# Technical Appendix for Report:

## Climate Change in the United States: Benefits of Global Action

This document provides technical supporting information for the U.S. Environmental Protection Agency's (EPA's) report, *Climate Change in the United States: Benefits of Global Action*. 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 determine to what degree risks and damages to multiple sectors (e.g., human health, infrastructure, water resources, etc.) in the U.S. may be avoided or reduced in a future with significant global action to reduce greenhouse gas (GHG) emissions, compared to a future where business-as-usual trends in GHG emissions continue. This report is intended to provide insights to decision-makers and the engaged public regarding the potential direction and magnitude of climate change impacts and the benefits to the U.S. of global GHG reductions.

This technical appendix is intended to provide readers with a central repository of citations to the literature underlying the CIRA project, and to document processes related to information quality, the external peer review, and other technical information associated with the CIRA project. The data presented in the figures and graphics of the report are accessible at www.epa.gov/cira.

EPA may update this Technical Appendix as new and/or additional information about the underlying data and publications become available.

## Contents

## A. Ensuring Information Quality

The CIRA report and its underlying analyses were conducted in accordance with EPA's *Guidelines for Ensuring and Maximizing the Quality, Objectivity, Utility, and Integrity of Information Disseminated by the Environmental Protection* Agency,[1] which follows Office of Management and Budget (OMB) guidelines[2] and implements the Information Quality Act (IQA) (Section 515 of Public Law 106–554).[3] Section C of this Appendix describes the independent, external peer review that was performed on the report.

In accordance with OMB definitions, EPA defines the basic standard of "quality" by the attributes objectivity, utility, and integrity. For products meeting a higher standard of quality, the Agency requires an appropriate level of transparency regarding data and methods in order to facilitate the reproducibility of information by qualified third parties. The EPA uses various established Agency processes (e.g., the Quality System, peer review requirements and processes) to ensure the appropriate level of objectivity, utility, integrity, and transparency for its products based on the intended use of the information and the resources available. The following discussion describes how EPA determined that the CIRA report meets a high standard of information quality.

Objectivity focuses on whether the disseminated information is being presented in an accurate, clear, complete, and unbiased manner, and as a matter of substance, is accurate, reliable, and unbiased. The CIRA report meets the standard for objectivity, due to activities described in the following:

a) The information disseminated was determined to be complete, accurate, and reliable based on internal quality control measures adopted by the expert modeling teams. This included quality checks throughout the chain of analytic steps, including developing and processing climate projections, calibrating and validating the sectoral impact models, and checking data to ensure that no errors occurred in the process to compile and summarize the results.

b) The information disseminated was determined to be clear, complete, and unbiased based on multiple rounds of review by qualified personnel. Consistent with guidelines described in EPA's Peer Review Handbook,[4] the underlying sectoral modeling analyses of the CIRA project were peer-reviewed in the scientific literature. Section B of this Appendix provides a comprehensive list of this literature. The content of the CIRA report was also subject to an independent, external peer review to ensure that the findings of the underlying CIRA literature were accurately summarized, appropriately

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[1] U.S. EPA. 2002. Guidelines for ensuring and maximizing the quality, objectivity, utility, and integrity of information disseminated by the Environmental Protection Agency. EPA/260R-02-008. http://www.epa.gov/quality/informationguidelines/documents/EPA_InfoQualityGuidelines.pdf.

[2] Executive Office of the President, Office of Management and Budget. Information Quality Guidelines, October 1, 2002. http://www.whitehouse.gov/sites/default/files/omb/inforeg/iqg_oct2002.pdf

[3] The IQA requires the Office of Management and Budget and federal agencies to issue guidelines that "ensur[e] and maximize[e] the quality, objectivity, utility, and integrity of information (including statistical information) disseminated by Federal agencies" (Public Law 106-554; 44 U.S.C. 3516, note). The IQA does not impose its own standard of "quality" on agency information; instead, it requires only that an agency "issue guidelines" ensuring data quality. Following guidelines issued by the Office of Management and Budget, EPA released its own guidelines to implement the IQA: "Guidelines for Ensuring and Maximizing the Quality, Objectivity, Utility, and Integrity of Information Disseminated by the Environmental Protection Agency".

[4] EPA's Peer Review Handbook (3rd Edition, http://www.epa.gov/peerreview/pdfs/peer_review_handbook_2012.pdf).

interpreted and documented, and whether the risks, benefits and insights were clearly communicated for a non-technical audience.

Integrity refers to security of information, such as the protection of information from unauthorized access or revision, to ensure that the information is not compromised through corruption or falsification. The CIRA report and its underlying analyses meet the standard for integrity by taking multiple steps to ensure that the data and information remained secure. These steps include the use of password protected data storage repositories, password protected data transfer technology, and multiple layers of data validation checks to ensure that the integrity was not compromised.

Utility refers to the usefulness of the information to the intended users. The CIRA report and its underlying analyses meets the standard for utility because the information disseminated provides insights (quantitative estimates in physical and economic terms) regarding the potential direction and magnitude of the impacts of climate change on the U.S. Understanding the risks posed by climate change in futures with and without global GHG mitigation can inform policy decisions designed to address these risks.

Transparency refers to access to and description of (1) the source of the data used, (2) the various assumptions employed, (3) the analytic methods applied, and (4) the statistical procedures employed. The CIRA report and its underlying analyses meet the standard for transparency for the following reasons:

a) The technical approaches and results of the sectoral impact analyses have been published with open access in the peer-reviewed scientific literature, and are cited throughout the CIRA report. These papers, along with their online supplementary materials, provide detailed information on the source of data used, assumptions employed, the analytic and statistical methods applied, and important limitations regarding the approaches and/or how the results should be interpreted.

b) The data from all figures and graphs in the CIRA report are available for download, along with the full report, at www.epa.gov/cira.

c) Each sectoral impact described in the report has a brief description of the approach and assumptions used in developing the estimates, with citations to the underlying literature for more information.

## B. Literature Underlying the CIRA Project

As part of the process to ensure information quality, and consistent with guidelines described in EPA's Peer Review Handbook, the underlying modeling analyses of the CIRA project were peer-reviewed in the scientific literature. The CIRA project applies a large number of statistical and process-based models to quantify the risks of inaction on climate change and the benefits to the U.S. of global GHG mitigation. To ensure that the methods and results of these modeling analyses are technically rigorous, competently performed, properly documented, and consistent with established quality criteria, independent evaluation was undertaken through the external peer review processes of scientific journals. This approach is consistent with OMB and EPA guidelines.[5]

This literature documenting the CIRA methods and results, most of which have been published with open access (i.e., free access to the public), can be categorized into two groups:

### CIRA Special Issue

EPA and collaborators have published 11 papers as a special journal issue of *Climatic Change* describing the different elements of CIRA, including project objectives, scenario development, climate projection, and modeling of sectoral impacts and damages:

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*.

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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.
http://link.springer.com/article/10.1007/s10584-014-1206-0

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.
http://link.springer.com/article/10.1007%2Fs10584-013-0892-3

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.
http://link.springer.com/article/10.1007/s10584-014-1112-5

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[5] Peer review by a credible, refereed scientific journal is consistent with OMB's Final Information Quality Bulletin for Peer Review (http://www.whitehouse.gov/sites/default/files/omb/memoranda/fy2005/m05-03.pdf), EPA's Peer Review Handbook (3rd Edition, http://www.epa.gov/peerreview/pdfs/peer_review_handbook_2012.pdf), and EPA's Guidelines for Ensuring and Maximizing the Quality, Objectivity, Utility, and Integrity, of Information Disseminated by the Environmental Protection Agency (http://www.epa.gov/quality/informationguidelines). The EPA Peer Review Handbook states "peer review of journal articles (written by EPA or non-EPA authors) performed by a credible, refereed scientific journal contributes to the scientific and technical credibility of the reviewed product. Generally, EPA considers peer review by such journals as adequate for reviewing the scientific credibility and validity of the findings (or data) in that article, and therefore, a satisfactory form of peer review" (page 47).

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.
http://link.springer.com/article/10.1007/s10584-013-1048-1

Calvin, K., B. Bond-Lamberty, J. Edmonds, M. Hejazi, S. Waldhoff, M. Wise, and Y. Zhou. 2013. The effects of climate sensitivity and carbon cycle interactions on mitigation policy stringency. *Climatic Change*. DOI: 10.1007/s10584-013-1026-7.
http://link.springer.com/article/10.1007/s10584-013-1026-7

Mills, D., J. Schwartz, M. Lee, M. Sarofim, R. Jones, M. Lawson, 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.
http://link.springer.com/article/10.1007/s10584-014-1154-8

McFarland, J., Y. Zhou, L. Clarke, P. Schultz, P. Sullivan, J Colman J, P. Patel, J. Eom, S. Kim, G.P. Kyle, W. Jaglom, B. Venkatesh, J. Haydel, R. Miller, J. Creason, B. Perkins, 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.
http://link.springer.com/article/10.1007/s10584-015-1380-8

Neumann, J.E., J. Price, P. Chinowsky, L. Wright, L. Ludwig, R. Streeter, R. Jones, J.B. Smith, W. Perkins, L. Jantarasami, and J. Martinich. 2014. Climate change risks to US infrastructure: impacts on roads, bridges, coastal development, and urban drainage. *Climatic Change*. DOI: 10.1007/s10584-013-1037-4.
http://link.springer.com/article/10.1007/s10584-013-1037-4

Strzepek, K., J. Neumann, J. Smith, J. Martinich, B. Boehlert, M. Hejazi, J. Henderson, C. Wobus, R. Jones, K. Calvin, D. Johnson, E. Monier, J. Strzepek, and J. Yoon. 2014. Benefits of Greenhouse Gas Mitigation on the Supply, Management, and Use of Water Resources in the United States. *Climatic Change*. DOI: 10.1007/s10584-014-1279-9.
http://link.springer.com/article/10.1007/s10584-014-1279-9

Lane, D., R. Jones, D. Mills, C. Wobus, R.C. Ready, R.W. Buddemeier, E. English, J. Martinich, K. Shouse, and H. Hosterman. 2014. Climate change impacts on freshwater fish, coral reefs, and related ecosystem services in the United States. *Climatic Change*. DOI: 10.1007/s10584-014-1107-2.
http://link.springer.com/article/10.1007/s10584-014-1107-2

Mills, D., R. Jones, K. Carney, A.S. Juliana, R. Ready, A. Crimmins, J. Martinich, K. Shouse, B. DeAngelo, 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.
http://link.springer.com/article/10.1007/s10584-014-1118-z

### Method Papers on Individual CIRA Components

Separate from the CIRA special issue of *Climatic Change*, most of the underlying integrated assessment and sectoral impacts models that serve as the basis for the CIRA project have been independently peer reviewed in the scientific literature. The following papers describe the underlying integrated assessment and sectoral impacts models of the CIRA project. In-depth discussions of methodologies, model calibration/validation, calculations, and other technical details can be found in these papers. In some cases (e.g., for the integrated assessment models), additional publications are available that are not listed here. However, the references most applicable to how the application/model was used in the CIRA project are provided. The papers listed below are organized by model.


1. Integrated Global System Model (IGSM):
   Monier, E., J.R. Scott, A.P. Sokolov, C.E. Forest, and C.A. Schlosser. 2013. An integrated assessment modeling framework for uncertainty studies in global and regional climate change: the MIT IGSM-CAM (version 1.0). *Geoscientific Model Development*. DOI: 10.5194/gmdd-6-2213-2013. http://web.mit.edu/emonier/www/publications/Monier2013integrated.pdf

   Schlosser, C.A., X. Gao, K. Strzepek, A. Sokolov, C.E. Forest, S. Awadalla, and W. Farmer. 2013. Quantifying the Likelihood of Regional Climate Change: A Hybridized Approach. *Climate*. DOI: 10.1175/JCLI-D-11-00730.1. http://dx.doi.org/10.1175/JCLI-D-11-00730.1.

2. Global Change Assessment Model (GCAM):
   Kim, S., J. Edmonds, J. Lurz, S. Smith, and M. Wise. 2006. The ObjECTS: Framework for Integrated Assessment: Hybrid Modeling of Transportation. *The Energy Journal*. DOI: 10.5547/ISSN0195-6574-EJ-VolSI2006-NoSI2-4. http://connection.ebscohost.com/c/articles/23914017/objects-framework-integrated-assessment-hybrid-modeling-transportation

   Clarke, L., J. Lurz, M. Wise, J. Edmonds, S. Kim, S. Smith, and H. Pitcher. 2007. *Model Documentation for the MiniCAM Climate Change Science Program Stabilization Scenarios: CCSP Product 2.1a*. PNNL Technical Report. PNNL-16735. http://www.globalchange.umd.edu/data/publications/CCSP_MiniCAM_Documentation_Final.pdf

   Calvin, K., M. Wise, L. Clarke, J. Edmonds, P. Kyle, P. Luckow, and A. Thomson. 2012. Implications of simultaneously mitigating and adapting to climate change: initial experiments using GCAM. *Climatic Change* DOI: 10.1007/s10584-012-0650-y. http://link.springer.com/article/10.1007%2Fs10584-012-0650-y

3. Post-Processing Models:
   *Climate and Runoff Model (CLIRUN)*
   Kaczmarek, Z. 1993. Water balance model for climate impact assessment. *Acta Geophysica Polonica.* 41(4):423–437.

   Strzepek, K., M. Jacobsen, B. Boehlert, and J. Neumann. 2013. Toward evaluating the effect of climate change on investments in the water resources sector: insights from the forecast and analysis of hydrological indicators in developing countries. *Environmental Research Letters*. DOI: 10.1088/1748-9326/8/4/044014. http://iopscience.iop.org/1748-9326/8/4/044014

   *Integrated Climate and Land-Use Model (ICLUS)*
   Bierwagen, B., 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.

*Proceedings of the National Academy of Sciences*. DOI: 10.1073/pnas.1002096107.
http://www.pnas.org/content/early/2010/11/08/1002096107.abstract

*CO2SYS*
Lewis, E., and D. Wallace. 1998. *Program developed for CO2 system calculations*. Oak Ridge National Laboratory – Carbon Dioxide Information Analysis Center, Pub. No. 4735.
http://cdiac.ornl.gov/ftp/co2sys/CO2SYS_calc_DOS_v1.05/cdiac105.pdf

4. Health Sector Models:
*Air Quality*
Garcia-Menendez, F., R.K. Saari, E. Monier, and N.E Selin. 2015. U.S. air quality and health benefits from avoided climate change under greenhouse gas mitigation. *Environmental Science and Technology*. DOI: 10.1021/acs.est.5b01324.
http://pubs.acs.org/doi/full/10.1021/acs.est.5b01324

*Labor*
Graff Zivin, J. and M. Neidell. 2014. Temperature and the allocation of time: implications for climate change. *Journal of Labor Economics*. DOI: 10.1086/671766.
http://www.jstor.org/stable/10.1086/671766

*Water Quality*
Boehlert, B., K.M. Strzepek, S.C. Chapra, C. Fant, Y. Gebretsadik, M. Lickley, R. Swanson, A. McCluskey, J.E. Neumann, and J. Martinich. 2015. Climate change impacts and greenhouse gas mitigation effects on U.S. water quality. *Journal of Advances in Modeling Earth Systems*. DOI:10.1002/2014MS000400.
http://onlinelibrary.wiley.com/wol1/doi/10.1002/2014MS000400/abstract

5. Infrastructure Sector Models:
*Bridges*
Wright, L., P. Chinowsky, K. Strzepek, R. Jones, R. Streeter, J.B. Smith, J. Mayotte, A. Powell, L. Jantarasami, and W. Perkins. 2012. Estimated effects of climate change on flood vulnerability of U.S. bridges. *Mitigation and Adaptation Strategies for Global Change*. DOI: 10.1007/s11027-011-9354-2.
http://www.springerlink.com/content/080u67337157202k/

*Roads*
Chinowsky, P., J. Price, and J. Neumann. 2013. Assessment of Climate Change Adaptation Costs for the U.S. Road Network. *Global Environment Change*. DOI: 10.1016/j.gloenvcha.2013.03.004.
http://www.sciencedirect.com/science/article/pii/S0959378013000514

*Urban Drainage*
Price, J., L. Wright, C. Fant, and K. Strzepek. 2014. Calibrated Methodology for Assessing Climate Change Adaptation Costs for Urban Drainage Systems. *Urban Water Journal*. DOI: 10.1080/1573062X.2014.991740.
http://www.tandfonline.com/doi/abs/10.1080/1573062X.2014.991740

*National Coastal Property Model (NCPM)*
Neumann, J.E., D.E. Hudgens, J. Herter, and J. Martinich. 2010. Assessing Sea-Level Rise Impacts: A

GIS-Based Framework and Application to Coastal New Jersey. Coastal Management. DOI: 10.1080/08920753.2010.496105. http://dx.doi.org/10.1080/08920753.2010.496105

Neumann, J.E., D.E. Hudgens, J. Herter, and J. Martinich. 2010. The economics of adaptation along developed coastlines. *Wiley Interdisciplinary Reviews (WIREs) Climate Change*. DOI: 10.1002/wcc.90. http://onlinelibrary.wiley.com/doi/10.1002/wcc.90/full

Martinich, J., J.E. Neumann, L. Ludwig, and L. Jantarasami. 2012. Risks of sea level rise to disadvantaged communities in the United States. *Mitigation and Adaptation Strategies for Global Change*. DOI: 10.1007/s11027-011-9356-0.
http://www.springerlink.com/content/x411112212347762/

Neumann, J., K. Emanuel, S. Ravela, L. Ludwig, P. Kirshen, K. Bosma, and J. Martinich. 2014. Joint Effects of Storm Surge and Sea-level Rise on US Coasts. *Climatic Change*. DOI: 10.1007/s10584-014-1304-z.
http://link.springer.com/article/10.1007/s10584-014-1304-z

6. Electricity Sector Models
*GCAM-USA Model*
Zhou, Y., J. Eom, and L. Clarke. 2013. The effect of global climate change, population distribution, and climate mitigation on building energy use in the U.S. and China. *Climatic Change*. DOI: 10.1007/s10584-013-0772-x.
http://link.springer.com/article/10.1007%2Fs10584-013-0772-x

Zhou, Y., L. Clarke, J. Eom, P. Kyle, P. Patel, S. Kim, et al. 2014. Modeling the effect of climate change on U.S. state-level buildings energy demands in an integrated assessment framework. *Applied Energy*. DOI: 10.1016/j.apenergy.2013.08.034.
http://dx.doi.org/10.1016/j.apenergy.2013.08.034

*Integrated Planning Model (IPM)*
Jaglom, W., McFarland, J., M. Colley, C. Mack, B. Venkatesh, R. Miller, J. Haydel, P. Schultz, B. Perkins, J. Casola, J. Martinich, P. Cross, M. Kolian, and S. Kayin. 2014. Assessment of projected temperature impacts from climate change on the U.S. electric power industry using the Integrated Planning Model. *Energy Policy*. DOI: 10.1016/j.enpol.2014.04.032.
http://dx.doi.org/10.1016/j.enpol.2014.04.032

*Regional Energy Deployment System (ReEDS)*
Bird, L., C. Chapman, J. Logan, J. Sumner, and W. Short. 2011. Evaluating renewable portfolio standards and carbon cap scenarios in the U.S. electric sector. *Energy Policy*. DOI: 10.1016/j.enpol.2011.02.025.
http://www.sciencedirect.com/science/article/pii/S0301421511001054

7. Water Resource Models
*Inland Flooding Damages*
Wobus, C., and M. Lawson, R. Jones, J. Smith, and J. Martinich. 2013. Estimating monetary damages from flooding in the United States under a changing climate. *Journal of Flood Risk Management*. DOI: 10.1111/jfr3.12043. http://onlinelibrary.wiley.com/doi/10.1111/jfr3.12043/abstract

*Drought Risk*
Strzepek, K., G. Yohe, J. Neumann, and B. Boehlert. 2010. Characterizing changes in drought risk for the United States from climate change. *Environmental Research Letters*. DOI: 10.1088/1748-9326/5/4/044012.
http://iopscience.iop.org/1748-9326/5/4/044012/fulltext/

Boehlert, B., E. Fitzgerald, J. Neumann, K. Strzepek, J. Martinich. 2015. Effects of greenhouse gas mitigation on drought impacts in the U.S. *Weather, Climate, and Society*. DOI: 10.1175/WCAS-D-14-00020.1.
http://journals.ametsoc.org/doi/abs/10.1175/WCAS-D-14-00020.1

*Supply and Demand*
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. *Mitigation and Adaptation Strategies for Global Change*. DOI: 10.1007/s11027-013-9483-x.
http://link.springer.com/article/10.1007%2Fs11027-013-9483-x

8. Agriculture and Forestry Model
*Forest and Agriculture Sector Optimization Model with Greenhouse Gases (FASOMGHG)*
Beach, R.H., Y. Cai, A. Thomson, X. Zhang, R. Jones, B. McCarl, A. Crimmins, J. Martinich, J. Cole, S. Ohrel, B. DeAngelo, J. McFarland, K. Strzepek, and B. Boehlert. (In press). Climate change impacts on U.S. agriculture and forestry: benefits of global climate stabilization. *Environmental Research Letters*.

9. Ecosystem Models
*Coral Mortality and Bleaching Output (COMBO) Model*
Lane, D.R., R.C. Ready, R.W. Buddemeier, J.A. Martinich, K.C. Shouse, and C.W. Wobus. 2013. Quantifying and Valuing Potential Climate Change Impacts on Coral Reefs in the United States: Comparison of Two Scenarios. *PLOS ONE*. DOI: 10.1371/journal.pone.0082579.
http://www.plosone.org/article/info:doi/10.1371/journal.pone.0082579

*Shellfish*
Moore, C. 2015. Welfare estimates of avoided ocean acidification in the U.S. mollusk market. *Journal of Agricultural and Resource Economics*. 40(1):50–62.
http://www.waeaonline.org/UserFiles/file/JAREJan20154Moorepp50-62.pdf

*Freshwater Recreational Fishing*
Jones, R., C. Travers, C. Rodgers, B. Lazar, E. English, J. Lipton, J. Vogel, K. Strzepek, and J. Martinich. 2012. Climate Change Impacts on Freshwater Recreational Fishing in the United States. *Mitigation and Adaptation Strategies for Global Change*. DOI: 10.1007/s11027-012-9385-3.
http://link.springer.com/article/10.1007/s11027-012-9385-3

*Wildfire*
Lee, C., C. Schlemme, J. Murray, and R. Unsworth. 2015. The cost of climate change: ecosystem services and wildland fires. *Journal of Ecological Economics*. DOI: 10.1016/j.ecolecon.2015.04.020.
http://www.sciencedirect.com/science/article/pii/S0921800915002050

## C. Peer Review of the CIRA Report

Consistent with guidelines described in EPA's Peer Review Handbook,[6, 7] the CIRA report was subject to an independent, external peer review. As described in Sections A and B of this Technical Appendix, the methods and results underlying the content of the CIRA report have been previously peer reviewed and published in the research literature. Since the CIRA report is a summary and communication document, this review of the report was not intended to focus on reevaluating or reassessing the adequacy or rigor of the analytical methods. Rather, the charge was to carefully review and provide feedback on whether the findings of the underlying peer-reviewed literature are accurately summarized, appropriately interpreted, adequately documented, whether the results across impact sectors and regions are appropriately summarized, and whether the insights are clearly communicated to a non-technical audience (primarily policymakers and the interested public).

The review was managed by a contractor (Eastern Research Group, Inc.) under the direction of a designated EPA peer review leader, who prepared a peer review plan, the scope of work for the review contract, and the charge for the reviewers. Importantly, the EPA peer review leader played no role in producing the draft report.

The contractor identified, screened, and selected seven reviewers who had no conflict of interest in performing the review, and who collectively met the following technical selection criteria provided by EPA:

- Expertise in environmental economics (particularly the valuation or monetization of climate change impacts).
- Expertise in applied climate change impacts modeling and analysis.
- Expertise in communication of environmental issues (particularly related to climate change).
- Expertise in climate change impacts on water resources (particularly expertise in one or more of these areas: flooding damages, drought, and supply and demand economic modeling).
- Expertise in climate change impacts on electric power (particularly expertise in one or more of these areas: electricity demand, electricity supply, hydropower, and thermo-electric cooling impacts).
- Expertise in the impacts of climate change on infrastructure (particularly expertise in one or more of these areas: coastal development, bridges, roads, and urban drainage).

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[6] EPA's Peer Review Handbook (3rd Edition, http://www.epa.gov/peerreview/pdfs/peer_review_handbook_2012.pdf).

[7] EPA has determined that the CIRA report falls under the classification of "Other Scientific and/or Technical Work Products." The report does not meet the criteria for "influential scientific information," as defined by OMB and further described in the EPA Peer Review Handbook, since it is not being used to support a regulatory program or policy position, and does not meet one or more of the factors listed in Section 2.2.3 of the EPA Peer Review Handbook for consideration as influential scientific information. As a corollary, the report also cannot be considered a "highly influential scientific assessment," as defined by OMB.

- Expertise with the ecological impacts of climate change (particularly in one or more of these areas: coral reefs, mollusks fisheries, freshwater fish, wildfires, and terrestrial vegetative carbon storage).
- Expertise in human health impacts of climate change on air quality, extreme temperature mortality, and water quality.
- Expertise with the impacts of climate change on agriculture and forestry, preferably in estimating crop yield impacts from climate change.

The seven external, independent expert reviewers were: Donald Boesch, Larry Dale, Kristie Ebi, Anthony Janetos, Denise L. Mauzerall, Michael Meyer, and Timothy Randhir.

The contractor provided the selected reviewers with instructions for conducting the review, the review document, the charge to reviewers prepared by EPA, a comment spreadsheet template (for insertion of written comments), and copies of the literature underlying the CIRA analyses (as background reference material). Reviewers worked individually (i.e., without contact with other reviewers, colleagues, or EPA) to prepare written comments in response to the charge questions over a four-week period.

The peer review charge directed reviewers to provide responses to the following questions:

1. Does the introductory chapter clearly explain the purpose of the report? If not, please provide recommendations for improvement.
2. Does the report adequately explain its relationship to other significant and well-known climate change risk analysis efforts (e.g., the National Climate Assessment), and are these descriptions properly placed in the report?
2. The report has been written for an educated but not overly technical audience, including decision makers, stakeholders, and engaged members of the public. Are the writing level and graphics appropriate for these audiences? Are there sections that are too technical for this audience?
3. Does the report adequately explain the overall analytic framework of the project, such that results across multiple sectors can be communicated in a consistent manner?
4. Important sources of uncertainty have been characterized in the underlying literature of the CIRA project. This includes uncertainty in climate projection (GHG emissions, climate sensitivity, climate model, and natural variability), and structural uncertainties in impacts modeling (e.g., the electricity sector uses three models). Because of the desire to provide a consistent, concise, and easy to understand storyline across impact sectors, the results described in this report focus on a core set of scenarios that were processed through all of the models - a reference and global GHG mitigation case using the IGSM-CAM climate model and assuming a climate sensitivity of 3°C. For some sectors, the influence of alternative inputs/assumptions (e.g., different climate sensitivity or climate model) are explored and compared to these core scenarios. Given this, has the report struck the right balance in presenting and communicating clear findings and insights while also adequately acknowledging the uncertainties surrounding climate projection and impacts estimation?

5. Do the text, figures and tables in the sector specific chapters clearly communicate the modeling results from the underlying research papers?
6. Are the conclusions in the Key Findings and Synthesis sections supported by the results of the sector specific chapters? Is the draft report missing important findings or messages?
7. Do the figures and tables clearly communicate the key points in the Key Findings and Synthesis section? Do you have any suggestions for alternative figures or tables (e.g., akin to the "burning embers" diagram that has been commonly featured in Intergovernmental Panel on Climate Change or IPCC reports) that could possibly synthesize or communicate key, overarching findings more effectively?
8. Report Format: Please comment on whether any aspects of the layout help or hinder the reader to understand the content and key messages of the report.

A quality control check was undertaken to ensure that the authors took sufficient action and provided an adequate response for every peer review comment. This check found that the authors addressed those comments with changes to the report or a detailed response to the comment describing the rationale for not making a change. The response to comments document was incorporated into the formal peer review record for the report.

Peer Review Comment Summary:

The seven peer reviewers submitted general and specific comments on the draft report. This section provides a summary of comments commonly raised by the reviewers, along with how the comments were addressed in revising the report.

- Several reviewers recommended that the report provide additional information on the global GHG mitigation scenario used (referred to in the report as "Mitigation" scenario), including a description of how GHG emissions are projected to change in the future and how this pathway compares to current domestic and international policies.

  In response to this comment, additional information was added to the CIRA Framework describing the two GHG emission scenarios used in the report, including a figure comparing their global GHG emissions through 2100 (with a comparison to the four representative concentration pathways, or RCPs, used by the IPCC in their Fifth Assessment Report). With regards to comparing the global GHG reductions under the Mitigation scenario to current U.S. and/or international policies, we note that this report and the CIRA analyses are not intended to evaluate any particular policy, and therefore, the connection between the illustrative scenarios used in the report and specific domestic or international policy targets is intentionally not made. In the CIRA Framework section of the report, we refer the reader to the NCA Mitigation chapter and IPCC Working Group III report where these issues regarding the adequacy of current mitigation efforts are addressed in detail. However, a brief, qualitative discussion was added to the conclusion of the report describing how the estimated benefits of GHG emission reductions would likely be larger with more stringent mitigation compared to the Mitigation scenario, and vice versa.

- Several reviewers noted the importance of variability in projections across climate models, especially with regards to precipitation, and recommended that additional detail be included describing the limitations in the CIRA approach to climate projection, and how the projections compare to those used in the assessment literature.

  As described in the CIRA Framework section of the report, the analyses are based primarily on one climate model (IGSM-CAM) to estimate impacts across sectors. While this approach allowed for consistent comparisons across sectors, projections from another climate model were used in sectors sensitive to changes in precipitation to better reflect a range of potential future impacts. The pattern-scaled climate model, MIROC, which projects drying across most of the lower 48 states, was used in addition to the IGSM-CAM, which projects increases in precipitation across many parts of the contiguous U.S. The reviewers noted that the use of a larger set of climate models would provide a more complete understanding of the uncertainties involved with projecting future climate (especially with regards to future precipitation) and the impacts driven by these changes. We agree with the point raised by the reviewers, and note that this limitation is thoroughly discussed throughout the report and in the scientific literature underlying the CIRA project. Given the large number of sectoral models (>20) in CIRA, and the effort necessary to run each using projections from any one climate model, the approach of bounding potential precipitation futures was deemed reasonable and appropriate. Focusing on a narrower set of climate models also allowed for the exploration of other uncertainty sources, such as climate sensitivity and natural variability. Regardless, the following changes were made to the report in response to these comments: 1) additional description of the limitations to the CIRA approach to climate projection, 2) brief descriptions comparing the CIRA climate projections and those from ensemble means of the climate models used in the assessment literature, and 3) a new section in the Technical Appendix (Section E) comparing the CIRA climate projections and the CMIP-5 models used in IPCC's Fifth Assessment Report in terms of estimated precipitation changes in the contiguous U.S.

- Several reviewers noted that the rates of sea level rise used to estimate impacts to coastal property, in particular the rate under the Mitigation scenario, are larger than those estimated by a couple of recent studies. As a result, the reviewers expressed concern that the CIRA sea level rise scenarios likely underestimate the benefits of global GHG mitigation in the coastal property sector.

  The CIRA sea level rise scenarios (56 inches by 2100 under the Reference and 37 inches under the Mitigation scenario) include an adjustment for the effects of rapid response of sea level to warming temperatures (i.e., from greater ice sheet and glacial melting), based on the semi-empirical method described in Vermeer and Rahmstorf (2009). This approach accommodates the contribution from dynamic ice sheet and glacial melting. Both of the CIRA rates fall within the risk-based range projected in the U.S. Global Change Research Program’s (USGCRP) 2014 Third National Climate Assessment (NCA) of 8 to 79 inches by 2100, with the Reference rate being slightly larger than the Assessment's likely range of 12-48 inches It is true that the CIRA projections are larger than those found in some recent literature, for example Horton et al. (2014),[8] which found a likely sea level rise by 2100 of 28-47 inches (very likely range of 20-59 inches) under a high-emissions scenario, and 16-24 inches (very likely

[8] Horton, BJ, S Rahmstorf, SE Engelhart, and AC Kemp. 2014. Expert assessment of sea-level rise by AD 2100 and AD 2300. Quaternary Science Reviews 84:1-6.

range of 12-28 inches) under a low-emissions scenario. It is to be expected that differences would exists between the CIRA sea level rise rates and those found in some studies, such as Horton et al. (2014), due to differences in how the scenarios were developed (i.e., the semi-empirical approach to accommodate dynamic ice melting used in CIRA versus expert elicitation) and the use of different GHG emission pathways driving the rates of sea level change. Regarding the impact of the CIRA rates on estimated benefits of GHG mitigation, we note that an important consideration regarding the effect of mitigation is the difference between the two scenarios being used to estimate the benefits of GHG mitigation. While one reviewer suggested that the difference between the two CIRA scenarios is smaller than expected leading to an underestimate of the benefits of mitigation, we note that the difference (19 inches) is consistent with those reported between RCP 8.5 and RCP2.6 in Horton et al. (2014; 20 inches) and Kopp et al. (2014; 16 inches).[9] In response to this comment, we added a new discussion to the Coastal Property section describing three primary reasons why the effect of GHG mitigation in reducing adaptation costs are likely underestimates, which include: 1) that the CIRA scenarios have a smaller proportional effect of GHG mitigation in reducing the rate of rise compared to other scenarios, 2) the fact that the majority of estimated benefits occur late in the century, and are therefore diminished in relative value due to the effect of discounting, and 3) assumptions in the analysis that adaptive actions will be well-timed and optimally implemented, which are optimistic given historical trends.

- Several reviewers requested additional discussion of important sources of uncertainty that were not sufficiently explained in the original draft, such as the connectivity between sectoral modeling analyses and the interactions between climate and social vulnerabilities.

  There are a number of important sources of uncertainty involved with estimating the impacts of climate change, including uncertainties in projecting future climate. The report discusses these issues in the Uncertainty and Limitation sections, and also provides many references to the literature underlying the CIRA project where these uncertainty sources are explored in greater detail (but were not included in the report due to space constraints and the technical nature of the topic for the intended audience). Regarding the specific sources of uncertainty raised by the reviewers, new discussions were added to the Limitations section of the report highlighting the importance inter-sectoral connectivity, uncertainties in societal characteristics, and others that were not given sufficient attention in the original draft. Additional discussion was also added in throughout the Sectors section of the report describing the potential influence of key uncertainty sources on impact estimates.

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

## D. Treatment of Adaptation in the Sectoral Impact Analyses

The CIRA report estimates the impacts of unmitigated climate change, and the potential reduction of those impacts through global GHG mitigation, for a large number of U.S. sectors. Although adaptation is not the focus of the CIRA project, it is appropriate to consider adaptation where the data are available and in certain instances, where the cost of adaptation is an appropriate metric to assess climate change damages. Sectoral impact estimates in the broader climate change impacts literature typically take one of three approaches to measure impacts. The first approach is to estimate impacts net of adaptation actions that could be cost-effectively adopted to reduce those impacts – for example, the CIRA analyses for coastal property[10] and agriculture/forestry use this method. The second approach is to estimate impacts assuming no adaptation, either owing to data limitations or because it is reasoned that adaptation actions for that sector would involve a level of planning that cannot be assumed.[11] The third approach is to assume that responses to climate change will be implemented to maintain the service level of the affected sector, regardless of the cost-effectiveness of those responses, and the impacts of climate change are therefore well-represented by the costs of those responses. This approach is used, for example, in the CIRA road and bridge infrastructure analyses.

The following table briefly describes where and how adaptation was modeled in each sectoral analysis presented in the report.[12] The scientific literature underlying each CIRA sectoral model, as cited throughout the report and listed in Section B of this Technical Appendix, further describes the treatment of adaptation in each analysis.

[10] The coastal property analysis considers total damages with and without adaptation.

[11] A subset of this second approach is often applied when estimating impacts to ecosystems and species. While autonomous adaptation may occur at the species level, such as thermally-tolerant coral species becoming more dominant over time, the second approach would assume no active human adaptation or intervention to preserve or conserve the resource.

[12] This section, in part, draws upon content from 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, J. Li J. 2014. Overview of the Special Issue: A multi-model framework to achieve consistent evaluation of climate change impacts in the United States. Climatic Change, DOI:10.1007/s10584-014-1206-0.

| Impact Sector | Impact | Treatment of Adaptation |
|---|---|---|
| Human Health | Air quality | Adaptive response (autonomous or planned) not analyzed. |
| | Extreme temperature mortality | Primary results do not assume adaption. Natural acclimatization by humans and autonomous adaptation are modeled using an analogue city approach as a sensitivity analysis. |
| | Labor | Results do not assume adaption (autonomous or planned). |
| | Water quality | Adaptive response (planned) not analyzed. |
| Infrastructure | Bridges | When estimated to be vulnerable, climate change response measures are assumed taken to maintain the condition and level of service of the bridges at levels consistent with their current state.  Repairs can be estimated in the model as proactive or reactive expenditures. |
| | Roads | Climate change response measures (e.g., resealing, regarding, use of new pavement binders) are implemented to maintain the current level of service for roads such that residual impacts are zero. Climate change can either reduce or increase baseline maintenance costs. |
| | Urban drainage infrastructure | Climate change response costs associated with changes in runoff are estimated assuming that urban areas will utilize a range of urban storm water management practices that focus on limiting the quantity of runoff instead of expanding formal drainage networks of catch basins and conveyance systems. The incremental response costs provide an estimate of economic damages of climate impacts. |
| | Coastal property | The most cost-efficient response (i.e., beach nourishment, property elevation, seawall construction, or property abandonment) is implemented when a coastal property requires protection from sea level rise or storm surge. |
| Electric Power Sector | Electricity demand | Consumers (primarily residential and commercial) adjust to higher temperatures by increasing electricity demand for cooling services and decreasing demand for heating. No adaptation, in the form of energy efficiency measures or changes in energy using devices, is modeled. |
| | Electricity supply | Producers adjust capacity and output to meet changes in demand and compensate for the derating of thermal generating units due to higher air temperatures. |
| Water Resources | Inland flooding | Adaptive response (autonomous or planned) not analyzed, i.e., no assumed changes in flood protection or exposure. |
| | Drought | Adaptive response (autonomous or planned) not analyzed. |
| | Water supply and demand | Reactive adaptation is modeled, as water is re-optimized and allocated to competing uses based on available supply. |

| Impact Sector | Impact | Treatment of Adaptation |
|---|---|---|
| Agriculture and Forestry | Agricultural and forestry yields and market impacts | The approach simulates the allocation of land, over time, to competing activities in both agricultural and forestry sectors. Land owners may change land cover, crop mix, and production practices to maximize welfare. Major technological advancements in the future for agricultural and forestry productivity are not modeled. |
| Ecosystems | Coral reefs | Three different types of coral species can be modeled in the COMBO model, each of which exhibits unique autonomous adaptive responses to changes in environmental conditions.[13] No changes in human management (e.g., preservation activities) of coral reefs are modeled. |
| | Shellfish | Consumption of mollusk seafood products vary over time based on catch and price. No species-level acclimatization to the effects of acidification is assumed, and there are no modeled changes in human management (e.g., restoration activities) of the stocks. |
| | Freshwater fish | Autonomous adaptation via changes in the thermal tolerance of fish is neither well-understood nor characterized in the literature, and is therefore not modeled. However, the analysis assumes no barriers to fish movement, which likely leads to underestimates of potential climate change damages. Changes in recreational fishing behavior are estimated based on availability of suitable habitat to support different fish guilds. |
| | Wildfire | Wildfire response costs are estimated, however no specific future changes in forest management are modeled. |
| | Carbon storage | Autonomous adaptation modeled through changes in the composition and spatial distribution of vegetation. No specific future changes in ecosystem management are modeled. |

[13] The results shown in the Coral Reefs section of the report use average results across the coral types.

## E. Comparison of CIRA Climate Projections for Precipitation to CMIP5 Models

As described in the CIRA Framework - Uncertainty section of the report, 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.

As described in the report, sectors sensitive to changes in precipitation were simulated using climate projections from two climate models projecting different patterns of future precipitation. Specifically, projections from the IGSM-CAM climate model, which estimates a wetter future for most of the contiguous U.S., were complemented with drier projections from the MIROC model to investigate the influence on impact estimates.

The purpose of this section is to compare the CIRA precipitation projections for the contiguous U.S. to those from the Coupled Model Intercomparison Project – Phase 5 (CMIP5)[14], which were used in the IPCC Fifth Assessment Report. It is important to note that the below maps showing the CIRA precipitation projections differ slightly from those presented in the CIRA Framework - Uncertainty section of the report due to differences in the timeframes used in the analyses and differences in presentation (i.e., smooth versus gridded). This format for presentation was made to enable a more consistent comparison between the CIRA and CMIP5 projections.

Figures 1 and 2 present the projected changes in mean annual precipitation in the contiguous U.S. in 2100. As there is better agreement amongst climate models regarding the patterns and magnitude of regional temperature change, this section focuses on precipitation projections.

> Figure 1: The CIRA Reference and stabilization (Policy 3.7, referred to in the report as Mitigation; and Policy 4.5) scenarios using the two primary climate models employed in the analyses presented in the report (IGSM-CAM and the pattern-scaled MIROC) with a climate sensitivity of 3°C. The maps show the projected mean annual change from 1980-2009 to 2086-2100.
>
> Figure 2: Three models from the CMIP5 archive that represent the largest decrease, median change, and maximum increase in precipitation projected among the 23 models which ran RCP4.5 and 20 models which ran RCP8.5 (global GHG emissions scenarios that generally correspond to the CIRA Policy 4.5 and Reference scenarios). The maps show the projected mean annual change from 1980-2009 to 2071-2100. Note that the MIROC_5 model, which represents the "medium change" CMIP5 model under RCP4.5, is not the same as the pattern-scaled MIROC model used in the CIRA analyses.

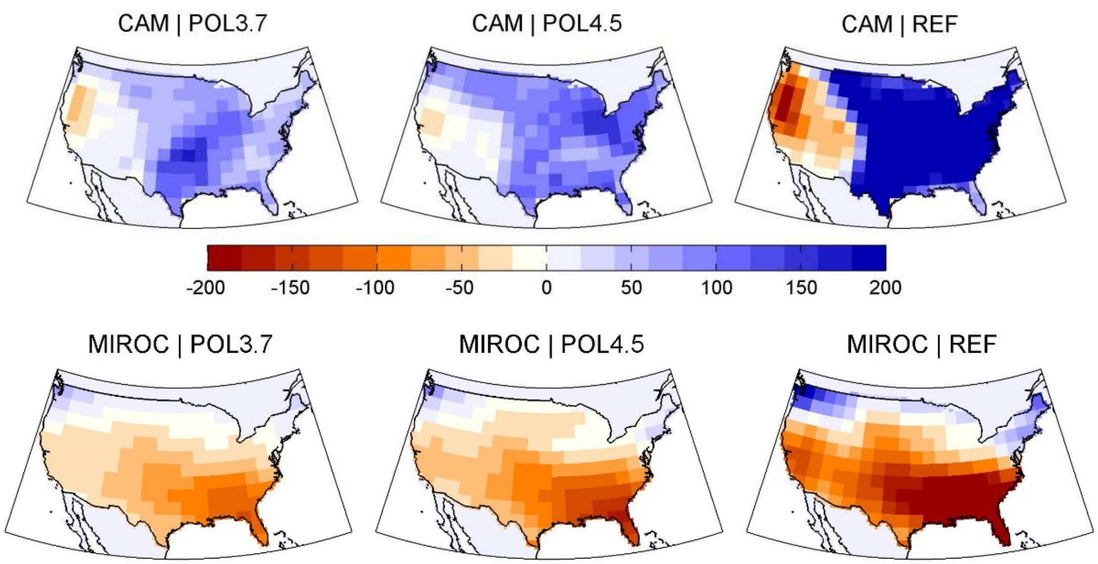
As shown in Figure 1, the pattern-scaled MIROC model projects a drier future for the contiguous U.S. compared to IGSM-CAM. As shown in Figure 2, Access 1-0 is the CMIP5 model that projects the largest

[14] The purpose of the CMIP5 experiments was to address outstanding scientific questions that arose as part of the IPCC AR4 (the Intergovernmental Panel on Climate Change 4th Assessment Report) process, improve understanding of climate, and to provide estimates of future climate change that will be useful to those considering its possible consequences. For more information, see Taylor et al (2009) A summary of the CMIP5 Experiment Design, available at: http://cmip-pcmdi.llnl.gov/cmip5/docs/Taylor_CMIP5_design.pdf.

decrease in precipitation among the 23 models which ran RCP4.5 and 20 models which ran RCP8.5, while CCSM4 and Access 1-3 are the models that project the largest increase in precipitation among the RCP4.5 and RCP8.5 models, respectively. As shown, there is regional variation in the spatial patterns of wetting and drying within the U.S., but the overall levels of change amongst the CIRA and CMIP5 projections are comparable. Specifically, precipitation generally increases more towards the northern regions of the contiguous U.S., and especially in the Northeast. Also, the Southwest, in general, is either projected to become drier or show little change.

Figure 3, which appeared in the USGCRP NCA,[15] shows seasonal precipitation change from the CMIP5 climate models, including areas of statistical agreement amongst the climate models regarding the directional change in precipitation. These projections also show wetter conditions in the northern locations of the contiguous U.S. and drier conditions in the Southwest.

Figure 1. Projected change in mean annual precipitation in 2100 for the CIRA models (mm/year)




[15] Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, (...) and R. Somerville, 2014: Ch. 2: Our Changing Climate. Climate Change Impacts in the United States: The Third National Climate Assessment, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 19-67. doi:10.7930/J0KW5CXT.

Figure 2. Projected change in mean annual precipitation in 2100 for the CMIP5 models (mm/year)

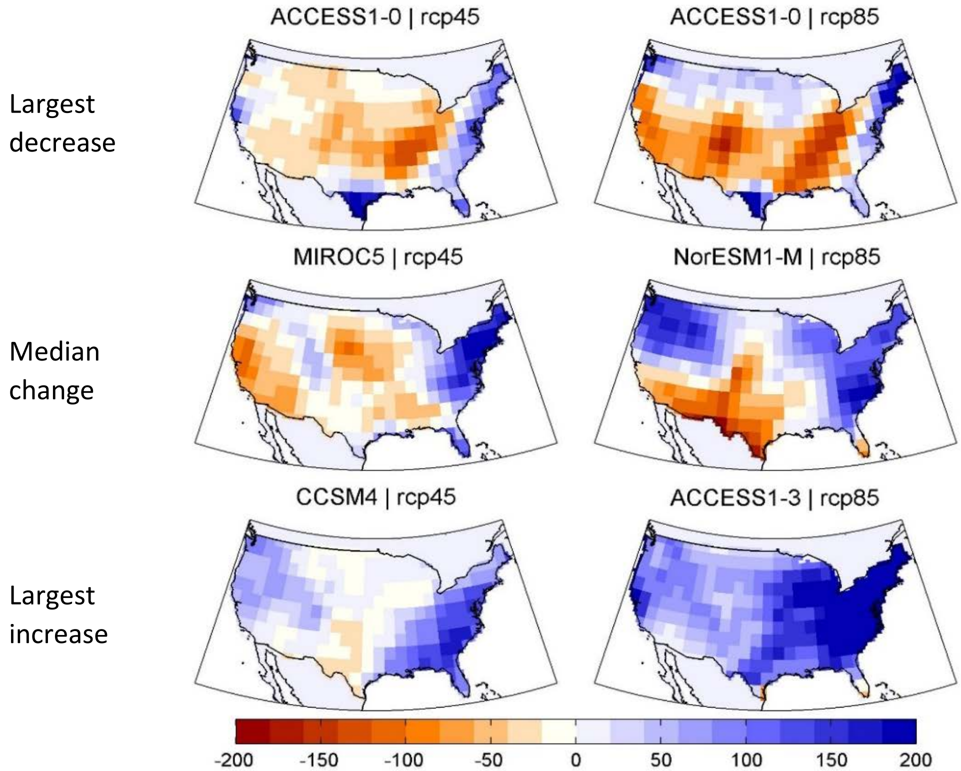
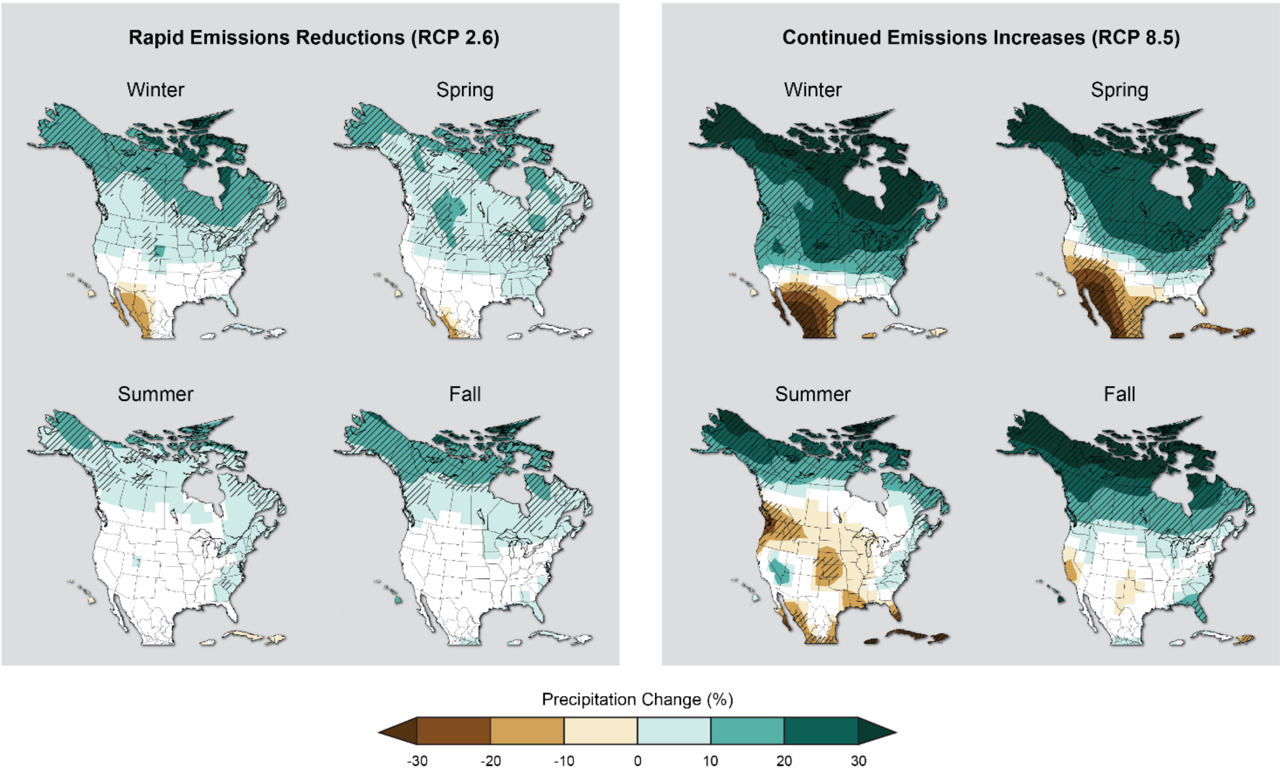


Figure 3. Seasonal precipitation change for 2071-2099 (compared to 1970-1999) as projected by the CMIP5 models for low (RCP2.6) and high (RCP8.5) emission scenarios. Hatched areas indicate that the projected changes are statistically significant and consistent among the CMIP5 models. White areas indicate that the changes are not projected to be larger than could be expected from natural variability. (Figure source: NOAA NCDC / CISCS-NC).



## F. Exploring Uncertainty

As described in the CIRA Framework section of the report, the CIRA project analyzes four important sources of uncertainty inherent to climate change analysis: future GHG emissions, climate sensitivity, natural variability, and climate model. With the goal of presenting a consistent and straightforward set of climate change impact analyses, the Sectors section of the CIRA report presents results for two future emissions scenarios (Reference and Mitigation) assuming a climate sensitivity of 3°C. For sectors sensitive to precipitation, a range of projections are used to estimate potential impacts in the future.

As examples of uncertainty analyses in the CIRA project, this section explores how results compare when using a different, slightly less stringent global GHG mitigation scenario, and also analyzes how impacts would change if the climate system is more sensitive to GHG emissions than scientists understand it to be. Results are presented for a subset of sectors; results for other sectors, where available, can be found in the underlying CIRA literature cited in the Sectors section of the report and in this Technical Appendix.

### Consideration of Other Mitigation Scenarios

As described in the CIRA Framework section, the CIRA report considers a global GHG mitigation scenario, where the total additional heating effect, or radiative forcing, of the atmospheric buildup of GHGs is limited to 3.6 W/m$^2$ (3.2 W/m$^2$ using the IPCC RCP calculation method) – see the CIRA Framework section of the report for more information.[16] This scenario, referred to in this report as the "Mitigation" scenario, has a level of global GHG reductions consistent with the amount required to limit the increase of global average temperature to no more than 2°C (3.6°F) relative to pre-industrial levels, which has become an internationally-recognized goal for avoiding dangerous levels of climate change.[17,18] This scenario is used throughout the report to communicate the benefits of avoiding a future where the global emissions of GHGs continue to grow.[19]

Although not featured in the report, the CIRA analyses also investigated the potential benefits of less stringent GHG mitigation in a scenario in which radiative forcing is limited to 4.2 W/m$^2$ (3.8 W/m$^2$ using the IPCC RCP calculation method) by 2100. In this scenario, future global average temperature increase from preindustrial times is projected to slightly exceed 2°C, reaching approximately 2.4°C (4.3°F) in 2100. In this section of the Technical Appendix, we show how the potential benefits may vary under the two CIRA GHG mitigation scenarios for three example sectors: bridges, water quality, and urban drainage. Results for other sectors, where available, can be found in this underlying literature of the CIRA project

[16] These radiative forcing values reflect GHG radiative forcing (i.e., not including aerosols) and use a baseline of 1750 (necessary adjustments for comparing to the IPCC RCPs), therefore making them slightly different than the values reported previously in the CIRA literature (Reference 10 W/m$^2$ for the Reference, and 3.7 W/m$^2$ and 4.5 W/m$^2$ for the two global mitigation scenarios).

[17] 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, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

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

[19] The CIRA report examines how the U.S. would benefit from a significant, but illustrative, level of action to reduce GHG emissions globally. The results of the report should not be interpreted as an evaluation of any specific policy in the U.S. or in other world regions.

that is cited in the report and this Technical Appendix. For ease of interpretation, we refer to the scenarios as "Policy 3.7" and "Policy 4.5" in this section, consistent with the language used in the underlying research papers.

Finally, this section presents sectoral impact results projected using the IGSM-CAM climate model. The use of other climate models, such as the MIROC model shown in other parts of the report, may result in different magnitudes and patterns of regional impacts, particularly for those sectors that are sensitive to precipitation.

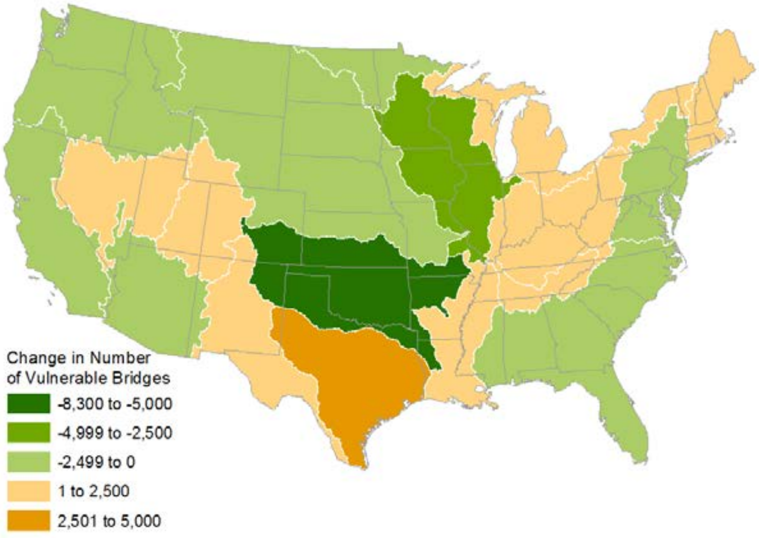
Bridges

As described in the Bridges section of the report, global GHG mitigation under Policy 3.7 substantially reduces the number of bridges across the U.S. projected to become vulnerable due to unmitigated climate change. To determine the benefits that accrue under Policy 3.7 compared to the slightly less stringent Policy 4.5, we compare the projected reduction in the number of vulnerable bridges in each scenario relative to the Reference for the period from 2051-2100.

As shown in Figure 1, the majority of the country experiences fewer vulnerable bridges under Policy 3.7 compared to Policy 4.5, particularly in the central U.S. However, the areas shaded in orange are projected to experience a higher number of vulnerable bridges under Policy 3.7 compared to Policy 4.5 due to regional differences in the climate projections. Nevertheless, it is estimated that there are fewer vulnerable bridges nationally under Policy 3.7 compared to 4.5 (approximately 11,000 fewer). Furthermore, both GHG mitigation scenarios are projected to have far fewer vulnerable bridges compared to the Reference scenario.

Figure 1. Effect of More Stringent Mitigation under Policy 3.7 Compared to Policy 4.5 for U.S. Bridge Infrastructure in the Second Half of the 21st Century

*Map shows the change in the number of vulnerable bridges from the Reference scenario under Policy 3.7 compared to Policy 4.5 for the period from 2051-2100. Areas with fewer vulnerable bridges due to more stringent mitigation are shaded in green.*

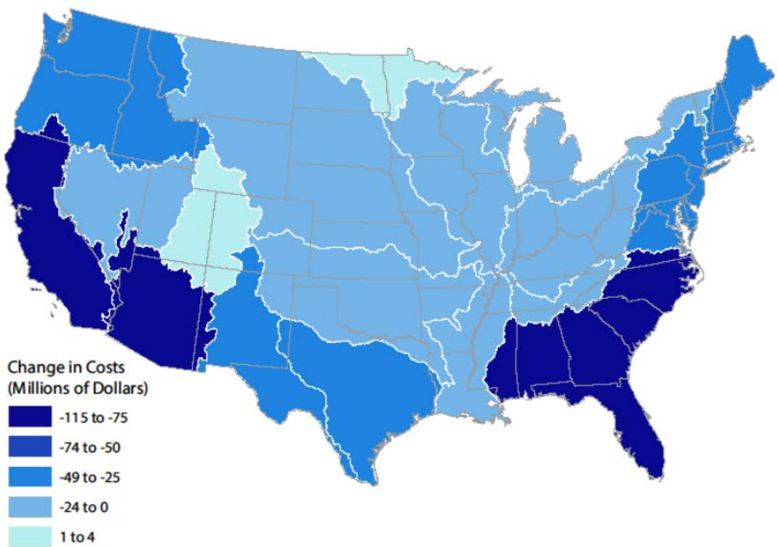


Water Quality

As described in the Water Quality section of the report, global GHG mitigation under Policy 3.7 reduces costs associated with changes in water quality across the contiguous U.S. Figure 2 shows the additional benefits of mitigation under Policy 3.7 compared to Policy 4.5 in the 2-digit Hydrologic Unit Codes (HUCs). Under Policy 3.7, the South Atlantic-Gulf and the Lower Colorado HUCs in particular are projected to experience the greatest benefits in 2100: $115 million and $100 million more in avoided costs, respectively, compared to Policy 4.5. Two HUCs shaded in grey (the Upper Colorado and Souris-Red-Rainy) are projected to experience disbenefits of more stringent mitigation under Policy 3.7 compared to Policy 4.5, primarily due to regional differences in the climate projections, but these disbenefits are very small relative to the benefits experienced across the country.

Figure 2. Effect of More Stringent Mitigation under Policy 3.7 Compared to Policy 4.5 for Water Quality in 2100

*Map shows the change in estimated costs from the Reference scenario under Policy 3.7 compared to Policy 4.5 (2014$). Areas with avoided costs due to more stringent mitigation are shaded in blue.*



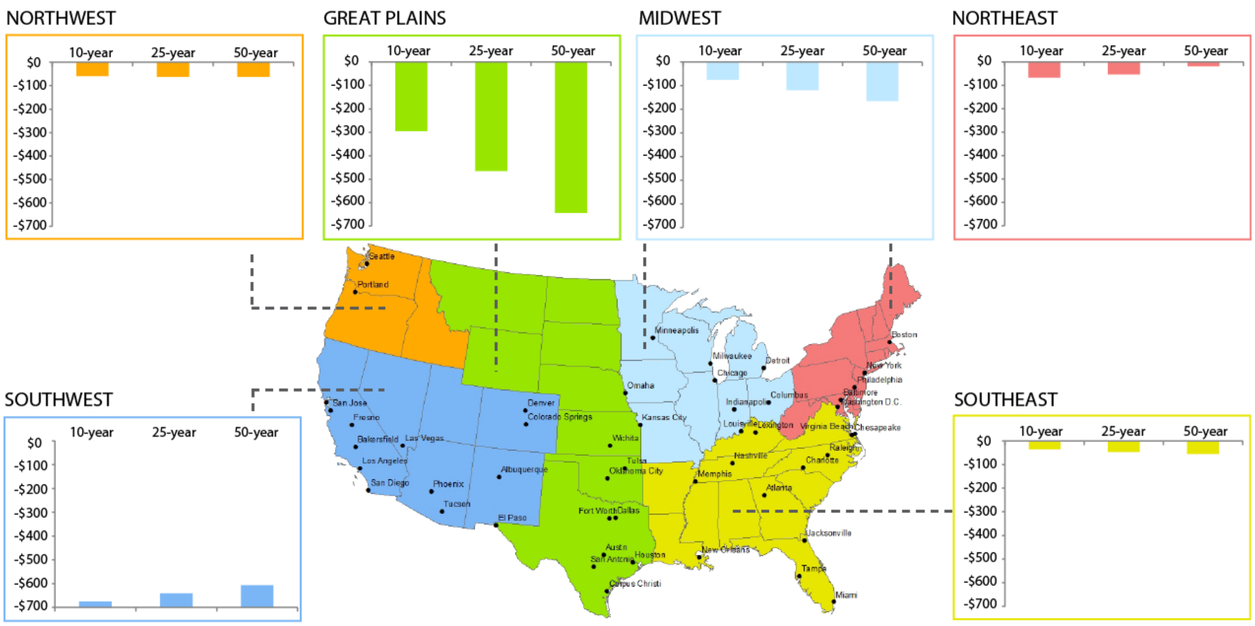
## Urban Drainage

As described in the Urban Drainage section, the CIRA analysis calculates average, per-square-mile adaptation costs for urban drainage systems in 50 U.S. cities in response to changes in heavy rainfall. Costs are aggregated to the six regions used in the USGCRP Third National Climate Assessment, weighted by the proportion of the area of each city in its respective region.

Figure 3 shows that costs under Policy 3.7 are lower (or avoided) relative to Policy 4.5 in all but one region, the Southwest, where average annual precipitation is much less than in the rest of the country. The benefits of Policy 3.7 compared to Policy 4.5 are particularly high in the Great Plains region, where average annual costs per square mile for the 50-year storm are projected to be approximately $640,000 less.

Figure 3. Effect of More Stringent Mitigation under Policy 3.7 Compared to Policy 4.5 for Urban Drainage Systems in 2100

*Bar charts show the change in weighted average adaptation costs in 2100 (thousands of 2014$, undiscounted) from the Reference scenario under Policy 3.7 compared to Policy 4.5. Costs are provided for the 10-, 25-, and 50-year storms.*



## Extreme Levels of Climate Change

As described in the CIRA Framework section, future climate change depends not only on future GHG emission pathways, but also on the sensitivity of the global climate system to rising GHG emissions (i.e., how much temperatures will rise in response to a given increase in atmospheric carbon dioxide). The CIRA project considers four values of climate sensitivity (CS): 2.0, 3.0, 4.5, and 6.0°C.[20] According to the IPCC, these values represent the lower bound (CS2.0), best estimate (CS3.0), and upper bound (CS4.5) of climate sensitivity, and a low-probability/high-risk climate sensitivity (CS6.0).[21] Throughout this report, results are presented using the best estimate for climate sensitivity of 3.0°C. However, in order to assess and compare the potential benefits of global GHG mitigation under more extreme levels of climate change, this section presents results for three sample sectors (freshwater fish, roads, and coral reefs) using both a climate sensitivity of 3.0°C and the high-risk climate sensitivity of 6.0°C. Results for other sectors, where available, can be found in the underlying CIRA literature cited in the report and this Technical Appendix.

Finally, this section presents sectoral impact results projected using the IGSM-CAM climate model. The use of other climate models, such as the MIROC model shown in other parts of the report, may result in different magnitudes and patterns of regional impacts, particularly for those sectors that are sensitive to precipitation.

[20] According to the National Climate Assessment, climate sensitivity is generally summarized as the response of global temperature to a doubling of $CO_2$ levels in the atmosphere relative to pre-industrial levels of 280 parts per million. Source: Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M. Wehner, J. Willis, D. Anderson, V. Kharin, T. Knutson, F. Landerer, T. Lenton, J. Kennedy, and R. Somerville, 2014: Appendix 3: Climate Science Supplement. 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, 735-789. doi:10.7930/J0KS6PHH.

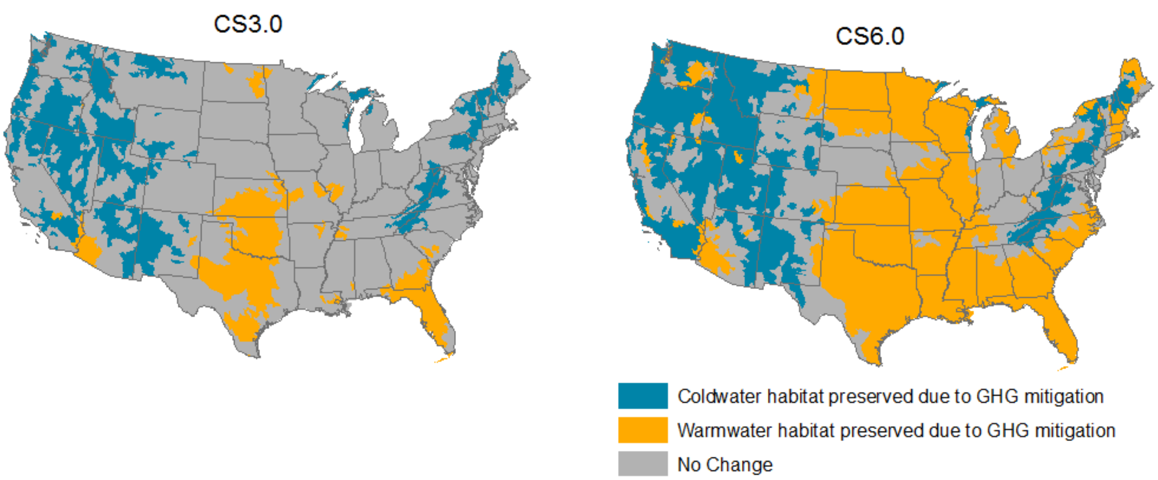
[21] IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Freshwater Fish

Figure 4 presents the projected benefits of global GHG mitigation for the distribution of freshwater fish habitat across the contiguous U.S. in 2100. The maps show the projected change in the distribution of habitat under the Mitigation scenario compared to the Reference with climate sensitivities of 3.0°C and 6.0°C. In both cases, global GHG mitigation preserves coldwater and warmwater habitat that is otherwise projected to be lost under the Reference. However, the CS6.0 projections show a greater extent of habitat preservation than the CS3.0 projections. Specifically, approximately 170 thousand more coldwater acres and 1.6 million more warmwater acres are preserved in the CS6.0 projections compared to the CS3.0 projections by 2100. This primarily occurs because the CS6.0 projections contain greater warming than those assuming CS3.0, and therefore GHG mitigation has a larger impact.

Figure 4. Projected Benefits of GHG Mitigation on Freshwater Fish Habitat in 2100 Assuming Climate Sensitivities of 3.0°C and 6.0°C

*Estimated change in the distribution of suitable freshwater fish habitat across the contiguous U.S. in 2100 under the Mitigation scenario compared to the Reference with climate sensitivities of 3.0°C and 6.0°C.*

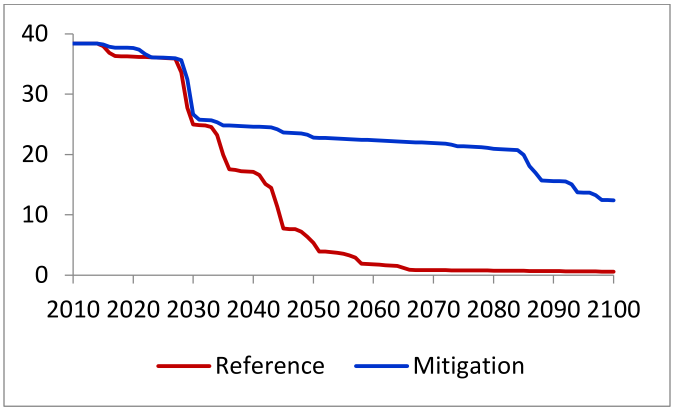


Coral Reefs

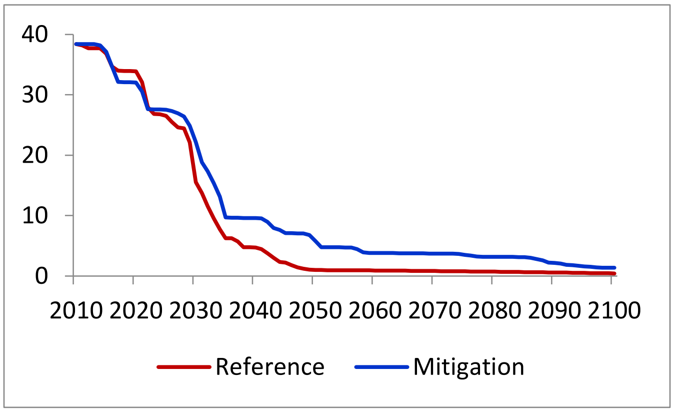
Figure 5 illustrates the projected effect of global GHG mitigation on coral cover in Hawaii under both climate sensitivities. In both scenarios, the Mitigation scenario results in benefits relative to the Reference, but the CS6.0 projections show far less benefits of global GHG mitigation compared to the CS3.0 projections. This is due to the fact that the extreme levels of climate change simulated in the CS6.0 projections, particularly with regards to sea surface temperatures, result in such substantial effects on coral that even significant global GHG emission reductions are unable to prevent large losses.

Figure 5. Projected Impacts of GHG Mitigation on Hawaii's Percent Coral Reef Cover with a Climate Sensitivity Values of 3.0°C and 6.0°C

3.0°C Climate Sensitivity




6.0°C Climate Sensitivity

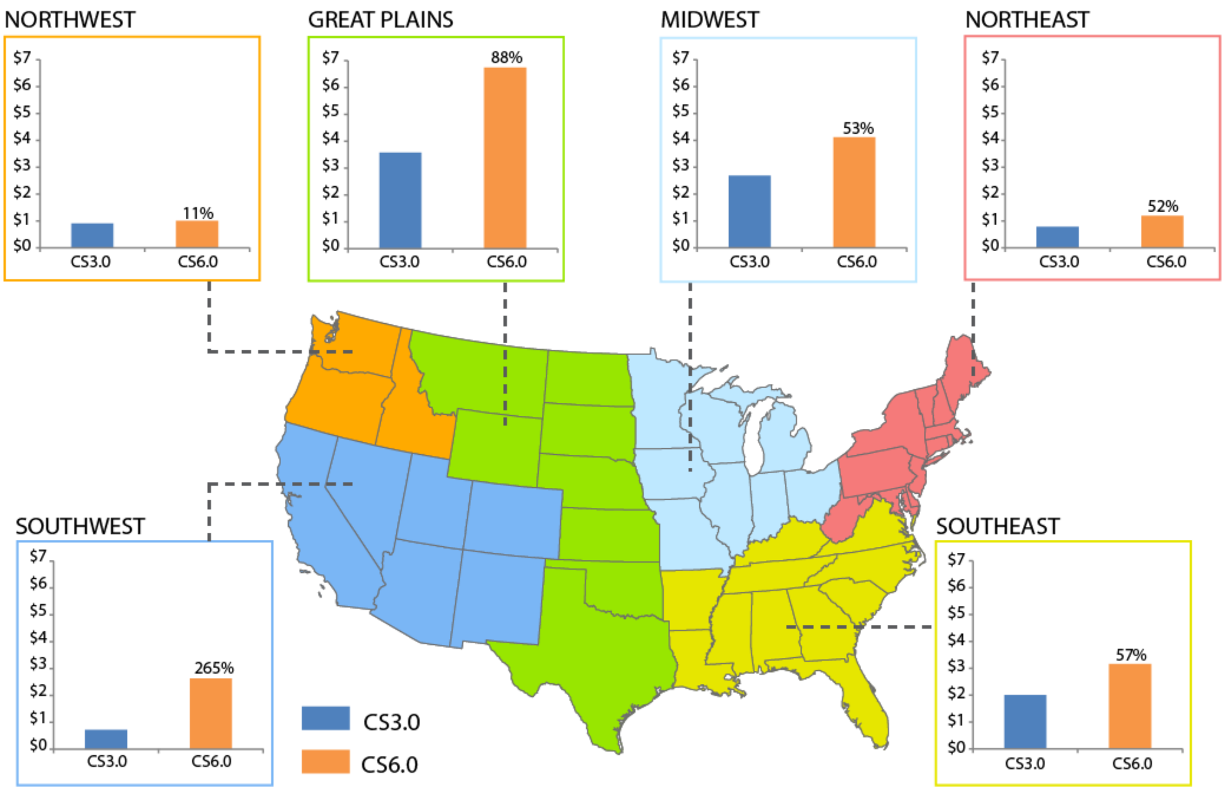


Roads

Figure 6 shows that the effect of global GHG mitigation on U.S. road infrastructure (compared to the Reference scenario) is larger in all regions when assuming a climate sensitivity of 6°C compared to 3°C. Across all regions, the benefits assuming a climate sensitivity of 6°C are approximately $8.2 billion higher in 2100 than the benefits under a climate sensitivity of 3°C ($10.7 billion). In the Southwest region, in particular, benefits under the Mitigation scenario are 265% higher in 2100 with a climate sensitivity of 6°C ($2.6 billion in annual benefits compared to $720 million assuming a climate sensitivity of 3°C).

Figure 6. Projected Impacts of Global GHG Mitigation on U.S. Road Infrastructure in 2100 with Climate Sensitivities of 3.0°C and 6.0°C

*Estimated change in annual adaptation costs under the Mitigation scenario for six regions of the U.S. with climate sensitivities of 3.0°C and 6.0°C. Costs are undiscounted and are presented in billions of 2014$.*



## G. Technical Details Related to Labor Analysis

The CIRA labor impacts analysis focuses on the effect of changes in extreme temperatures on labor 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 of temperature and labor from Graff Zivin and Neidell (2014).[22] The original study described in Graff Zivin and Neidell (2014) did not use the CIRA GHG emission, population, and climate scenarios. Therefore the purpose of this section of the Appendix is to describe the steps taken to process the CIRA data for use in the impacts modeling approach described in Graff Zivin and Neidell (2014) – all other methods used in the CIRA labor analysis were consistent with the original paper.

Labor-Response to Temperature

The impacts of a given weather realization on labor has been estimated in Graff-Zivin and Neidell (2014). They examined impacts across 5°F degree bins (from 25 to 105°F) and found that temperature increases at the higher end of the distribution reduce hours worked in industries with high exposure to climate. The analysis here utilizes the point estimates for responses in each 5° temperature bin to calculate labor impacts under future scenarios. More details on the derivation of this response-function can be found in Graff Zivin and Neidell (2014).

Climate

County-level labor impacts under climate change were estimated using the CIRA climate projections of daily maximum temperatures. This was done using the following process:

A baseline daily "observed" data set was developed by Princeton University (gridded, 0.5° resolution),[23] along with the daily future climate projections using the IGSM-CAM model. The data processing steps were as follows:

1. Calculate average maximum temperature for daily observed baseline over the years 2003-2007 using from Princeton data;
2. Calculate the average maximum temperature for daily modeled baseline over the years 2003-2007 using hindcast IGSM-CAM data;
3. Calculate the modeled change in daily maximum temperature for 5 future years (centered on the target years[24]) from the hindcast modeled baseline (IGSM-CAM data);
4. Calculate a projected daily maximum temperature by applying the delta value (i.e., modeled change from #3) to the observed average daily baseline for each day in each future year;
5. Extract the cell value for the daily future years for the corresponding location of each climate station (8,938 stations);
6. Calculate the mean temperature for all stations within the same county by day for each future projected year.

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

[23] The observed daily data is a reanalysis product from the Terrestrial Hydrology Research Group at Princeton University (http://hydrology.princeton.edu/data.pgf.php).

[24] Target years were: 2025, 2050, 2075, and 2100, with 5-year windows centered on the target year (e.g., 2025 is represented by years 2023, 2024, 2025, 2026, 2027).

Projections were developed for three distinct climate scenarios: a Reference case (climate sensitivity of 3°C), a Reference case with climate sensitivity of 6°C (not shown in the CIRA report), and a global GHG mitigation scenario (the Mitigation scenario referred to in the report, climate sensitivity of 3°C).

To account for climate variability from year to year, projections were provided for a 5-year window centered on the future year of interest. For example, for the 2025 projection year, we developed daily forecasts for all dates in 2023, 2024, 2025, 2026, and 2027. An analogous approach was taken to forecast daily maximum temperatures in 2050, 2075, and 2100 under the climate scenarios of interest.

Developing County-Level Estimates of the Size of the Impacted Labor Pool

This calculation was made in two steps.

First, the 'at-risk' set of workers to climate change in each county was calculated for the baseline period based on averaging labor pool data from 2003-2007. In particular, the fraction of county-level employment within high-risk sectors was calculated. High-risk is defined as in Graff-Zivin and Neidell (2014) and includes those employed in agriculture, forestry, fishing, and hunting, mining, construction, manufacturing, and transportation and utilities industries. This fraction was calculated based on annual employment numbers from the Quarterly Census of Employment and Wages produced by the U.S. Bureau of Labor Statistics.[25] An average national wage for workers in the high-risk sector in 2005 was estimated at $23.02 per hour. That figure was calculated based on an assumption of a 35-hour work week and data on average weekly wages reported in those sectors by the U.S. Bureau of Labor Statistics. Future year real wage growth was projected based on an index of future year GDP/population ratios relative to the 2005 GDP/population ratio. Future year GDP estimates are those developed for CIRA using the MIT EPPA model, see Paltsev et al. (2013)[26] for more information.

Second, the CIRA-ICLUS population dataset[27] was used to project county-level estimates of the working age (15-64 year old) population in each of the identified years. Multiplying these figures by the fraction above generates county-level estimates of the number of individuals working in high-risk sectors in 2025, 2050, 2075, and 2100. The implicit assumption here is that county-level industrial composition remains largely unchanged in the future, and while that assumption is imperfect, it is currently the simplest credible assumption on which to base this analysis.

Development of Results

Results are obtained by combining estimates of the change in temperature in each projection year (relative to the baseline year) and the high-risk working population in the future with estimates on the temperature-labor dose-response relationship from Graff-Zivin and Neidell (2014). For the future time periods of interest, the daily responses for each of the 5 years of data surrounding that year (e.g., 2023-

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[25] U.S. Bureau of Labor Statistics. Quarterly Census of Employment and Wages. http://www.bls.gov/cew/

[26] 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.

[27] See Lane et al. (2014) and Mills et al. (2014) for a description of the CIRA-ICLUS dataset, as well as how it was applied in other impact analyses in the CIRA project.

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

Mills, D., R. Jones, K. Carney, A.S. Juliana, R. Ready, A. Crimmins, J. Martinich, K. Shouse, B. DeAngelo, 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.

2027 for 2025) were computed, and then averaged account for inter-annual variability in climate projections. The sensitivity of the labor response results are assessed by using the lower- and upper-confidence interval of the point estimates in Graff Zivin and Neidell (2014). These results should not be interpreted as the 95% confidence interval on the projections, since there are many uncertainties embedded in the population and climate projections that cannot be easily parameterized in this way. Results are expressed in terms of hours lost as well as foregone wages.

## H. Comparison of CIRA Estimates to Findings of the Assessment Literature

The sectoral sections of the CIRA report include brief comparisons of the estimated impacts to the findings of the comprehensive science assessment of the U.S. Global Change Research Program: C*limate Change Impacts in the United States: The Third National Climate Assessment* (NCA).[28] This section of the Appendix provides a more detailed comparison between the key findings of the CIRA report and the conclusions from the underlying chapters of the NCA and the Intergovernmental Panel on Climate Change's (IPCC) *Climate Change 2014: Impacts, Adaptation, and Vulnerability*.[29] This comparison shows that while the CIRA analyses differ in approach and purpose compared to the recent science assessments (see Introduction and CIRA Framework sections of the report), the CIRA key findings are consistent with the NCA and IPCC conclusions.[30]

### Air Quality

CIRA

- 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.
- 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.

NCA

- Climate change is projected to harm human health by increasing ground-level ozone and/or particulate matter air pollution in some locations. Ground-level ozone (a key component of smog) is associated with many health problems, such as diminished lung function, increased hospital admissions and emergency room visits for asthma, and increases in premature deaths (Luber et al. 2014).
- Increases in global temperatures [of unmitigated climate change] could cause associated increases in premature deaths related to worsened ozone and particle pollution. Estimates made assuming no change in regulatory controls or population characteristics have ranged from 1,000 to 4,300 additional premature deaths nationally per year by 2050 from combined ozone and particle health

[28] 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, 841 pp. doi:10.7930/J0Z31WJ2.

[29] Romero-Lankao, P., J.B. Smith, D.J. Davidson, N.S. Diffenbaugh, P.L. Kinney, P. Kirshen, P. Kovacs, and L. Villers Ruiz, 2014: North America. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1439-1498.

[30] The comprehensive science assessments of the NCA and IPCC primarily describe projections of impacts in futures without GHG mitigation (i.e., business as usual). The estimated benefits of GHG mitigation, which are well-described in the CIRA report, are not a focus of the assessment reports. Therefore, a full comparison of CIRA results to the assessments is limited.

effects. There is less certainty in the responses of airborne particles to climate change than there is about the response of ozone (Luber et al. 2014).

IPCC

- Ozone and particulate matter (e.g., particulate matter with aerodynamic diameter <2.5 µm ($PM_{2.5}$) and $PM_{10}$) have been associated with adverse health effects in many locations in North America. Emissions, transport, dilution, chemical transformation, and eventual deposition of air pollutants all can be influenced by meteorological variables such as temperature, humidity, wind speed and direction, and mixing height (Romero-Lankao et al. 2014).
- Several recent studies have projected future health impacts due to air pollution in a changing climate. There is a large literature examining future climate influences on outdoor air quality in North America, particularly for ozone. This work suggests with medium confidence that ozone concentrations could increase under future climate change scenarios if emissions of precursors were held constant. However, analyses show that future increases can be offset through measures taken to limit emission of pollutants. The literature for $PM_{2.5}$ (fine particulates) is more limited than that for ozone, and shows a more complex pattern of climate sensitivities, with no clear net influence of warming temperatures. On the other hand, $PM_{2.5}$ plays a crucial role in potential health co-benefits of some climate mitigation measures (Romero-Lankao et al. 2014).

### Extreme Temperature Mortality

CIRA

- 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.
- 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 would decrease the number.

NCA

- Heat waves have become more frequent and intense, especially in the West. Cold waves have become less frequent and intense across the nation (Walsh et al. 2014).
- Milder winters resulting from a warming climate can reduce illness, injuries, and deaths associated with cold and snow. Vulnerability to winter weather depends on many non-climate factors, including housing, age, and baseline health. While deaths and injuries related to extreme cold events are projected to decline due to climate change, these reductions are not expected to compensate for the increase in heat-related deaths (Luber et al. 2014).

IPCC

- Climate warming will lead to continuing health stresses related to extreme high temperatures, particularly for the northern parts of North America. The health implications of warming winters remain uncertain. (Romero-Lankao et al. 2014).

### Labor Supply

CIRA

- 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.
- 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.

NCA

- Construction crews may have to operate on altered time schedules to avoid the heat of the day, with greater safety risks for workers. The construction season may lengthen in many localities (Schwartz et al. 2014).

IPCC

- Another potential concern for manufacturing relates to impacts of heat on worker safety and productivity. Several studies suggest that higher temperatures and humidity would lead to decreased productivity and increased occupational health risks (Romero-Lankao et al. 2014).
- Some populations are more vulnerable to heat stress because of age, preexisting medical conditions, working conditions and lifestyles (e.g., outdoor workers, athletes) (Romero-Lankao et al. 2014).

### Water Quality

CIRA

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

NCA

- Increasing air and water temperatures, more intense precipitation and runoff, and intensifying droughts can decrease river and lake water quality in many ways, including increases in sediment, nitrogen, and other pollutant loads (Georgakakos et al. 2014).

IPCC

- Climate change is projected to reduce raw water quality, posing risks to drinking water quality even with conventional treatment (medium evidence, high agreement). The sources of the risks are increased temperature, increases in sediment, nutrient and pollutant loadings due to heavy rainfall, reduced dilution of pollutants during droughts, and disruption of treatment facilities during floods. (Jiménez Cisneros et al. 2014)

### Bridges

CIRA

- 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.

- 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.
- 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%).

<u>NCA</u>

- Streamflows based on increasingly more frequent and intense rainfall instead of slower snowmelt could increase the likelihood of bridge damage from faster-flowing streams (Schwartz et al. 2014).
- Bridge piers are subject to scour as runoff increases stream and river flows, potentially weakening bridge foundations (Schwartz et al. 2014).

<u>IPCC</u>

- Much of the transportation infrastructure across North America is aging, or inadequate (Mexico), which may make it more vulnerable to damage from extreme events and climate change (Romero-Lankao et al. 2014).
- Tens of thousands to more than 100,000 bridges in the USA could be vulnerable to increasing peak river flows in the mid- and late-21st century under the A1B and A2 scenarios. Strengthening vulnerable bridges to be less vulnerable to climate change is estimated to cost approximately US$100 to US$250 billion (Romero-Lankao et al. 2014).

### Roads

<u>CIRA</u>

- 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.
- 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.
- Without global GHG mitigation, adaptation costs in 2100 in the U.S. roads sector are estimated to range from $5.8-$10 billion.
- Global GHG mitigation is projected to avoid an estimated $4.2-$7.4 billion of the damages under the Reference scenario in 2100.

<u>NCA</u>

- The impact on transportation systems not designed for such extreme temperatures would be severe. At higher temperatures, expansion joints on bridges and highways are stressed and some asphalt pavements deteriorate more rapidly (Schwartz et al. 2014).
- Over the coming decades, all modes of transportation and regions will be affected by increasing temperatures, more extreme weather events, and changes in precipitation (Melillo et al. 2014).

<u>IPCC</u>

- Much of North American infrastructure is currently vulnerable to extreme weather events and, unless investments are made to strengthen them, would be more vulnerable to climate change (medium confidence). Water resources and transportation infrastructure are in many cases deteriorating, thus more vulnerable to extremes than strengthened ones (high confidence). Extreme events have caused significant damage to infrastructure in many parts of North America; risks to infrastructure are

particularly acute in Mexico but are a big concern in all three countries (high confidence) (Romero-Lankao et al. 2014).
- A 1°C to 1.5°C increase in global mean temperature would increase the costs of keeping paved and unpaved roads in the USA in service by, respectively, US$2 to US$3 billion per year by 2050 (Romero-Lankao et al. 2014).

### Urban Drainage

CIRA

- 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.
- 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.
- 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.

NCA

- Climate change will stress the nation's aging water infrastructure to varying degrees by location and over time. Much of the country's current drainage infrastructure is already overwhelmed during heavy precipitation and high runoff events, an impact that is projected to be exacerbated as a result of climate change, land-use change, and other factors (Georgakakos et al. 2014).

IPCC

- The 21$^{st}$ century is projected to witness decreases in water quality and increases in urban drainage flooding throughout most of North America under climate change as well as a decrease in instream uses such as hydropower in some regions (high confidence) (Romero-Lankao et al. 2014).

### Coastal Property

CIRA

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

NCA

- Nationally important assets, such as ports, tourism, and fishing sites, in already-vulnerable coastal locations, are increasingly exposed to sea level rise and related hazards. This threatens to disrupt economic activity within coastal areas and the regions they serve and results in significant costs from protecting or moving these assets (Melillo et al. 2014).
- Socioeconomic disparities create uneven exposures and sensitivities to growing coastal risks and limit adaptation options for some coastal communities, resulting in the displacement of the most vulnerable people from coastal areas (Melillo et al. 2014).

IPCC

- Differences in the severity of climate impacts on human settlements are strongly influenced by context-specific social and environmental factors and processes that contribute to risk, vulnerability, and adaptive capacity such as hazard magnitude, populations access to assets, built environment features, and governance (high confidence) (Romero-Lankao et al. 2014).

### Electricity Demand

CIRA

- 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.
- 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.

NCA

- Higher summer temperatures will increase electricity use, causing higher summer peak loads, while warmer winters will decrease energy demands for heating. Net electricity use is projected to increase (Dell et al. 2014).

IPCC

- Demand for summer cooling is projected to increase and demand for winter heating is projected to decrease. Total energy demand in North America is projected to increase in coming decades because of non-climate factors. Climate change is projected to have varying geographic impacts (Romero-Lankao et al. 2014).

### Electricity Supply

CIRA

- 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.
- 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.

NCA

- Several studies suggest that if substantial reductions in emissions of heat-trapping gases were required, the electricity generating sector would switch to using alternative (non-fossil) fuel sources first, given the multiple options available to generate electricity from sources that do not emit heat-trapping gases, such as wind and solar power. Under these circumstances, electricity would displace direct use of fossil fuels for some applications, such as heating, to reduce overall emissions of heat-trapping gases (Dell et al. 2014).
- In addition to being vulnerable to the effects of climate change, electricity generation is a major source of the heat-trapping gases that contribute to climate change. Therefore, regulatory or policy efforts aimed at reducing emissions would also affect the energy supply system. (Dell et al. 2014).

IPCC
- Decarbonizing (i. e. reducing the carbon intensity of) electricity generation is a key component of cost effective mitigation strategies in achieving low-stabilization levels (430 – 530 ppm CO2eq); in most integrated modelling scenarios, decarbonization happens more rapidly in electricity generation than in the industry, buildings, and transport sectors (medium evidence, high agreement). In the majority of low-stabilization scenarios, the share of low-carbon electricity supply (comprising renewable energy, nuclear and CCS) increases from the current share of approximately 30 % to more than 80 % by 2050, and fossil fuel power generation without CCS is phased out almost entirely by 2100 (IPCC, 2014).

### Inland Flooding

CIRA
- 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.
- 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.

NCA
- Heavy downpours are increasing nationally, especially over the last three to five decades. Largest increases are in the Midwest and Northeast. Increases in the frequency and intensity of extreme precipitation events are projected for all U.S. regions (Walsh et al. 2014).
- Flooding may intensify in many U.S. regions, even in areas where total precipitation is projected to decline (Georgakakos et al. 2014).
- Increasing flooding risk affects human safety and health, property, infrastructure, economies, and ecology in many basins across the United States (Georgakakos et al. 2014).

IPCC
- Ntelekos et al. (2010) estimate that annual riverine flood losses in the USA could increase from approximately US$2 billion now to US$7 to US$19 billion annually by 2100 depending on emission scenario and economic growth rate (Romero-Lankao et al. 2014).

### Drought

CIRA
- 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.
- 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.
- 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%).

NCA
- Short-term (seasonal or shorter) droughts are expected to intensify in most U.S. regions. Longer-term droughts are expected to intensify in large areas of the Southwest, southern Great Plains, and Southeast (Georgakakos et al. 2014).

IPCC

- Global warming of approximately 2°C (above the preindustrial baseline) is very likely to lead to more frequent extreme heat events and daily precipitation extremes over most areas of North America, more frequent low-snow years, and shifts toward earlier snowmelt runoff over much of the western USA and Canada. Together with climate hazards such as higher sea levels and associated storm surges, more intense droughts, and increased precipitation variability, these changes are projected to lead to increased stresses to water, agriculture, economic activities, and urban and rural settlements (high confidence) (Romero-Lankao et al. 2014).

### Water Supply and Demand

CIRA

- 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.
- 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.
- 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.

NCA

- Climate change affects water demand and the ways water is used within and across regions and economic sectors. The Southwest, Great Plains, and Southeast are particularly vulnerable to changes in water supply and demand (Georgakakos et al. 2014).
- Changes in precipitation and runoff, combined with changes in consumption and withdrawal, have reduced surface and groundwater supplies in many areas. These trends are expected to continue, increasing the likelihood of water shortages for many uses (Georgakakos et al. 2014).

IPCC

- In the southwest and southeast USA, ecosystems and irrigation are projected to be particularly stressed by decreases in water availability due to the combination of climate change, growing water demand, and water transfers to urban and industrial users (Romero-Lankao et al. 2014).

### Agriculture and Forestry – Crop and Forest Yields and Market Impacts

CIRA

- Unmitigated climate change is projected to result in substantial decreases in yields for most major agricultural crops.
- Global GHG mitigation is projected to substantially benefit U.S. crop yields compared to the Reference scenario.
- 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).
- Based on the projected changes in yields, global GHG mitigation is estimated to result in lower crop prices over the course of the 21$^{st}$ century compared to the Reference.

- 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.
- 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.

<u>NCA</u>

- Climate change has the potential to both positively and negatively affect the location, timing, and productivity of crop systems at local and national scales (Hatfield et al. 2014).
- Climate disruptions to agricultural production have increased in the past 40 years and are projected to increase over the next 25 years. By mid-century and beyond, these impacts will be increasingly negative on most crops and livestock (Hatfield et al. 2014).
- By mid-century, when temperature increases are projected to be between 1.8°F and 5.4°F and precipitation extremes are further intensified, yields of major U.S. crops and farm profits are expected to decline. There have already been detectable impacts on production due to increasing temperatures (Hatfield et al. 2014).
- Climate change is increasing the vulnerability of many forests to ecosystem changes and tree mortality through fire, insect infestations, drought, and disease outbreaks (Joyce et al. 2014).

<u>IPCC</u>

- Effects of temperature and climate variability on yields of major crops have been observed (high confidence). Projected increases in temperature, reductions in precipitation in some regions, and increased frequency of extreme events would result in net productivity declines in major North American crops by the end of the 21st century without adaptation, although the rate of decline varies by model and scenario, and some regions, particularly in the north, may benefit (very high confidence) (Romero-Lankao et al. 2014)
- Studies project productivity gains in northern regions and where water is not projected to be a limiting factor, across models, time frames, and scenarios (high confidence). Overall yields of major crops in North America are projected to decline modestly by mid-century and more steeply by 2100 among studies that do not consider adaptation (very high confidence). Certain regions and crops may experience gains in the absence of extreme events, and projected yields vary by climate model (Romero-Lankao et al. 2014).

### Coral

<u>CIRA</u>

- 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.
- 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.
- 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.

NCA

- Recent research indicates that 75% of the world's coral reefs are threatened due to the interactive effects of climate change and local sources of stress, such as overfishing, nutrient pollution, and disease. In Florida, all reefs are rated as threatened, with significant impacts on valuable ecosystem services they provide. Caribbean coral cover has decreased 80% in less than three decades. These declines have in turn led to a flattening of the three dimensional structure of coral reefs and hence a decrease in the capacity of coral reefs to provide shelter and other resources for other reef-dependent ocean life (Doney et al. 2014).
- Significant habitat loss will continue to occur due to climate change for many species and areas, including Arctic and coral reef ecosystems, while habitat in other areas and for other species will expand. These changes will consequently alter the distribution, abundance, and productivity of many marine species (Doney et al. 2014).

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- Continuing ocean acidification will decrease coral growth and interactions with temperature increases will lead to increased risk of coral bleaching, leading to declines in coral ecosystem biodiversity (Romero-Lankao et al. 2014).

### Shellfish

CIRA

- 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.
- 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.
- 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.

NCA

- Increased ocean acidification, low-oxygen events, and rising temperatures are already affecting shellfish aquaculture operations. Higher temperatures are predicted to increase aquaculture potential in poleward regions, but decrease it in the tropics. Acidification, however, will likely reduce growth and survival of shellfish stocks in all regions (Doney et al. 2014)

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- Along the temperate coasts of North America acidification directly affects calcareous organisms, including colonial mussel beds, with indirect influences on food webs of benthic species (Romero-Lankao et al. 2014).
- Using a partial equilibrium model, Narita et al. (2012) estimate the economic impact of ocean acidification on shellfish. By the turn of this century the aggregate cost could be greater than US$100 billion (Arent et al. 2014).

### Freshwater Fish

CIRA

- 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.

- 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.
- 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%).

NCA

- As temperatures rise and precipitation patterns change, many fish species (such as salmon, trout, whitefish, and char) will be lost from lower-elevation streams, including a projected loss of 47% of habitat for all trout species in the western U.S. by 2080 (Groffman et al. 2014).
- Although suitable habitats will be shrinking for some species (such as coldwater fish like brook trout) and expanding for others (such as warmwater fish like bass), it is difficult to predict what proportion of species will be able to move or adapt as their optimum climate zones shift (Horton et al. 2014 ).

IPCC

- Projected impacts of increased water temperatures include contraction of coldwater fish habitat and expansion of warmwater fish habitat, which can increase the presence of invasive species that threaten resident populations (Romero-Lankao et al. 2014).

### Wildfire

CIRA

- 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.
- 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.
- 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.

NCA

- Given strong relationships between climate and fire, even when modified by land use and management, such as fuel treatments, projected climate changes suggest that western forests in the United States will be increasingly affected by large and intense fires that occur more frequently... Eastern forests are less likely to experience immediate increases in wildfire, unless a point is reached at which rising temperatures combine with seasonal dry periods, more protracted drought, and/or insect outbreaks to trigger wildfires – conditions that have been seen in Florida (Joyce et al. 2014).

IPCC

- Drought index projections and climate change regional models show increases in wildfire risk during the summer and fall on the southeast Pacific Coast, Northern Plains, and the Rocky Mountains (Romero-Lankao et al. 2014).

### Carbon Storage

CIRA

- 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.
- 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%).

NCA

- U.S. forests and associated wood products currently absorb and store the equivalent of about 16% of all carbon dioxide ($CO_2$) emitted by fossil fuel burning in the U.S. each year. Climate change, combined with current societal trends in land use and forest management, is projected to reduce this rate of forest $CO_2$ uptake (Joyce et al. 2014).
- Western forests could also lose substantial amounts of carbon storage capacity (Joyce et al. 2014).

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