-day U.S. oyster supply, 37% of the scallop supply, and 29% of the clam supply.

Figure 2 also indicates how the increase in demand and the decrease in supply are estimated to affect prices by 2100 for these shellfish under the two scenarios. Consumers are likely to substitute away from these shellfish as their prices increase, but not entirely, and not without some decrease in satisfaction. The Mitigation scenario keeps prices much closer to current levels, as indicated in Figure 2, resulting in smaller consumer losses in the shellfish market. In 2100, the benefits to shellfish consumers from global GHG emissions reductions under the Mitigation scenario are estimated at $380 million. The cumulative benefits over the century are estimated at $1.9 billion (discounted at 3%).

Figure 2. Estimated Impacts on the U.S. Shellfish Industry

Projected changes in the supplies and prices of oysters, scallops, and clams through 2100 under the Reference and Mitigation scenarios relative to the base period.



APPROACH

The CIRA analysis models the entire "impact pathway" shown in Figure 1, which can be divided into biophysical and economic components. The biophysical impacts are estimated using the CIRA CO_2 and sea surface temperature projections from the IGSM-CAM in the CO2SYS model[18] to simulate seawater chemistry conditions through the 21st century. These conditions are then used to estimate how the growth rates of oysters, scallops, and clams will change over time.

The economic analysis uses the projected growth rates of these species to estimate changes to the U.S. supply of shellfish. A consumer demand model of the shellfish market, described in Moore (2014),[19] projects changes in prices and consumer behavior under the Reference and Mitigation scenarios. This model does not estimate producer or supply-side welfare effects, which could also show benefits of mitigation. Comparing the model results under the two scenarios provides an estimate of the benefits to the shellfish market of avoiding significant amounts of CO_2 from being added to ocean waters. By considering impacts to these three species, this approach estimates just a fraction of the potential economic damages from ocean acidification, but, nonetheless, provides some insight into the benefits of global GHG mitigation.

In addition, by preventing the loss of shellfish populations, global GHG mitigation would preserve ecosystem services provided by these species (e.g., water filtration). Inclusion of these effects would likely increase the total benefits of GHG mitigation in this sector.

For more information on the CIRA approach to estimating the economic impacts of ocean acidification in the shellfish market, see Moore (2015).[20]

Freshwater Fish

KEY FINDINGS

1. Warming waters and changes in stream flow due to climate change will likely alter the distribution of freshwater fisheries across the country. Without global GHG mitigation, coldwater species are projected to be replaced in many areas by less economically valuable fisheries over the course of the 21st century, especially in the Mountain West and Appalachia.

2. Habitat suitable for coldwater fisheries is estimated to decline nationally by approximately 62% through 2100 under the Reference, but by only 12% under the Mitigation scenario. Global GHG mitigation is projected to preserve coldwater habitat in most of Appalachia and the Mountain West.

3. GHG mitigation avoids an estimated $380 million to $1.5 billion in total recreational fishing damages through 2100 compared to the Reference (discounted at 3%).

Climate Change and Freshwater Fish

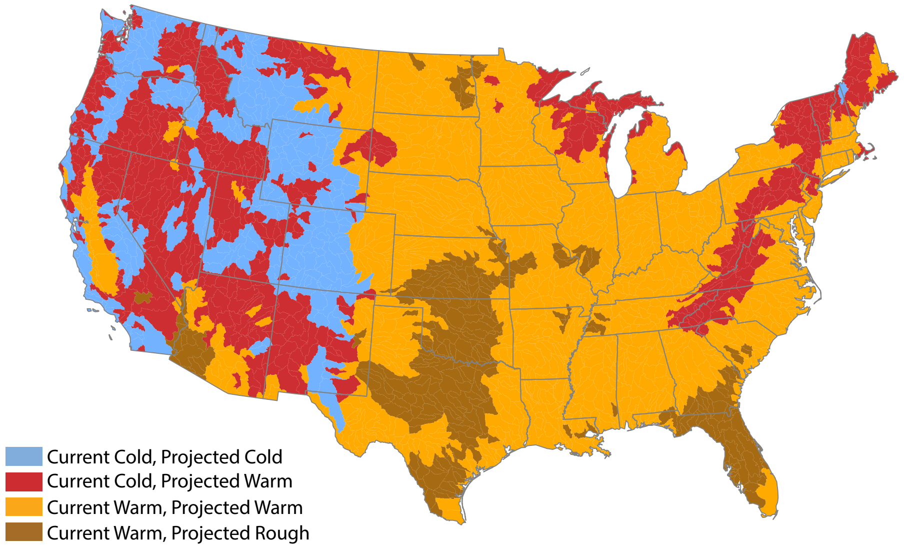
Freshwater fishing is an important recreational activity that contributes significantly to local economies in many parts of the country. Most fish species thrive only in certain ranges of water temperature and stream flow conditions. For example, trout and salmon can only tolerate coldwater streams, while shad and largemouth bass thrive in warmwater habitats (see below infographic). Climate change threatens to disrupt these habitats and affect certain fish populations through higher temperatures and changes in river flow.[21]

Risks of Inaction

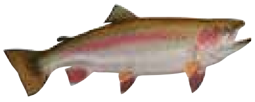
Without GHG mitigation, climate change is projected to have a significant impact on freshwater fishing in the contiguous U.S. Increasing stream temperatures and changes in stream flow are likely to transform many habitats that are currently suitable for coldwater fish into areas that are only suitable for warmwater species that are less recreationally valuable. Under the IGSM-CAM climate projections, coldwater fisheries are estimated to be limited almost exclusively to the mountainous West in 2100, and would almost disappear from Appalachia. In addition, substantial portions of Texas, Oklahoma, Kansas, and Florida would shift from warmwater to rough habitat (Figure 1). Overall, unmitigated climate change is projected to result in a 62% decline in coldwater fish habitat by 2100, which includes approximately 440,000 acres of lost stream habitat. Meanwhile, warmwater and rough stream habitats are projected to increase by 1.3 million and 450,000 acres, respectively. The projected loss of coldwater fish habitat and expansion of warmwater and rough fisheries are consistent with the findings of the assessment literature.[22, 23]

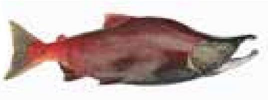
Figure 1. Projected Impact of Unmitigated Climate Change on Potential Freshwater Fish Habitat in 2100

Change in distribution of areas where stream temperature supports different fisheries under the Reference scenario using the IGSM-CAM climate model. Results are presented for the 8-digit hydrologic unit codes (HUCs) of the contiguous U.S.



COLDWATER FISHERY EXAMPLES


Trout


Salmon

WARMWATER FISHERY EXAMPLES


Smallmouth Bass


Shad

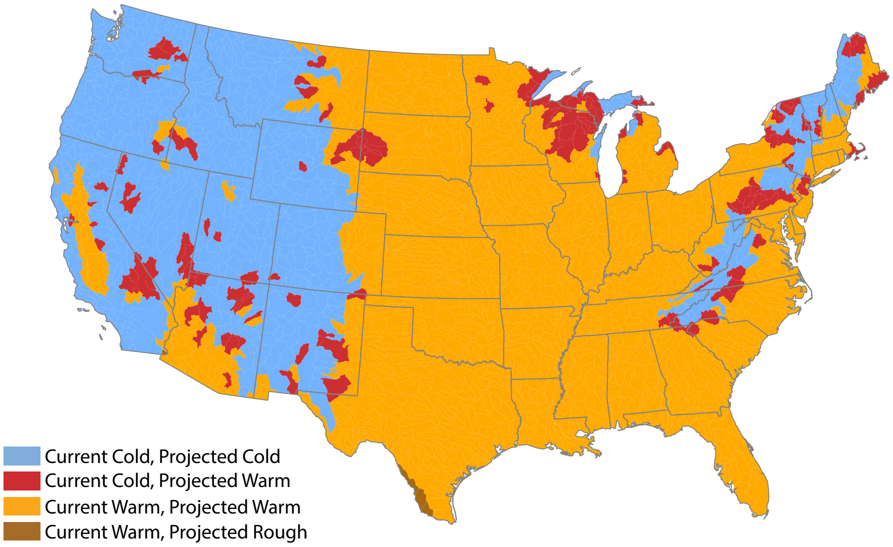
Reducing Impacts through GHG Mitigation

Global GHG mitigation is projected to prevent much of the loss of coldwater fish habitat that occurs in the Reference (Figure 2). Although coldwater stream habitat will likely still be reduced under the Mitigation scenario (by approximately 85,000 acres by 2100), mitigation avoids approximately 81% of the losses incurred under the Reference, preserving an area equal to approximately 360,000 acres of suitable stream habitat nationally. This habitat supports valuable recreational fishing, especially in Appalachia and large areas of the Mountain West. Also, fewer acres are converted to less economically valuable warmwater and rough fisheries under the Mitigation scenario than under the Reference. Specifically, stream habitat suitable for warmwater and rough fisheries increase by 450,000 and 13,000 acres, respectively, under the Mitigation scenario, which is 36% and 3% of the expansions estimated under the Reference.

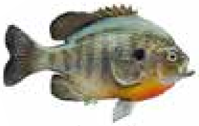
Compared to the Reference, the Mitigation scenario provides economic benefits of approximately $1.5 billion through 2100 for coldwater fishing only, and $380 million when all three freshwater fishery types (cold, warm, and rough) are considered (discounted at 3%). These results rely upon climate projections from the IGSM-CAM, which projects a relatively wetter future for most of the U.S. compared to the MIROC climate model. The projected benefits of global GHG mitigation through 2100 are lower with the drier MIROC model (not shown) for coldwater fishing only, at approximately $1.2 billion, but higher when all three fisheries are considered, at approximately $1.5 billion (discounted at 3%).[24]

Figure 2. Projected Impact on Potential Freshwater Fish Habitat in 2100 with Global GHG Mitigation

Change in distribution of areas where stream temperature supports different fisheries under the Mitigation scenario using the IGSM-CAM climate model. Results are presented for the 8-digit HUCs of the contiguous U.S.



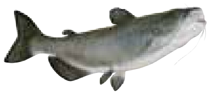
Largemouth Bass



Bluegill

ROUGH FISHERY EXAMPLES

Carp



Catfish

APPROACH

The CIRA analysis assesses 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 changes are simulated for the CIRA emissions scenarios using the IGSM-CAM and MIROC climate models to estimate changes in suitable habitat (in stream acres) for three types of freshwater fisheries: cold, warm, and rough (species tolerant to warmest stream temperatures). Each fishery type represents a categorization of individual species based on their tolerance for different river and stream water temperatures. This analysis does not evaluate impacts to fisheries in lakes and reservoirs, which are vulnerable to climate change in different ways compared to streams and rivers.[25] As shown at the bottom of this section, the coldwater fish guild contains species that are the least tolerant to increasing stream temperatures, and are therefore the most vulnerable to climate change.

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 the value of recreational fishing. 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.[26] As implications of changes to the distribution of freshwater fisheries extend beyond recreational use by humans, this analysis underestimates the economic benefits of GHG mitigation.

For more information on the CIRA approach and results for the freshwater fish sector, please refer to Lane et al. (2014)[27] and Jones et al. (2012).[28]

Wildfire

KEY FINDINGS

1. Without global GHG mitigation efforts, climate change is projected to dramatically increase the area burned by wildfires across most of the contiguous U.S., especially in the West.

2. Global GHG mitigation is projected to reduce the cumulative area burned by wildfires over the course of the 21st century by approximately 210-300 million acres compared to the Reference.

3. Global GHG mitigation avoids an estimated $8.6-$11 billion in wildfire response costs and $3.4 billion in fuel management costs on conservation lands (discounted at 3%) through 2100 compared to the Reference. Other impacts, such as property damage or health effects from decreased air quality, are not estimated, but could have large economic implications.

Climate Change and Wildfire

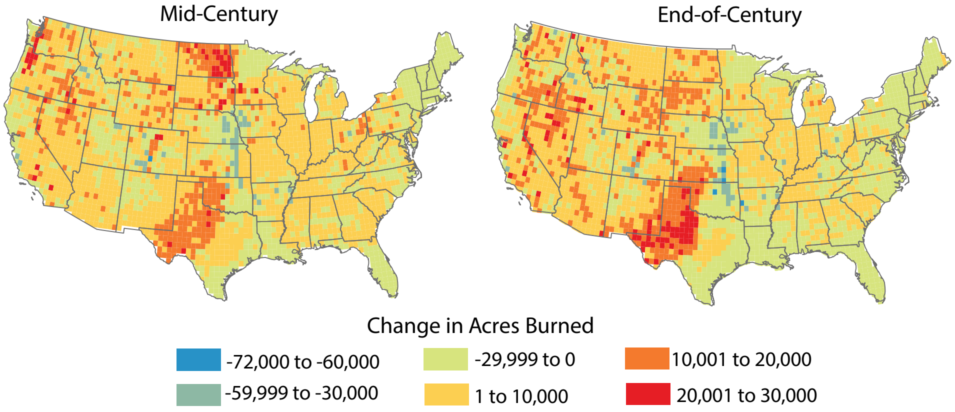
Terrestrial ecosystems in the U.S. provide a wealth of goods and services such as timber, wildlife habitat, erosion management, water filtration, recreation, and aesthetic value. Climate change threatens these ecosystems as heat, drought, and other disturbances bring larger and more frequent wildfires. Wildfires can damage property, disrupt ecosystem services, destroy timber stocks, impair air quality, and result in loss of life.[29] In the last decade (2004-2013), more than 72 million acres of forest have burned due to wildfires, and the U.S. government has spent in excess of $15 billion on wildfire suppression.[30] Additionally, wildfires release carbon stored in terrestrial ecosystems, potentially further accelerating climate change.[31, 32]

Risks of Inaction

Without GHG mitigation, climate change is projected to dramatically increase the area burned by wildfires across most of the contiguous U.S., a finding that is consistent with the assessment literature.[33] Under the Reference using the IGSM-CAM climate projections, approximately 5.3 million[34] more acres—an area greater than the state of Massachusetts—are projected to burn each year at the end of the century compared to today. This represents a doubling of acres burned compared to today's rates.[35] However, the estimated impacts vary across regions and through time (Figure 1). Consistent with the assessment literature,[36] the western U.S.[37] is projected to experience large increases in burned area by the end of the century (an increase of approximately 43%). In particular, the Southwestern region (comprising Arizona, New Mexico, and West Texas) is projected to experience increases of 140% on average.[38] Wildfire in other regions is not projected to change significantly compared to today, and some regions, such as the Northeast, are estimated under the IGSM-CAM projections to experience decreases in wildfire activity.

Figure 1. Projected Impact of Unmitigated Climate Change on Wildfire Activity

Change in average annual acres burned under the Reference scenario by mid-century (2035-2064) and end of century (2085-2114) compared to the historic baseline (2000-2009) using the IGSM-CAM climate model. Acres burned include all vegetation types and are calculated at a cell resolution of 0.5° x 0.5°.

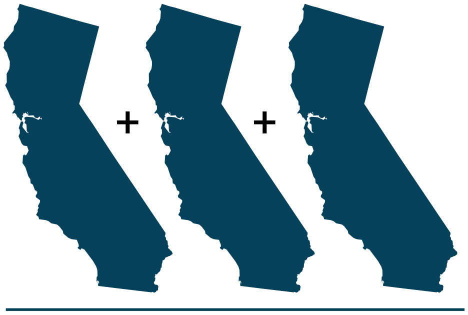


Reducing Impacts through GHG Mitigation

As shown in Figure 2, global GHG mitigation significantly reduces the area burned by wildfire in the U.S. over the course of the 21st century. By 2100, the Mitigation scenario reduces the cumulative area burned by approximately 210-300 million acres, depending on the climate model used. This corresponds to a 13-14% reduction relative to the Reference. As shown, the combined area of wildfires avoided in the contiguous U.S. due to GHG mitigation is equivalent to two to three times the size of California. These benefits of GHG mitigation would largely occur in the West, where approximately 64%-75% of the avoided burned area is located.

Benefits of GHG Mitigation

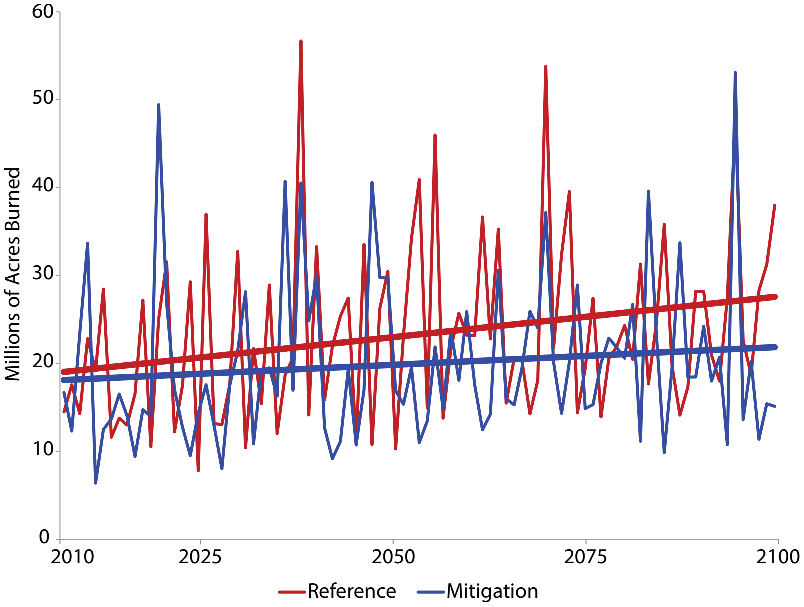
210-300 million fewer acres burned *over the course of the 21st century, an area* ***2-3 times*** *the size of California*



Nationally, the avoided wildfire due to GHG mitigation corresponds $11 billion in reduced wildfire response costs and $3.4 billion[39] in avoided fuel management costs for conservation lands through 2100 (both discounted at 3%). Other economic damages from wildfire that are not estimated in this analysis, such as human health effects from decreased air quality, could have large implications at national and regional scales. These results rely upon climate projections from the IGSM-CAM, which projects a relatively wetter future for most of the U.S. compared to the MIROC climate model (see the Levels of Certainty section of this report for more information). The projected benefits of global GHG mitigation are slightly lower for the drier MIROC model, with wildfire response cost savings estimated at $8.6 billion through 2100 (discounted at 3%).[40]

Figure 2. Estimated Acres Burned with and without Global GHG Mitigation

Estimated acres burned by wildfire in the contiguous U.S. over the course of the 21st century under the Reference and Mitigation scenarios using the IGSM-CAM climate model, with trends shown in bold. The large inter-annual variability reflects simulated periods of fuel accumulation followed by seasons of large wildfire activity.



APPROACH

To estimate the effect of climate change on areas burned by wildfires, the CIRA analysis uses the MC1 dynamic global vegetation model. The model simulates future terrestrial ecosystem cover and burned area across the contiguous U.S. in the 21st century. The vegetation model is driven by changes in future climate (e.g., temperature, precipitation, humidity) based on five initializations of the IGSM-CAM climate model for the Reference and Mitigation scenarios.[41,42] Results presented in this section represent the average of the initializations. Simulations using the drier MIROC model were also performed. Projected changes in fire regime over time are adjusted to account for fire suppression tactics.

The projected impacts of wildfires are summarized by scenario and geographic area, and then monetized using average wildfire response costs for each region. These costs include the costs associated with labor (e.g., fire crews) and equipment (e.g., helicopters, bulldozers) that are required for fire-fighting efforts.[43] Using the approach described in Lee et al. (2015),[44] the analysis also estimates the environmental damages resulting from moderate and severe wildfires on conservation lands (e.g., Forest Service lands, national parks and preserves, and other protected lands) across the contiguous U.S. under the Reference and Mitigation scenarios. To estimate the value of the lost ecosystem services resulting from these wildfires, the analysis quantifies the costs of fuels management needed to offset the injury caused by wildfires. Air quality impacts, property loss, loss of recreation, and the effects of pest infestations (e.g., pine bark beetles) on wildfire activity are additional and important impacts, but are not included in the reported estimates.

For more information on the CIRA approach and results for wildfires, please refer to Mills et al. (2014)[45] and Lee et al. (2015).[46]

Carbon Storage

KEY FINDINGS

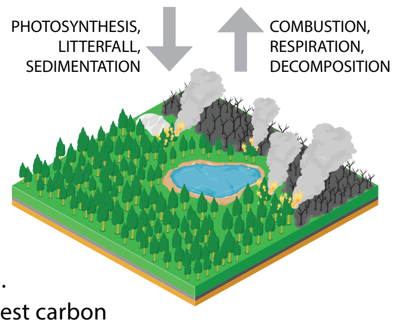
① Changes in vegetative carbon storage in the contiguous U.S. are highly dependent on the projected future climate, with the magnitude, regional distribution, and directionality of impacts changing over time.

② The estimated effect of global GHG mitigation on carbon storage ranges from a decrease in carbon stocks of 0.5 billion metric tons to an increase in carbon stocks of 1.4 billion metric tons by the end of the century, depending on the climate model used. The economic value of these changes in carbon storage ranges from $9 billion in disbenefits to $120 billion in GHG mitigation benefits (both discounted at 3%).

Climate Change and Terrestrial Carbon Storage

Terrestrial ecosystems influence the climate system through their important role in the global carbon cycle. These ecosystems capture and store carbon from the atmosphere, thereby reducing its climate impact. However, they can also act as a source, releasing carbon through decomposition and wildfires (Figure 1). Terrestrial ecosystems in the U.S., which include forests, grasslands, and shrublands, are currently a net carbon sink. Today, forests store more than 227 million tons of carbon per year, which offsets approximately 16% of all annual U.S. carbon dioxide emissions from fossil fuel burning.[47] Forest carbon storage has increased due to net increases in forest area, improved forest management, as well as higher productivity rates and longer growing seasons driven by climate change.[48] However, 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.[49]

Figure 1. Carbon Storage Basics

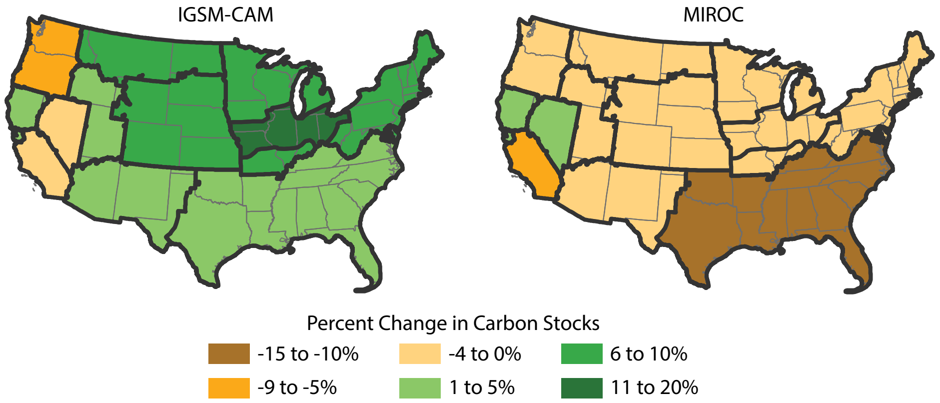


Risks of Inaction

Climate change impacts on terrestrial ecosystem carbon storage under the Reference are on the order of billions of tons of carbon from 2000 to 2100, with some regions showing substantial changes in terrestrial carbon stocks (total amount of carbon in the vegetation). Under the IGSM-CAM climate projections, terrestrial ecosystem storage across the contiguous U.S. is projected to increase 3.4% from 2000 to 2100 (equal to 2.9 billion metric tons),[50] primarily due to generally warmer, wetter, and CO_2-rich future conditions that are favorable to vegetative growth. Much of the national trend is driven by the Rocky Mountains, South, and East regions, which have the largest projected increases in terrestrial ecosystem carbon. However, as shown in Figure 2, there is substantial regional variation, and projections for carbon storage vary greatly depending on the projected future climate. Results using the drier MIROC climate model project net reductions in stored carbon under the Reference in most regions. These results are consistent with the findings of the assessment literature.[51]

Figure 2. Projected Impact of Unmitigated Climate Change on Stored Carbon in 2100

Simulated changes in carbon stocks from the baseline (2000-2009 average) projected by the IGSM-CAM and MIROC climate models are aggregated by U.S. Forest Service Geographic Area Coordination Center region.



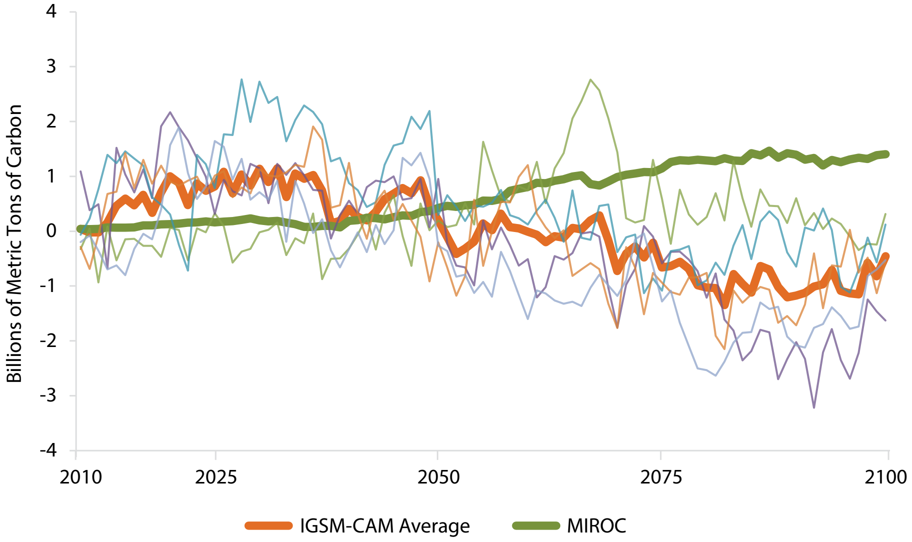
Reducing Impacts through GHG Mitigation

The impacts of GHG mitigation on national terrestrial ecosystem carbon storage are highly dependent upon the projected future climate, with the magnitude and even directionality of impacts varying over time (Figure 3). Across the contiguous U.S., average results across the IGSM-CAM initializations show that GHG mitigation reduces stored carbon compared to the Reference by 0.5 billion metric tons over the course of the century. The economic value of this lost carbon under the Mitigation scenario is an estimated $9.0 billion (discounted at 3%). As shown in Figure 3, carbon stocks under the Mitigation scenario are larger than the Reference in the first half of the century under the IGSM-CAM, but the trend reverses after 2050, as climate conditions under the Reference (generally warmer and wetter) are more favorable for vegetative growth. There is an early savings from the near-term gain in stored carbon of approximately 1.1 billion metric tons, estimated at $170 billion by 2030 (discounted at 3%). However, these initial gains are not large enough to offset projected losses in the second half of the century.

The projected impacts of climate change on vegetative carbon storage and the effects of GHG mitigation are different when using the relatively drier climate projections from the MIROC model (Figure 3). The MIROC results project a consistent increase in carbon storage benefits when comparing the Mitigation scenario to the Reference, with a carbon stock increase of 1.4 billion metric tons by 2100. The economic value of this carbon gain under the Mitigation scenario is an estimated $120 billion (discounted at 3%). Results using IGSM-CAM projections show much more variability over time than the MIROC results, which is primarily a reflection of the climate projection method.[52]

Figure 3. Projected Impact of Global GHG Mitigation on Carbon Stocks in the Contiguous U.S.

Estimated change in the size of terrestrial ecosystem carbon stocks under the Mitigation scenario compared to the Reference. Positive values indicate larger carbon stocks under the Mitigation scenario compared to the Reference, and vice versa. The thin lines represent estimated changes in carbon stocks under the different initializations of the IGSM-CAM climate model.



APPROACH

To estimate climate change impacts on terrestrial ecosystem carbon storage, the MC1 dynamic global vegetation model was used to simulate terrestrial vegetative growth and cover (e.g., grasses, shrubs, hard and softwood forests) for the contiguous U.S. from 2000 to 2100.[53] Vegetative cover estimates from MC1 reflect simulated changes in climate, biogeography, biogeochemistry, and fire dynamics. MC1 was run using the five initializations of the IGSM-CAM climate model for both the Reference and Mitigation scenarios (see the CIRA Framework section of this report for more information).[54] The results described in this section represent the average of these initializations. Because IGSM-CAM projects a wetter future for a majority of the nation, MC1 was also run using the MIROC climate model. These drier climate projections for the U.S. were used to capture a broader range of possible precipitation futures under the same GHG emissions scenarios.

Projected annual changes in terrestrial carbon storage for non-agricultural, non-developed lands across the contiguous U.S. were summarized by scenario and geographic area, and then monetized using the central estimate of the U.S. Government's updated social cost of carbon (SCC) values for the years 2010-2050, with extrapolation to 2100.[55]

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 CIRA approach and results for carbon storage, please refer to Mills et al. (2014).[56]

Overview of Results

This section provides an overview of the national and regional results for all sectors included in the report. The National Highlights section presents the estimated physical and monetary benefits (avoided impacts) to the U.S. of the global GHG mitigation scenario compared to the Reference scenario in 2050 and 2100.

The Regional Highlights section shows regional impacts that are particularly notable, presenting changes in both the Reference and Mitigation scenarios to highlight the potential benefits of global GHG mitigation. The individual monetized estimates presented in these sections are not aggregated, as there are differences in the types of costs being quantified across sectors; furthermore, not all potential impacts of climate change are represented in this report.

National Highlights

This section provides an overview of the national-scale results presented throughout this report. It presents the estimated physical and monetary benefits (avoided impacts) to the U.S. of global GHG mitigation compared to the Reference scenario in the years 2050 and 2100. Although not available for all sectors, cumulative benefits for the entire 21st century would likely be much larger than the annual estimates presented here. In addition, the individual monetized estimates are not aggregated, as only a subset of climate change impacts is quantified in this report, and there are differences in the types of costs being quantified across the sectors. For detailed information on the results, and a summary of the methodologies used, please refer to the Sectors section of this report.

	In the year 2050, global GHG mitigation is projected to result in...	In the year 2100, global GHG mitigation is projected to result in...
HEALTH		
AIR QUALITY	An estimated 13,000 fewer deaths from poor air quality, valued at $160 billion.*	An estimated 57,000 fewer deaths from poor air quality, valued at $930 billion.*
EXTREME TEMPERATURE	An estimated 1,700 fewer deaths from extreme heat and cold in 49 major U.S. cities, valued at $21 billion.	An estimated 12,000 fewer deaths from extreme heat and cold in 49 major U.S. cities, valued at $200 billion.
LABOR	An estimated avoided loss of 360 million labor hours, valued at $18 billion.	An estimated avoided loss of 1.2 billion labor hours, valued at $110 billion.
WATER QUALITY	An estimated $507-$700 million in avoided damages from poor water quality.†	An estimated $2.6-$3.0 billion in avoided damages from poor water quality.†
INFRASTRUCTURE		
BRIDGES	An estimated 160-960 fewer bridges made structurally vulnerable, valued at $0.12-$1.5 billion.†	An estimated 720-2,200 fewer bridges made structurally vulnerable, valued at $1.1-$1.6 billion.†
ROADS	An estimated $0.56-$2.3 billion in avoided adaptation costs.†	An estimated $4.2-$7.4 billion in avoided adaptation costs.†
URBAN DRAINAGE	An estimated $56 million to $2.9 billion in avoided adaptation costs from the 50-year, 24-hour storm in 50 U.S. cities.†	An estimated $50 million to $6.4 billion in avoided adaptation costs from the 50-year, 24-hour storm in 50 U.S. cities.†
COASTAL PROPERTY	An estimated $0.14 billion in avoided damages and adaptation costs from sea level rise and storm surge.	An estimated $3.1 billion in avoided damages and adaptation costs from sea level rise and storm surge.
ELECTRICITY		
DEMAND AND SUPPLY	An estimated 1.1%-4.0% reduction in energy demand and $10-$34 billion in savings in power system costs.‡	Not estimated.

* These results do not reflect the additional benefits to air quality and human health that would stem from the co-control of traditional air pollutants along with GHG emissions.

† For sectors sensitive to changes in precipitation, the estimated range of results is generated using projections from two climate models showing different patterns of future precipitation in the contiguous U.S. The IGSM-CAM model projects a relatively "wetter" future for most of the contiguous U.S. compared to the "drier" MIROC model (see the CIRA Framework section of this report for more information).

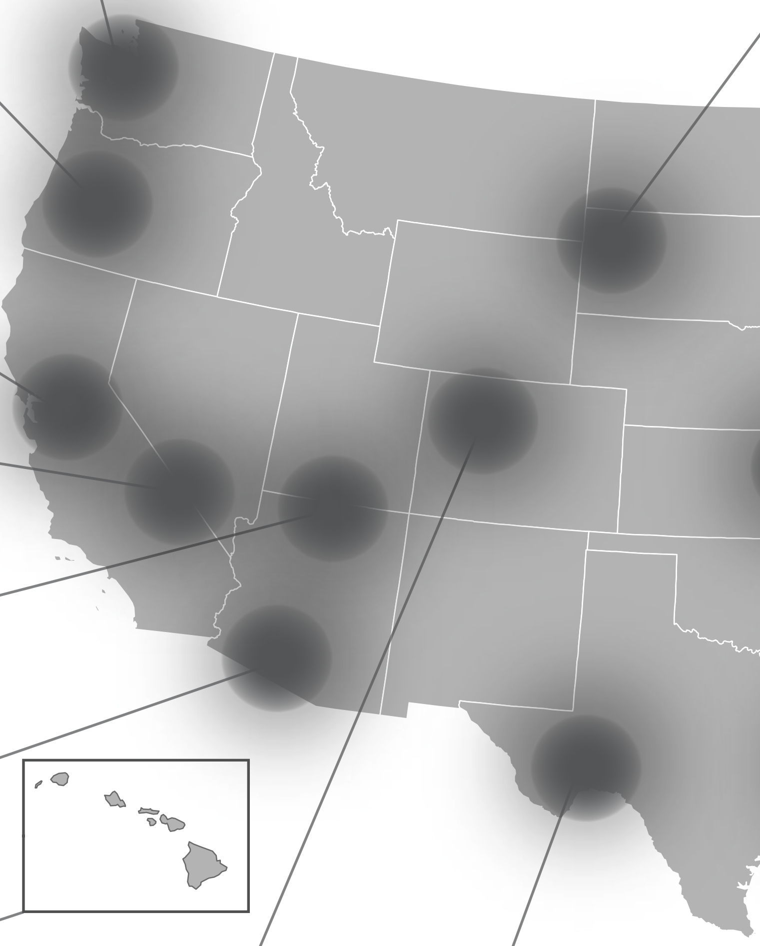
‡ Estimated range of benefits from the reduction in demand and system costs resulting from lower temperatures associated with GHG mitigation. The electricity section in this report presents an analysis that includes the costs to the electric sector of reducing GHG emissions.

	In the year 2050, global GHG mitigation is projected to result in...	In the year 2100, global GHG mitigation is projected to result in...
WATER RESOURCES		
INLAND FLOODING	An estimated change in flooding damages ranging from $260 million in damages to $230 million in avoided damages.[†]	An estimated change in flooding damages ranging from $32 million in damages to $2.5 billion in avoided damages.[†]
DROUGHT	An estimated 29%-45% fewer severe and extreme droughts, with corresponding avoided damages to the agriculture sector of approximately $1.2-$1.4 billion.[†]	An estimated 40%-59% fewer severe and extreme droughts, with corresponding avoided damages to the agriculture sector of $2.6-$3.1 billion.[†]
WATER SUPPLY AND DEMAND	An estimated $3.9-$54 billion in avoided damages due to water shortages.[†]	An estimated $11-$180 billion in avoided damages due to water shortages.[†]
AGRICULTURE & FORESTRY		
AGRICULTURE	An estimated $1.5-$3.8 billion in avoided damages.	An estimated $6.6-$11 billion in avoided damages.
FORESTRY	Estimated damages of $9.5-$9.6 billion.	An estimated $520 million to $1.5 billion in avoided damages.
ECOSYSTEMS		
CORAL REEFS	An estimated avoided loss of 53% of coral in Hawaii, 3.7% in Florida, and 2.8% in Puerto Rico. These avoided losses are valued at $1.4 billion.	An estimated avoided loss of 35% of coral in Hawaii, 1.2% in Florida, and 1.7% in Puerto Rico. These avoided losses are valued at $1.2 billion.
SHELLFISH	An estimated avoided loss of 11% of the U.S. oyster supply, 12% of the U.S. scallop supply, and 4.6% of the U.S. clam supply, with corresponding consumer benefits of $85 million.	An estimated avoided loss of 34% of the U.S. oyster supply, 37% of the U.S. scallop supply, and 29% of the U.S. clam supply, with corresponding consumer benefits of $380 million.
FRESHWATER FISH	An estimated change in recreational fishing ranging from $13 million in avoided damages to $3.8 million in damages.[†]	An estimated $95-$280 million in avoided damages associated with recreational fishing.[†]
WILDFIRE	An estimated 2.1-2.2 million fewer acres burned and corresponding avoided wildfire response costs of $160-$390 million.[†]	An estimated 6.0-7.9 million fewer acres burned and corresponding avoided wildfire response costs of $940 million to $1.4 billion.[†]
CARBON STORAGE	An estimated 26-78 million fewer metric tons of carbon stored, and corresponding costs of $7.5-$23 billion.[†]	An estimated 1-26 million fewer metric tons of carbon stored, and corresponding costs of $880 million to $12 billion.[†]

OVERVIEW OF RESULTS

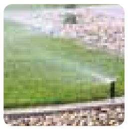
Regional Highlights

This section highlights regional impacts of climate change in the U.S. For each sector, the map presents a region where substantial benefits of global GHG mitigation are projected to occur in the years 2050 or 2100.* Note that the geographic scale at which impacts are →



CARBON STORAGE

The Northwest is projected to experience a 6.1% decrease in terrestrial carbon storage in 2100 under the Reference scenario, compared to a 2.4% decrease in the Mitigation scenario.



WATER SUPPLY AND DEMAND

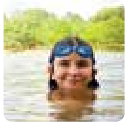
California is projected to incur $4.5 billion in damages in 2100 due to changes in water supply and demand in the Reference scenario. However, climate change under the Mitigation scenario is projected to result in an increase in welfare of $40 million.

LABOR

In 2100, the Southwest is projected to experience a 3.4% decrease in high-risk labor hours worked in the Reference scenario, compared to a decrease of 0.82% in the Mitigation scenario.

DROUGHT

In the Southwest, the number of severe and extreme droughts is projected to nearly quadruple by the end of the century in the Reference scenario compared to today. In the Mitigation scenario, the incidence of drought is not projected to change substantially from present day.



WATER QUALITY

The Southwest is projected to experience water quality damages of approximately $1.8 billion in 2100 under the Reference scenario, compared to $470 million in the Mitigation scenario.

CORAL REEFS

By the end of the century, Hawaii is projected to lose 98% of its current shallow-water coral in the Reference scenario, compared to 64% in the Mitigation scenario.

SHELLFISH

Acidification in the Pacific Northwest is already affecting U.S. shellfish harvests. The U.S. supplies of oysters, clams, and scallops are projected to decline 45%, 32%, and 48%, respectively, in the Reference scenario in 2100, compared to 11%, 3%, and 11%, respectively, in the Mitigation scenario.

WILDFIRE

In the Rocky Mountains, an estimated 1.9 million more acres are projected to burn in 2100 under the Reference scenario compared to today. In the Mitigation scenario, an estimated 1.5 million fewer acres are projected to burn compared to today.

INLAND FLOODING

In Texas, projected damages associated with the 100-year flood event are $3.6 billion in 2100 under the Reference scenario, compared to $2.6 billion in the Mitigation scenario.

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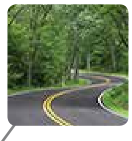
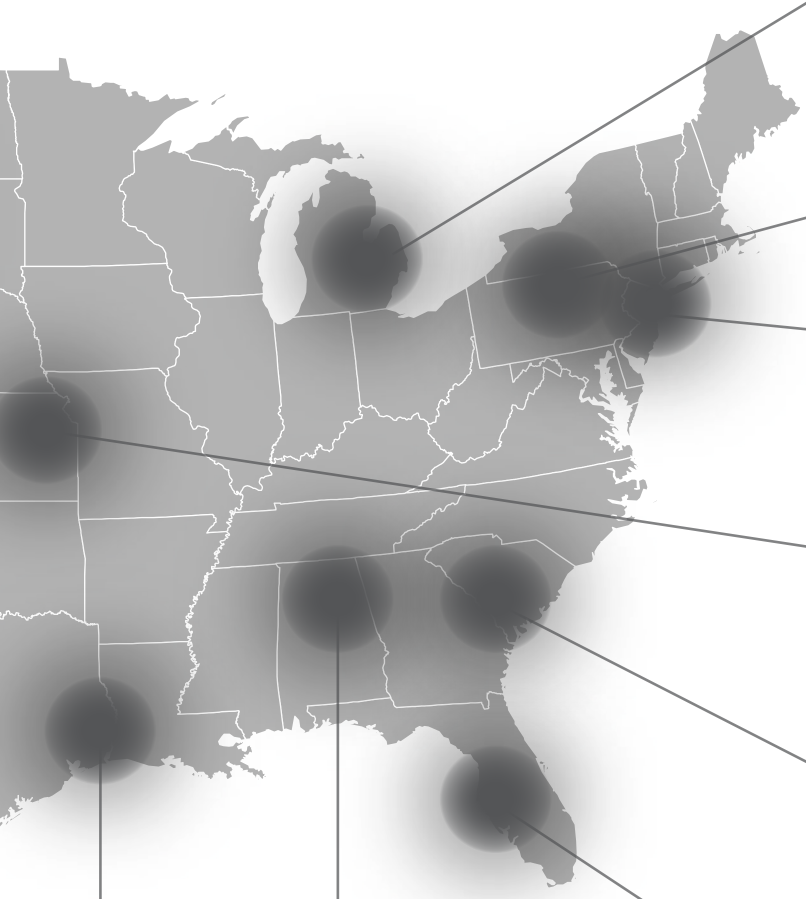
* Estimates are presented in undiscounted 2014 dollars and rely upon climate projections from the IGSM-CAM climate model. Results using projections from other climate models, such as the MIROC model used throughout this report, could lead to variations in results for some sectors.

quantified in the sectoral analyses vary. For example, some of the analyses calculate impacts for large watersheds, while others use the National Climate Assessment regions. For purposes of highlighting regional impacts, this section approximates the regions.



ROADS

In 2100, the Great Plains region is projected to incur road damages of approximately \$3.5 billion in the Reference scenario, compared to \$1.1 billion in the Mitigation scenario.

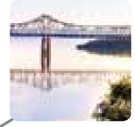


ELECTRICITY DEMAND

The South Central region is projected to experience a 2.0% to 4.2% increase in electricity demand under the Reference scenario in 2050. In the Mitigation scenario, the projected change in demand ranges from -1.4% to 1.6%.

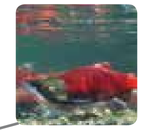
AGRICULTURE

In the Southeast, yields of irrigated soybeans are projected to decrease 23% in 2100 under the Reference scenario. Under the Mitigation scenario, yields are projected to increase 4.7%.



BRIDGES

In the Great Lakes region, approximately 520 bridges are projected to be vulnerable in 2100 under the Reference scenario, compared to 65 in the Mitigation scenario.

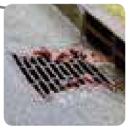


FRESHWATER FISH

Throughout the Appalachians, global GHG mitigation is projected to preserve approximately 70% of habitat for coldwater fish species (e.g., trout) that would otherwise be lost by the end of the century to rising temperatures from unmitigated climate change.

EXTREME TEMPERATURE

Without mitigation, major cities in the Northeast from D.C. to Boston are projected to suffer a combined 2,600 extreme temperature mortalities in 2100, compared to 190 in the Mitigation scenario.



URBAN DRAINAGE

In 2100, major cities analyzed in the Great Plains are estimated to incur \$2.1 million per square mile in damages associated with urban drainage systems in the Reference scenario, compared to \$750,000 per square mile in the Mitigation scenario.

AIR QUALITY

In 2100, areas of the Southeast are projected to experience an annual increase in ozone (O_3) and fine particulate matter ($PM_{2.5}$) of 0.7 ppb and 1 $\mu g/m^{-3}$, respectively. In the Mitigation scenario, the levels of O_3 and $PM_{2.5}$ are projected to decrease by 120% and 88%, respectively, compared to the Reference.

COASTAL PROPERTY

In 2100, the Tampa Bay area is projected to incur \$2.8 billion in damages from sea level rise and storm surge in the Reference scenario without adaptation. When adaptation measures are implemented, total costs in 2100 fall to \$500 million in the Reference scenario, compared to \$450 million in the Mitigation scenario.

Conclusion

Understanding the potential timing and magnitude of climate change impacts in the U.S., and how they could be reduced or avoided through GHG mitigation, informs near- and long-term policies to address these risks. This report describes climate change damages in the U.S. across multiple sectors using a consistent set of scenarios and underlying assumptions.[1] In doing so, the study estimates the physical and economic risks of unmitigated climate change and the potential benefits to the U.S. of reducing global GHG emissions. Importantly, only a small portion of the impacts of climate change are estimated, and therefore this report captures just some of the total benefits of reducing GHGs. Looking across the large number of sectoral impacts described in this report, a number of key findings emerge:

- **Unmitigated climate change is projected to profoundly affect human health, the U.S. economy, and the environment.** The CIRA analyses demonstrate substantial and far-reaching changes over the course of the 21st century—and particularly at the end of the century—with negative consequences for a large majority of the impact sectors. In addition, the analyses suggest that climate change impacts will not be uniform across the U.S., with most sectors showing a complex pattern of regional-scale impacts.
- **Global action to mitigate GHG emissions is projected to reduce and avoid impacts in the U.S. that would otherwise occur in a future with continued high growth in GHG emissions.** Importantly, these benefits are projected to increase over the course of the century. The analyses indicate that risks and impacts over the long term will not be avoided unless there is near-term action to significantly reduce GHG emissions. This report presents benefits for one illustrative global GHG mitigation scenario. More stringent emissions reductions would likely increase the benefits compared to the Reference scenario, and, conversely, less stringent reductions would likely decrease the benefits.
- **Global GHG mitigation substantially reduces the risk of some extreme weather events and their subsequent impacts on human health and well-being by the end of the century.**
- **Adaptation, especially in the infrastructure sector, can substantially reduce the estimated damages of climate change.** For some impacts, such as those described in the Coastal Property section, well-timed adaptation can have a larger effect on reducing the risks of inaction than global GHG mitigation, particularly in the near term, highlighting the need for concurrent mitigation and adaptation actions.

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- **For some impacts, the effects of global GHG mitigation can vary across different projections of future climate.** This is particularly true for those sectors sensitive to changes in precipitation. For a few of these sectors, mitigation results in either benefits or disbenefits depending upon the simulated level of future precipitation.[2] By analyzing multiple types of impacts by sector, such as flooding, drought, water quality, and supply/demand in the water realm, and using a range of projections for future precipitation, a more comprehensive understanding of potential impacts and mitigation benefits is gained.

Next Steps

This report represents a significant and important contribution to estimating the multi-sectoral benefits to the U.S. of global GHG mitigation. Although the results presented in this report do not provide comprehensive coverage of all potential impacts, the breadth and depth of the analyses will expand in future work within the CIRA project. Comprehensive and quantitative estimates of climate change impacts are not only needed to evaluate the benefits of GHG mitigation, but also to evaluate the cost-effectiveness of adaptation responses, and to support the improvement of other economic tools used to analyze climate and energy policies. Although CIRA only begins to capture many of the dynamics and uncertainties involved in impact analysis (e.g., interactions among sectoral models), this report provides timely and quantitative estimates as the science continues to advance in this field. Future work to refine projections of how GHG emissions affect the climate, and how these changes affect society and the environment, will improve our understanding and confidence in the estimates presented in this report.

Additional Climate Change Resources

EPA's Climate Change website (www.epa.gov/climatechange) provides a good starting point for further exploration of this topic. From this site, you can:

- Read about greenhouse gas emissions, look through EPA's greenhouse gas inventories, and explore EPA's Greenhouse Gas Data Publication Tool.
- Learn about EPA's regulatory initiatives and partnership programs.
- Find out what you can do at home, on the road, at work, and at school to help reduce greenhouse gas emissions.

Other government and nongovernment websites also provide information about climate change. Here are some examples:

- The Intergovernmental Panel on Climate Change (IPCC) is the international authority on climate change science. The IPCC website (www.ipcc.ch/index.htm) summarizes the current state of scientific knowledge about climate change and includes links to their most recent Fifth Assessment Report.
- The U.S. Global Change Research Program (www.globalchange.gov) is a multi-agency effort focused on improving our understanding of the science of climate change and its potential impacts on the U.S. through reports like the National Climate Assessment.

Finally, other groups are working to estimate the impacts of climate change in the U.S. and/or other world regions. Here are some examples:

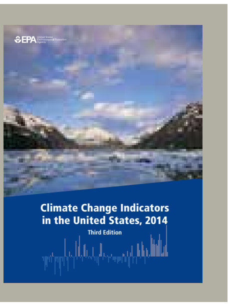
- The Inter-Sectoral Impact Model Inter-comparison Project (ISI-MIP; https://www.pik-potsdam.de/research/climate-impacts-and-vulnerabilities/research/rd2-cross-cutting-activities/isi-mip) is an international, community-driven modelling effort bringing together impact models across sectors and scales.
- The Risky Business Project (http://riskybusiness.org/) focuses on quantifying and publicizing the economic risks from the impacts of a changing climate in the U.S.
- The European Commission Joint Research Centre's PESETA II project (Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis; http://peseta.jrc.ec.europa.eu/) is a consistent multi-sectoral assessment of the impacts of climate change in Europe.

- AVOID (http://www.metoffice.gov.uk/avoid/) is a research program that provides modeling and scientific information to the U.K. Government on avoiding dangerous climate change brought on by greenhouse gas emissions.
- The project on the Benefits of Reduced Anthropogenic Climate Change (BRACE; https://chsp.ucar.edu/brace) focuses on differences in impacts resulting from climate change driven by high and low emissions scenarios.

Observed Climate Change

Climate Change Indicators in the United States: EPA publishes a set of indicators describing trends related to the causes and effects of climate change. Focusing primarily on the U.S., this resource presents compelling evidence that many fundamental measures of observed climate are changing.

Please visit EPA's website for more information: http://www.epa.gov/climatechange/science/indicators/index.html



Endnotes

INTRODUCTION

1 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*.

2 While beyond the scope of this report, analyses of the adequacy of current GHG mitigation efforts, at domestic and global scales, relative to the magnitude of climate change risks are described in the assessment literature. See: 1) Jacoby, H. D., A. C. Janetos, R. Birdsey, J. Buizer, K. Calvin, F. de la Chesnaye, ... and J. West. 2014. Ch. 27: Mitigation. In *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/J0C8276J; and 2) IPCC. 2014. Climate Change 2014: Mitigation of Climate Change. *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, ... and J.C. Minx, Eds. New York, NY: Cambridge University Press.

3 United Nations Framework Convention on Climate Change. 2013. Report of the Conference of the Parties on its nineteenth session, held in Warsaw from November 11-23, 2013. Part one: Proceedings. FCCC/CP/2013/10.

4 CIRA uses sectoral impact models driven by consistent climate and socioeconomic scenarios to analyze both physical impacts and economic damages of climate change at national and regional scales in the U.S. This unique multi-model design allows for 'apples-to-apples' comparisons of impacts and benefits of global GHG mitigation across sectors, but is not comprehensive in scope. The impact estimates presented in this report are consistent with the key findings of the U.S. Global Change Research Program's Third National Climate Assessment. See Section H of the Technical Appendix for this report for a more detailed comparison of key findings.

5 The Social Cost of Carbon (SCC) is a metric that estimates the economic value of impacts associated with the global emission of one ton of carbon dioxide (CO_2) or, conversely, the economic benefit of avoiding or reducing one ton of CO_2 (in dollars per ton of CO_2 in a given year). Unlike CIRA, the SCC draws from models of anticipated climate change impacts and benefits across the entire globe, not just for the U.S. The SCC has already been applied to estimate the global economic benefits of CO_2 emission reductions from certain U.S. regulations, but it does not provide explicit information about how the actual physical impacts in specific sectors of the U.S. may change over time and space. For more information, see: U.S. Interagency Working Group on the Social Cost of Carbon. 2013. Technical support document: Technical update of the social cost of carbon for regulatory impact analysis under Executive Order 12866.

6 The CIRA project estimates the benefits to the U.S. of global action on climate change. Importantly, the costs of GHG mitigation are not assessed in the project. As such, the analysis presented in the report does not constitute a cost-benefit assessment of climate policy. The costs of reducing GHG emissions have been well examined in the scientific literature (see references below), where recent assessments have used multiple economic models to investigate the sensitivity of costs to policy design, assumptions about the availability of low carbon-emitting energy technologies, socioeconomic and demographic changes, and other important sources of uncertainty. The one instance in the CIRA project where mitigation costs are considered is in the electricity sector (see Electricity section for details). For that sector, the impact of climate change on costs to the U.S. electric power system is estimated along with the costs associated with GHG emission reductions in that sector. See: Fawcett, A., L. Clarke, and J. Weyant. 2013. Introduction to EMF 24. *The Energy Journal.* DOI:10.5547/01956574.35.SI1.1; White House Council of Economic Advisors. 2014. The Cost of Delaying Action to Stem Climate Change. Executive Office of the President of the United States; CCSP. 2007. Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations (Part A) and Review of Integrated Scenario Development and Application (Part B). *A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research,* Clarke, L., J. Edmonds, J. Jacoby, H. Pitcher, J. Reilly, R. Richels, ... and M. Webster (Authors). Washington, DC: Department of Energy; Kriegler, E., J.P. Weyant, G.J. Blanford, V. Krey, L. Clarke, J. Edmonds, ... and D.P van Vuuren. 2013. The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. *Climatic Change*. DOI:10.1007/s10584-013-0953-7; and Kriegler, E., K. Riahi, N. Bauer, V.J. Schwanitz, N. Petermann, V. Bosetti, ... and O. Edenhofer. 2015. Making or breaking climate targets: the AMPERE study on staged accession scenarios for climate policy. *Technological Forecast and Social Change*. DOI:10.1016/j.techfore.2013.09.021; *Energy Economics*. Volume 31, Supplement 2, Pages S63-S306 (2009). International, U.S. and E.U. Climate Change Control Scenarios: Results from EMF 22. Edited by Leon Clarke, Christoph Böhringer and Tom F. Rutherford.

7 Example of co-benefit literature: IPCC. 2014. Climate Change 2014: Mitigation of Climate Change. *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, ... and J.C. Minx, Eds. New York, NY: Cambridge University Press.

SUMMARY OF KEY FINDINGS

1 This section draws upon conclusions described in the overview paper for the CIRA special issue: Waldhoff, S., J. Martinich, M. Sarofim, B. DeAngelo, J. McFarland, L. Jantarasami, K. Shouse, A. Crimmins, S. Ohrel, and J. Li. 2014. Overview of the Special Issue: A multi-model framework to achieve consistent evaluation of climate change impacts in the United States. *Climatic Change*. DOI:10.1007/s10584-014-1206-0.

2 Changes in extreme weather events across the CIRA scenarios are discussed in more detail in: 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.

3 See, for example: 1) Ciscar, J-C, A. Iglesias, L. Feyen, L. Szabó, D. Van Regemorter, B. Amelung, … and A. Soria. 2011. Physical and economic consequences of climate change in Europe. *Proc Natl Acad Sci USA*. DOI:10.1073/pnas.1011612108; 2) Frumhoff, P.C., J.J. McCarthy, J.M. Melillo, S.C. Moser, and D.J. Wuebbles. 2007. Confronting climate change in the U.S. Northeast: science, impacts, and solutions. Report of the Northeast Climate Impacts Assessment. Cambridge, MA: Union of Concerned Scientists; and 3)Hayhoe, K., D. Cayan, C.B. Field, P.C. Frumhoff, E.P. Maurer, N.L. Miller, … and J.H. Verville. 2004. Emissions pathways, climate change, and impacts on California. *Proc Natl Acad Sci USA*. DOI:10.1073/pnas.0404500101.

4 Throughout the report, future benefits—i.e., the annual time series of avoided costs—are discounted at a 3% rate to reflect their value in the present day, which is defined as the year 2015 in this report. In short, discounting provides an equal basis to compare the value of benefits (and costs) 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. A higher discount rate implies a greater preference for present-day consumption and a lower present value of future damages. A lower discount rate implies a greater value on future damages. That is, the present value of future damages calculated at a 5% rate will be lower than those calculated using a 3% rate. There are many ways to select a discount rate and little consensus about which discount rate is most appropriate, particularly when assessing benefits that span multiple generations. Therefore, we selected 3%, a commonly employed rate in the climate impacts and benefits literature. This rate was also used to calculate two of the U.S. Government's four Social Cost of Carbon estimates (including the central value), which estimate climate damages that occur over long time horizons. In particular, the U.S. Government review found that it was consistent with estimates provided in the economics literature and noted that 3% roughly corresponds to the after-tax riskless interest rate. For a detailed discussion on discount rate selection, please see the Social Cost of Carbon Technical Support Document, available at http://www.epa.gov/oms/climate/regulations/scc-tsd.pdf.

CIRA FRAMEWORK

1 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*.

2 Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds. 2014. Climate Change Impacts in the United States: The Third National Climate Assessment. Appendix 5: Scenarios and Models. U.S. Global Change Research Program. DOI:10.7930/J0Z31WJ2.

3 While beyond the scope of this report, analyses of the adequacy of current GHG mitigation efforts, at domestic and global scales, relative to the magnitude of climate change risks are described in the assessment literature. See, for example: 1) Jacoby, H. D., A. C. Janetos, R. Birdsey, J. Buizer, K. Calvin, F. de la Chesnaye, ... and J. West. 2014. Ch. 27: Mitigation. *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/J0C8276J; and 2) IPCC. 2014. Climate Change 2014: Mitigation of Climate Change. *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, ... and J.C. Minx, Eds. New York, NY: Cambridge University Press.

4 A third emissions scenario was applied in most CIRA sectoral analyses, as described and presented in the research papers supporting the project. In 2100, this scenario, called Policy 4.5 in the CIRA project, achieves a radiative forcing of approximately 4.2 W/m^2 with an atmospheric GHG concentration of 600 ppm (CO_2 equivalent). This radiative forcing value reflects GHG radiative forcing (i.e., not including aerosols) and uses a baseline of 1750 (both of which are necessary adjustments for comparing to the IPCC RCPs), therefore making it slightly different than the value reported previously in the CIRA literature (4.5 W/m^2).

5 Paltsev, S., J.M. Reilly, H.D. Jacoby, R.S. Eckaus, J. McFarland, M. Sarofim, M. Asadoorian, and M. Babiker. 2005. The MIT Emissions Prediction and Policy Analysis (EPPA) model: version 4. Report 125, MIT Joint Program on the Science and Policy of Global Change. http://globalchange.mit.edu/publications.

6 By 2100 (using a baseline of 1750), the CIRA Reference scenario has a total radiative forcing of 9.8 W/m^2, which appears considerably larger than RCP 8.5. However, the contrast is primarily due to differences in how forcing is calculated by different GCMs used in developing those scenarios. The IGSM radiation code was derived from the GISS climate model, and therefore when calculating radiative forcing due to increased concentrations in the IGSM, forcing functions fit to the GISS code were used rather than the more common approach of using simplified equations, such as those defined in IPCC's Third Assessment Report. Using these simplified equations, total radiative forcing for the CIRA Reference is 8.6 W/m^2, and 3.2 W/m^2 for the Mitigation scenario. Other differences between the IGSM scenarios and the RCPs are due to differences in anthropogenic emissions, natural emissions responses to warming, and atmospheric chemistry.

7 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. We also note that the Reference scenario is calibrated using historic GHG emissions through 2010; see Paltsev et al. (2013) for more information.

8 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.

9 Radiative forcing (including CO_2, CH_4, N_2O, PFCs, SF_6, HFCs, CFCs and HCFCs) for the Reference and Mitigation scenarios (see Paltsev et al. 2013), compared to the four RCPs (data from Meinshausen et al. 2011). The negative forcing effects of aerosols are not included. See: Meinshausen, M., S. J. Smith, K. V. Calvin, J. S. Daniel, M. L. T. Kainuma, J.-F. Lamarque, ... and D. van Vuuren. 2011. The RCP Greenhouse Gas Concentrations and their Extension from 1765 to 2300. *Climatic Change*. DOI:10.1007/s10584-011-0156-z.

10 Please see the literature underlying the CIRA project for information on post-processing and bias-correction of climate outputs for use in the sector analyses.

11 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.

12 Adaptive actions modeled in the sectoral analyses of this report should not be interpreted as recommendations of these particular strategies.

13 Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, ... and R. Somerville. 2014. Chapter 2: Our Changing Climate. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J.M. Melillo, R.C. Richmond, and G. W. Yohe, Eds. U.S. Global Change Research Program. DOI:10.7930/J0KW5CXT.

14 The U.S. Global Change Research Program's National Climate Assessment (NCA) results are reported for the RCP 8.5 scenario, using a range (5th-95th percentile) of results from a suite of climate models, adjusted to match the same baseline period used for the IGSM-CAM model. The NCA also presents results from the older SRES models: the A2 scenario from SRES was projected to warm by 5-8°F by 2100.

15 Future climate change depends on the response of the global climate system to rising GHG concentrations (i.e., how much temperatures will rise in response to a given increase in atmospheric CO_2). Assumptions about this relationship are referred to as climate sensitivity.

16 IPCC. 2014. Summary for Policymakers. In: Climate Change 2014, Mitigation of Climate Change. *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, ... and J.C. Minx, Eds. New York, NY.

17 IPCC. 2013. Summary for Policymakers. 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, ... and P.M. Midgley, Eds. New York, NY.

18 The estimate of warming from the historical period (0.65°C) used in Figure 1 of the Temperature Projections section is slightly less than the IPCC's estimate of 0.85°C because the former utilizes a 30-yr average (1980-2009) to represent the current period.

19 Warming from the historical period (0.65°C) comparing 1880-1909 to 1980-2009 was calculated using the NOAA Global Historical Climatology Network GHCN-3 dataset of Global Land and Ocean Temperature Anomalies (available at http://www.ncdc.noaa.gov/cag/time-series/global/globe/land_ocean/ytd/12/1880-2014.csv). Combined with this historical warming, the 2°C target (relative to preindustrial) is equivalent to a warming of 2.43°F (relative to the 1980-2009 baseline period), as shown in Figure 1 of the Temperature Projections section. This value is consistent with the average of the last two decades of the century (2081-2100) for the CIRA Mitigation scenario: 2.23°F.

20 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.

21 Ibid.

22 The CIRA sea level rise scenarios are at the high end of projected sea level rise rates for similar scenarios based on recent publications (Horton et al. 2014, Kopp et al. 2014). However, we also note that the effect of GHG mitigation on reducing the increase in future sea level was found to be larger in these studies. The use of a smaller sea level rise would likely lead to a decrease in total damages, but a larger reduction in sea level rise due to the Mitigation scenario would likely yield larger economic benefits than those presented in this report. See: 1) Horton, B.J., S. Rahmstorf, S.E. Engelhart, and A.C. Kemp. 2014. Expert assessment of sea-level rise by AD 2100 and AD 2300. *Quaternary Science Reviews.* DOI:10.1016/j.quascirev.2013.11.002; and 2) 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*. DOI:10.1002/2014EF000239.

23 Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, ... and R. Somerville. 2014. Chapter 2: Our Changing Climate. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J.M. Melillo, R.C. Richmond, and G. W. Yohe, Eds. U.S. Global Change Research Program. DOI:10.7930/J0KW5CXT.

24 Meier, M.F., M.B. Dyurgerov, U.K. Rick, S. O'Neel, W.T. Pfeffer, R. S. Anderson, S.P. Anderson, and A.F. Glazovsky. 2007. Glaciers dominate eustatic sea-level rise in the 21st century. *Science*. DOI:10.1126/science.1143906.

25 Vermeer, M., and S. Rahmstorf. 2009. Global sea level linked to global temperature. *Proceedings of the National Academy of Sciences*. DOI:10.1073/pnas.0907765106.

26 The CIRA sea level rise projections were estimated following the methodology of Vermeer and Rahmstorf (2009). The methodology of Vermeer and Rahmstorf builds off that from Rahmstorf (2007) and is described in detail in those papers. In short, projections were estimated using an empirical relationship between global air temperature and sea level change, including contributions from glaciers and ice sheets. This relationship was then applied to the ambient average air temperature trajectories from the IGSM-CAM model (Paltsev et al. 2013) to project future sea levels.

27 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.

28 For each scenario, a site-specific, fixed annual rate of land subsidence or uplift is estimated, which combines with the SLR scenario to yield site-specific relative sea level rise. Historical vertical land movement is based on annual average measurements from National Oceanic and Atmospheric Administration (NOAA) tide gauge data from 68 sites with at least 25 years of continuous measurements and linear interpolation of subsidence rates for all cells that lie between the selected sites. An estimated 1.7 mm/year is subtracted from the tide gauge annual average to account for the component of relative sea level rise that is accounted for by 20th century sea level change, yielding the site-specific subsidence/uplift rate.

29 The CIRA approach for calculating relative sea level rise assumes that the difference in rate between global and relative sea level change will continue into the future. Because some physical processes (e.g., changes in differential ocean heating) will likely change in the future at rates different from what is reflected in historical tide gauge data, the CIRA approach does not capture all of these dynamics. For more information, see: Neumann, J., D. Hudgens, J. Herter, and J. Martinich. 2010. The Economics of Adaptation along Developed Coastlines. *Wiley Interdisciplinary Reviews: Climate Change*. DOI:10.1002/wcc.90.

30 Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, ... and R. Somerville. 2014. Appendix 3: Climate Science Supplement. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J.M. Melillo, T.C. Richmond, and G.W. Yohe, Eds., U.S. Global Research Program. DOI:10.7930/J0KS6PHH.

31 Ibid.

32 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.

Endnotes

33 Ibid.

34 All three CIRA emissions scenarios contain the same level of global and U.S. population change over time.

35 For each emissions scenario, values represent the ensemble mean of the five IGSM-CAM initializations using a climate sensitivity of 3°C.

36 IPCC. 2013. 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, ... and P.M. Midgley, Eds. New York, NY: Cambridge University Press.

37 A climate sensitivity of 6°C is considered "low probability" when considering feedbacks expected over the next century. However, there is literature suggesting that slower feedbacks involving ice sheet and vegetation changes can lead to higher "Earth System Sensitivity" on timescales of several centuries, such that a sensitivity of 6°C will have a higher probability on these longer timescales. Additional feedbacks including methane and carbon cycles are not included in the climate sensitivity definition.

38 Mapped values represent the ensemble mean of the five IGSM-CAM initializations with different climate sensitivities under the Reference scenario.

39 All five maps assume a climate sensitivity of 3°C under the Reference scenario.

40 A method by which the average change produced by running a climate model is combined with the specific geographic pattern of change calculated from a different model in order to approximate the result that would be produced by the second model.

41 Please refer to: 1) 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; and 2) Flato, G., J. Marotzke, B. Abiodun, P. Braconnot, S.C. Chou, W. Collins, ... and M. Rummukainen. 2013. Evaluation of Climate Models. 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. New York, NY: Cambridge University Press.

42 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.

43 This section draws upon conclusions described in the overview paper for the CIRA special issue: Waldhoff, S., J. Martinich, M. Sarofim, B. DeAngelo, J. McFarland, L. Jantarasami, K. Shouse, A. Crimmins, S. Ohrel, and J. Li. 2014. Overview of the Special Issue: A multi-model framework to achieve consistent evaluation of climate change impacts in the United States. *Climatic Change*. DOI:10.1007/s10584-014-1206-0.

44 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.

45 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.

46 Ongoing studies are investigating the influence of structural uncertainties across sectoral impact models. See: Huber, V., H.J. Schellnhuber, N.W. Arnell, K. Frieler, A.D. Friend, D. Gerten, ... and L. Warszawski. 2014. Climate impact research: beyond patchwork. *Earth System Dynamics.* DOI:10.5194/esd-5-399-2014.

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1 The economic estimates described throughout this report are presented in constant 2014 dollars. The literature underlying the CIRA project presents results primarily in 2005 dollars. This should be noted when comparing the results presented in this report with those in the CIRA literature. Dollar years were adjusted using the U.S. Bureau of Economic Analysis' Implicit Price Deflators for Gross Domestic Product. Source: U.S. Bureau of Economic Analysis, Table 1.1.9 Implicit Price Deflators for Gross Domestic Product, March 27, 2015, http://www.bea.gov/national/index.htm.

2 Throughout the report, future benefits—i.e., the annual time series of avoided costs—are discounted at a 3% rate to reflect their value in the present day, which is defined as the year 2015 in this report. In short, discounting provides an equal basis to compare the value of benefits (and costs) 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. A higher discount rate implies a greater preference for present-day consumption and a lower present value of future damages. A lower discount rate implies a greater value on future damages. That is, the present value of future damages calculated at a 5% rate will be lower than those calculated using a 3% rate. There are many ways to select a discount rate and little consensus about which discount rate is most appropriate, particularly when assessing benefits that span generations. Therefore, we selected 3%, a commonly employed rate in the climate impacts and benefits literature. This rate was also used to calculate two of the U.S. Government's four Social Cost of Carbon estimates (including the central value), which estimate climate damages that occur over long time horizons. In particular, the U.S. Government review found that it was consistent with estimates provided in the economics literature and noted that 3% roughly corresponds to the after-tax riskless interest rate. For a detailed discussion on discount rate selection, please see the Social Cost of Carbon Technical Support Document, available at http://www.epa.gov/oms/climate/regulations/scc-tsd.pdf.

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10 A climate-induced drop in ozone is caused by increased atmospheric water vapor under a warmer climate. Higher humidity shortens the atmospheric lifetime of ozone in low-NOx (typically less densely-populated) conditions by enhancing its breakdown. Projected reductions in ground-level concentrations over the northern and western parts of the country are largely driven by this decline in background ozone.

11 For comparison, the current national 8-hour daily maximum ozone standard is 75 parts per billion: primary and secondary standard in the form of annual fourth-highest daily maximum 8-hour concentration averaged over 3 years.

12 Changes in ozone and $PM_{2.5}$ concentrations in the Risks of Inaction section and in Figures 1 and 2 are not population-weighted.

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14 The ranges in mortality estimates are based on ensemble means and reflect the 95% confidence interval in concentration response functions. See Garcia-Menendez et al. (2015) for more information.

15 An additional mortality valuation approach using years of life saved is provided in Garcia-Menendez et al. (2015).

16 Reductions in $PM_{2.5}$ largely drive the change in mortality. However, the contribution of ozone pollution to these estimates increases towards the end of the century and accounts for 40% of the projected life years saved by 2100. See Garcia-Menendez et al. (2015) for more information.

17 For example: 1) Thompson, T.M., Rausch S., Saari R.K., and Selin N.E. 2014. A systems approach to evaluating the air quality co-benefits of U.S. carbon policies. *Nature Climate Change*. DOI: 10.1038/nclimate2342; 2) West, J., S. Smith, R. Silva, V. Naik, Y. Zhang, Z. Adelman, ... and J. Lamarque. 2013. Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. *Nature Climate Change*. DOI: 10.1038/nclimate2009; and 3) U.S. Environmental Protection Agency. 2014. Regulatory Impact Analysis for the Proposed Carbon Pollution Guidelines for Existing Power Plants and Emission Standards for Modified and Reconstructed Power Plants. Office of Air Quality Planning and Standards, Health & Environmental Impacts Division, Air Economics Group. Research Triangle Park, North Carolina.

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19 Fine particulate matter constituents analyzed include sulfate, elemental carbon, organic aerosol and ammonium nitrate.

20 Changes in mortality are estimated by applying the differences in daily-maximum 8-hour ozone (8-hr-max ozone) between May and September and daily average $PM_{2.5}$ to the concentration response functions.

21 At the time of this report's release, the U.S. Environmental Protection Agency's Guidelines for Preparing Economic Analyses report recommends a VSL of $7.9 million (2008$), based on 1990 incomes. To create a VSL using 2014$ and based on 2010 incomes, the standard value was adjusted for inflation using BEA implicit price inflator for gross domestic product and for income growth adjustment based on a method described in the user manual of EPA's BenMAP model (pg. 109). The resulting value, $9.45 million for 2010 (2014$), was adjusted to future years by assuming an elasticity of VSL to GDP per capita of 0.4. Projections of GDP and population for the CIRA Reference scenario were employed. Using this approach, the VSL in 2050 is estimated at $12.53 million and $16.39 million in 2100. Finally, we note that the VSL values used in this report differ slightly from those used in Garcia-Menendez et al. (2015), which therefore affects the valuation estimates reported in each. Sources: 1) U.S. Environmental Protection Agency. 2014. Guidelines for Preparing Economic Analyses. National Center for Environmental Economics. http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0568-52.pdf/$file/EE-0568-52.pdf; 2) U.S. Bureau of Economic Analysis, Table 1.1.9 Implicit Price Deflators for Gross Domestic Product, March 27, 2015, http://www.bea.gov/national/index.htm; and 3) U.S. Environmental Protection Agency. 2012. BenMAP Users Manual. Office of Air Quality Planning and Standards.

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27 Ibid.

28 Average results for the 49 cities included in the study.

29 See Mills et al. (2014) and Bierwagen et al. (2010) for details on usage of ICLUS population projections. Sources: 1) 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; and 2) Bierwagen, B.G., D.M. Theobald, C.R. Pyke, A. Choate, P. Groth, J.V. Thomas, and P. Morefield. 2010. National housing and impervious surface scenarios for integrated climate impact assessments. *Proc Natl Acad Sci*. DOI: 10.1073/pnas.1002096107.

30 At the time of this report's release, the U.S. Environmental Protection Agency's Guidelines for Preparing Economic Analyses report recommends a VSL of $7.9 million (2008$), based on 1990 incomes. To create a VSL using 2014$ and based on 2010 incomes, the standard value was adjusted for inflation using BEA implicit price inflator for gross domestic product and for income growth adjustment based on a method described in the user manual of EPA's BenMAP model (pg. 109). The resulting value, $9.45 million for 2010 (2014$), was adjusted to future years by assuming an elasticity of VSL to GDP per capita of 0.4. Projections of GDP and population for the CIRA Reference scenario were employed. Using this approach, the VSL in 2050 is estimated at $12.53 million and $16.39 million in 2100. Finally, we note that the VSL values used in this report differ slightly from those used in Garcia-Menendez et al. (2015), which therefore affects the valuation estimates reported in each. Sources: 1) U.S. Environmental Protection Agency. 2014. Guidelines for Preparing Economic Analyses. National Center for Environmental Economics. http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0568-52.pdf/$file/EE-0568-52.pdf; 2) U.S. Bureau of Economic Analysis, Table 1.1.9 Implicit Price Deflators for Gross Domestic Product, March 27, 2015, http://www.bea.gov/national/index.htm; and 3) U.S. Environmental Protection Agency. 2012. BenMAP Users Manual. Office of Air Quality Planning and Standards.

31 The approach described in Mills et al. (2014) was updated in several ways to develop the results presented here. First, the analysis was expanded from 33 cities to encompass a total of 49 out of 50 of the cities (excluding Honolulu) analyzed in the Medina-Ramon and Schwartz (2007) paper that was the foundation of the Mills et al. (2014) work. 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), and the choice was made in the Mills et al. (2014) work to not include those cities in the projections of future mortality. In a warming climate, cities that were too warm to meet the criteria for the cold threshold will continue to be too warm, so the lack of a cold mortality response function will not make a difference. However, 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 the benefit of GHG mitigation. However, inclusion of a wider range of cities gives a more complete picture of impacts in the U.S. There were a couple of additional updates. The first involved limiting the analysis to the actual counties corresponding to the cities specified in Medina-Ramon and Schwartz, rather than the MSAs used in Mills et al. (2014). This reduces the total population considered within the original 33 cities. The second involved updating to the most recent BenMAP data for the all-age mortality rates in the cities, which resulted in some small differences in the calculations.

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

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39 Bureau of Labor Statistics, Quarterly Census of Employment and Wages, data accessible 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.

40 Bureau of Labor Statistics, Quarterly Census of Employment and Wages, data accessible at http://www.bls.gov/cew/. Average wage ($23.02) calculated using high-risk labor categories only, as the majority of extreme temperature impacts on labor hours occur in these industries.

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21 The adaptation costs per square mile, calculated by city, storm, scenario, and year, were aggregated to the regions used in the Third 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.

22 More detailed models are often used by municipalities for local stormwater management planning, but applying these models across the 50 cities examined in this analysis was not practicable.

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29 The CIRA sea level rise scenarios are at the high end of projected sea level rise rates for similar scenarios based on recent publications (Horton et al. 2014, Kopp et al. 2014). However, we also note that the effect of GHG mitigation on reducing the increase in future sea level was found to be proportionally larger in these studies. The use of smaller sea level rise rates would likely lead to a decrease in total damages, but a larger reduction in sea level rise due to the Mitigation scenario compared to the Reference would likely yield larger economic benefits than those presented in this report. See: 1) Horton, B.J., S. Rahmstorf, S.E. Engelhart, and A.C. Kemp. 2014. Expert assessment

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30 Without discounting, the cumulative effect of mitigation is larger, reducing impacts by about 10% (from $1.2 trillion to $1.0 trillion), and the annual benefits rise rapidly from approximately $140 million in 2050 to nearly $3.1 billion in 2100.

31 The CIRA analysis evaluates risks of inaction and benefits of mitigation through the end of the 21st century. The high degree of inertia in processes leading to sea-level rise (i.e., the oceans and ice sheets respond slowly to warming conditions at the Earth's surface) suggest that the absence of 21st century GHG mitigation is likely to result in sea level rise rates equal to or larger than those experienced this century, with subsequent large and long-term implications for coastal development (Horton et al. 2014 and Levermann et al. 2013 provide projections of sea level rise beyond 2100). Therefore, the difference in sea level change rise between the CIRA Reference and Mitigation scenarios will only increase after 2100. This would likely result in larger GHG mitigation benefits to the coastal property sector, and it is important to note that these benefits would only be realized from GHG reductions occurring in this century. See: Horton, B.J., S. Rahmstorf, S.E. Engelhart, and A.C. Kemp. 2014. Expert assessment of sea-level rise by AD 2100 and AD 2300. *Quaternary Science Reviews* 84:1-6; and Levermann, A., P. Clark, B. Marzeion, G. Milne, D. Pollard, V. Radic, and A. Robinson. 2013. The multimillennial sea-level commitment of global warming. *PNAS*, DOI: 10.1073/pnas.1219414110.

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Electricity

1 The transportation sector accounts for 27 percent of emissions, followed by the residential, commercial, and industrial sectors at 21 percent. The remaining 22 percent of emissions come from biomass and various other sectors. The share of electricity generated by fossil fuels from 2009-2013 was 69% (42% from coal, 26% from natural gas, 0.8% from petroleum). U.S. Department of Energy. 2014. Electric Power Monthly: Table 1.1. Net Generation by Energy Source: Total (All Sectors), 2004-February 2014.

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18 Total generation across the models varies because electricity demand is independently calculated by each model based on changes in population, GDP, technology costs, and other factors.

19 McFarland, J., Y. Zhou, L. Clarke, P. Sullivan, J. Colman, W. Jaglom, ... 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.

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20 Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, ... 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. DOI:10.7930/J0KW5CXT.

21 Strzepek, K., G. Yohe, J. Neumann, and B. Boehlert. 2010. Characterizing changes in drought risk for the United States from climate change. *Environ. Res. Lett.* DOI:10.1088/1748-9326/5/4/044012.

22 Boehlert, B., E. Fitzgerald, J. Neumann, K. Strzepek, and J. Martinich. 2015. The Effect of Greenhouse Gas Mitigation on Drought Impacts in the U.S. *Weather, Climate and Society.* DOI: 10.1175/WCAS-D-14-00020.1.

23 The impact estimates for drought on crop-based agriculture both complement and overlap with the FASOM/EPIC estimates of the impact of climate change on agricultural crops. The drought methodology uses an econometric approach grounded in historical expenditures to alleviate historical droughts, and projections of drought occurrence—it addresses a subset of effects on agriculture associated with drought occurrence. The FASOM/EPIC results are more comprehensive in scope and address both droughts and many other aspects of climate change (e.g., changes in the timing of rainfall and extreme heat), and adopt a simulation approach which models specific actions by farmers and in agricultural markets that might be taken to respond to climate impacts.

24 Strzepek, K., J. Martinich, J. Neumann, B. Boehlert, J. Henderson, M. Hejazi, ... and J. Yoon. 2014. Benefits of Greenhouse Gas Mitigation on the Supply, Management, and Use of Water Resources in the United States. *Climatic Change*. DOI: 10.1007/s10584-014-1279-9.

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

27 Ibid.

28 Henderson, J., C. Rodgers, R. Jones, J. Smith, K. Strzepek, and J. Martinich. 2013. Economic impacts of climate change on water resources in the coterminous United States. *Mitig Adapt Strateg Glob Change*. DOI:10.1007/s11027-013-9483-x.

29 In-stream flows are modeled such that flows below minimum levels required to sustain vulnerable aquatic species are assessed a penalty. In addition, it should be noted that the agricultural water use simulated in the CIRA Water Supply and Demand model does not link with the model used to estimate impacts in that sector of this report.

30 While the Water Supply and Demand analysis accounts for reactive adaptation in response to changes in water supply, the effects from water resources technology improvements and proactive adaptation planning are not included. Adaptation planning in the water resource sector has increased at the federal level in the U.S., e.g., EPA National Water Program's Response to Climate Change and NOAA's Regional Integrated Sciences & Assessments (RISA) program.

31 Strzepek, K., J. Martinich, J. Neumann, B. Boehlert, J. Henderson, M. Hejazi, ... and J. Yoon. 2014. Benefits of Greenhouse Gas Mitigation on the Supply, Management, and Use of Water Resources in the United States. *Climatic Change*. DOI: 10.1007/s10584-014-1279-9.

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Agriculture and Forestry

1 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. DOI:10.7930/J02Z13FR.

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3 Ibid.

4 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. DOI:10.7930/JOZ60KZC.

5 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.

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9 A wetter future climate, as projected under the IGSM-CAM for many crop-growing parts of the U.S., will tend to reduce water stress such that some yields may increase even with higher temperatures. In the EPIC modeling, irrigated crops are assumed to be able to meet their water needs regardless of climate change effects on precipitation, so a wetter/hotter climate scenario just increases their temperature stress without reducing their water stress. This tends to make impacts on rainfed crops more negative than for irrigated yields. In addition, the ability of climate models to simulate precipitation as severe storms or as heavy rainfall rather than frequent drizzle is an emerging area of research in the climate modeling community. As such, the results presented here should be interpreted with acknowledgement of this uncertainty.

10 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.

11 The EPIC simulations assume that crops can be irrigated at 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.

12 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. DOI:10.7930/JOZ60KZC.

13 Mills, D., R. Jones, K. Carney, A. St Juliana, R. Ready, A. Crimmins ... 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.

14 The results in Figure 2 from the EPIC model show projected crop yields that do not reflect production and market adjustments.

15 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.

16 Thomson, A.M., R.A. Brown, N.J. Rosenberg, R.C. Izaurralde, and V. Benson. 2005. Climate Change Impacts for the Conterminous USA. Part 3: Dryland production of grain and forage crops. *Climatic Change*. DOI:10.1007/1-4020-3876-3.

17 The EPIC simulations assume that crops can be irrigated at 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.

18 The analysis uses climate projections from all five initializations of the IGSM-CAM. Given the sensitivity of the EPIC and MC1 models to natural variability, the use of the five initializations of the IGSM-CAM climate model, each of which has an equally plausible future climate, aids in understanding and constraining the potential magnitude of crop and vegetation changes in the future. Please refer to the Levels of Certainty section of this report for more information.

19 Mills, D., R. Jones, K. Carney, A. St Juliana, R. Ready, A. Crimmins ... 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.

20 The change in forest yield was assumed to be equal to the percentage difference in net primary productivity between future years and the average for the baseline (1980-2009).

21 While beyond the scope of this analysis, the effects of CO_2 fertilization on forest growth and productivity may be limited by the availability of nitrogen, which could influence the results estimated here.

22 Beach, R., Y. Cai, A. Thomson, X. Zhang, R. Jones, B. McCarl,… and B. Boehlert. (In press). Climate change impacts on US agriculture and forestry: benefits of global climate stabilization. *Environmental Research Letters*.

23 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.

24 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.

25 Beach, R., D. Adams, R. Alig, J. Baker, G. Latta, B. McCarl, ... and E. White. 2010. Model documentation for the Forest and Agricultural Sector Optimization Model with Greenhouse Gases (FASOMGHG). Prepared for U.S. Environmental Protection Agency.

26 EPIC, MC1, and FASOM results in the Agriculture and Forestry sections using the IGSM-CAM climate projections represent the average of the five initializations.

27 FASOM has perfect foresight of future climate change effects, and thus can optimize near term land owner behavior. The model also simulates changes in agricultural and forestry commodities beyond those modeled in EPIC (9 crops) and MC1 (hard and softwoods).

28 This analysis does not reflect climate change impacts on international forests and agriculture, which would also affect relative returns to different uses of land and trade patterns and therefore affect land use decisions. Also, numerous uncertainties remain regarding issues such as future changes in crop technology, energy policy, and other interactions that could affect market outcomes.

Endnotes

29 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.

30 FASOM directly models changes to productivity on private timberland, although timber from public lands enters the market exogenously based on public lands policy. Impacts on productivity due to climate change are only applied to the private timberland.

31 Boehlert, B., K. Strzepek, S. Chapra, C. Fant, Y. Gebretsadik, M. Lickley, ... and J. Martinich. 2015. Climate change impacts and greenhouse gas mitigation effects on U.S. water quality. Journal of Advances in Modeling Earth Systems. DOI:10.1002/2014MS000400.

32 Beach, R., Y. Cai, A. Thomson, X. Zhang, R. Jones, B. McCarl,… and B. Boehlert. (In press). Climate change impacts on US agriculture and forestry: benefits of global climate stabilization. *Environmental Research Letters*.

Ecosystems

1 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.

2 Ibid.

3 Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds. 2014. Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program. DOI:10.7930/J0Z31WJ2.

4 The impacts modeled in COMBO do not include non-climate stressors, such as overfishing or water pollution, and do 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 have the ability to adjust the estimates presented in this report upwards or downwards.

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14 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.

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24 Global GHG mitigation is projected to preserve 230,000 acres of coldwater fish habitat in 2100 under the MIROC climate projections. For all freshwater fishing guilds, the total damages in 2100 are estimated at $1.7 billion in the Reference scenario and $200 million in the Mitigation scenario.

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37 Comprised of the following Geographic Area Coordination Center regions: Northern Rockies, Rocky Mountain, Southwest, Eastern Great Basin, Western Great Basin, Northwest, California North, and California South.

38 Percent changes calculated by comparing acres burned under the Reference scenario at the end of the century (average of 2085-2114) compared to the historic baseline (average of 2000-2009).

39 Fuel management costs are estimated at $15 billion under the Reference and $12 billion under the Mitigation scenario through 2100 (average across all IGSM-CAM initializations, 2014$, discounted at 3%), corresponding to avoided costs (benefits) of $3.4 billion under the Mitigation scenario.

40 Fuel management costs were not estimated using the MIROC climate model.

41 The CIRA results simulated in the MC1 vegetation model suggest a substantial change to the wildfire regime we experience today. For example, unmitigated climate change is projected to increase area burned by wildfire annually by approximately 45% in California by the end of the century, 64% in the Mountain West, and 95% in the Northwest. Given the sensitivity of the MC1 climate model to natural variability, the use of the five initializations of the IGSM-CAM climate model, each of which has an equally plausible future climate, aids in understanding and constraining the potential magnitude of vegetation changes in the future.

42 Because the IGSM-CAM projects a wetter future for a majority of the nation, pattern-scaled output from two additional climate models were simulated in MC1 to encompass a broader range of possible climate futures. While all three sets of climate projections show increases in the area burned by wildfire compared to the historic period, only the IGSM-CAM and MIROC climate model results are presented in this report. For an in-depth discussion of the results, see: Mills, D., R. Jones, K. Carney, A. St Juliana, R. Ready, A. Crimmins, ... 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.

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CONCLUSION

1 The few efforts to date that have estimated multi-sector impacts in a consistent framework include the European Commission's PESETA project (http://peseta.jrc.ec.europa.eu), and the Risky Business Initiative (http://riskybusiness.org), a project focusing on economic risks in the U.S. Integrated assessment models, such as FUND (http://fund-model.org), are also being used to estimate the multi-sector social costs of GHG emissions.

2 The use of a climate model that generates a relatively higher amount of future precipitation may strongly influence results in a particular sector. For example, inland flooding damages may be larger under these wetter climate projections compared to those under a drier model. This same sensitivity of sectoral results to the choice of climate model could affect a different part of the water sector in complementary ways, such that drought damages could be smaller compared to those under a drier model.

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