

Overview of Results



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

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



National Highlights

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

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

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

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

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

	In the year 2050, global GHG mitigation is projected to result in...	In the year 2100, global GHG mitigation is projected to result in...
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WATER RESOURCES

INLAND FLOODING	An estimated change in flooding damages ranging from \$260 million in damages to \$230 million in avoided damages. [†]	An estimated change in flooding damages ranging from \$32 million in damages to \$2.5 billion in avoided damages. [†]
DROUGHT	An estimated 29%-45% fewer severe and extreme droughts, with corresponding avoided damages to the agriculture sector of approximately \$1.2-\$1.4 billion. [†]	An estimated 40%-59% fewer severe and extreme droughts, with corresponding avoided damages to the agriculture sector of \$2.6-\$3.1 billion. [†]
WATER SUPPLY AND DEMAND	An estimated \$3.9-\$54 billion in avoided damages due to water shortages. [†]	An estimated \$11-\$180 billion in avoided damages due to water shortages. [†]

AGRICULTURE & FORESTRY

AGRICULTURE	An estimated \$1.5-\$3.8 billion in avoided damages.	An estimated \$6.6-\$11 billion in avoided damages.
FORESTRY	Estimated damages of \$9.5-\$9.6 billion.	An estimated \$520 million to \$1.5 billion in avoided damages.

ECOSYSTEMS

CORAL REEFS	An estimated avoided loss of 53% of coral in Hawaii, 3.7% in Florida, and 2.8% in Puerto Rico. These avoided losses are valued at \$1.4 billion.	An estimated avoided loss of 35% of coral in Hawaii, 1.2% in Florida, and 1.7% in Puerto Rico. These avoided losses are valued at \$1.2 billion.
SHELLFISH	An estimated avoided loss of 11% of the U.S. oyster supply, 12% of the U.S. scallop supply, and 4.6% of the U.S. clam supply, with corresponding consumer benefits of \$85 million.	An estimated avoided loss of 34% of the U.S. oyster supply, 37% of the U.S. scallop supply, and 29% of the U.S. clam supply, with corresponding consumer benefits of \$380 million.
FRESHWATER FISH	An estimated change in recreational fishing ranging from \$13 million in avoided damages to \$3.8 million in damages. [†]	An estimated \$95-\$280 million in avoided damages associated with recreational fishing. [†]
WILDFIRE	An estimated 2.1-2.2 million fewer acres burned and corresponding avoided wildfire response costs of \$160-\$390 million. [†]	An estimated 6.0-7.9 million fewer acres burned and corresponding avoided wildfire response costs of \$940 million to \$1.4 billion. [†]
CARBON STORAGE	An estimated 26-78 million fewer metric tons of carbon stored, and corresponding costs of \$7.5-\$23 billion. [†]	An estimated 1-26 million fewer metric tons of carbon stored, and corresponding costs of \$880 million to \$12 billion. [†]

Regional Highlights

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



CARBON STORAGE

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



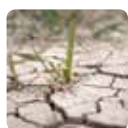
WATER SUPPLY AND DEMAND

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



LABOR

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



DROUGHT

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



WATER QUALITY

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



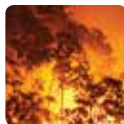
CORAL REEFS

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



SHELLFISH

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



WILDFIRE

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

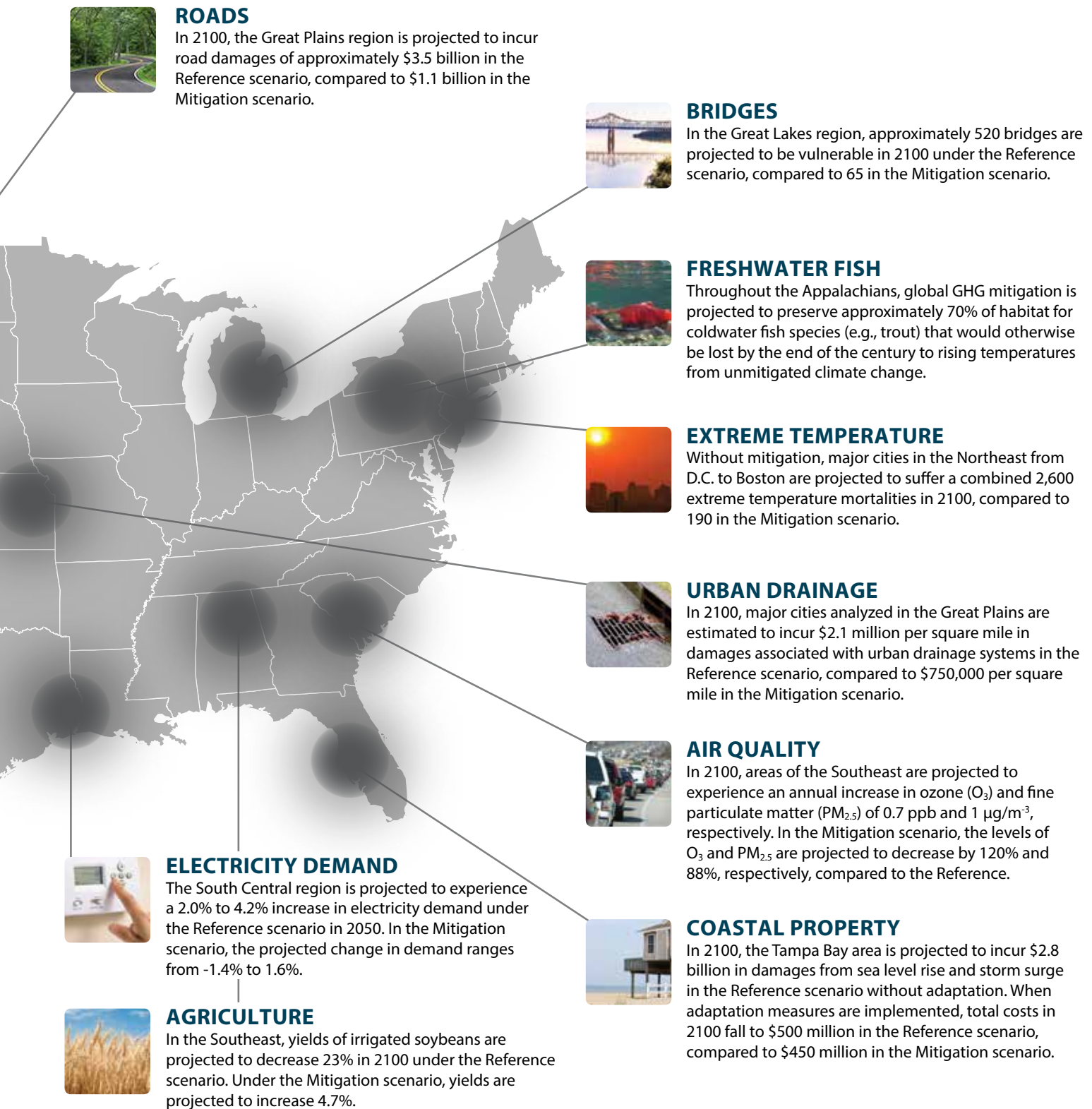


INLAND FLOODING

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

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

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



Conclusion

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

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



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

Next Steps

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

Additional Climate Change Resources

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

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

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

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

and its potential impacts on the U.S. through reports like the National Climate Assessment.

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

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

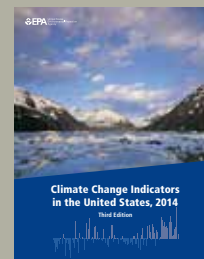


- AVOID (<http://www.metoffice.gov.uk/avoid/>) is a research program that provides modeling and scientific information to the U.K. Government on avoiding dangerous climate change brought on by greenhouse gas emissions.
- The project on the Benefits of Reduced Anthropogenic Climate Change (BRACE; <https://chsp.ucar.edu/brace>)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

Observed Climate Change

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

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





INTRODUCTION

- 1 Martinich, J., J. Reilly, S. Waldhoff, M. Sarofim, and J. McFarland, Eds. 2015. Special Issue on "A Multi-Model Framework to Achieve Consistent Evaluation of Climate Change Impacts in the United States." *Climatic Change*.
- 2 While beyond the scope of this report, analyses of the adequacy of current GHG mitigation efforts, at domestic and global scales, relative to the magnitude of climate change risks are described in the assessment literature. See: 1) Jacoby, H. D., A. C. Janetos, R. Birdsey, J. Buizer, K. Calvin, F. de la Chesnaye, ... and J. West. 2014. Ch. 27: Mitigation. In *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds. U.S. Global Change Research Program. DOI:10.7930/J0C8276J; and 2) IPCC. 2014. Climate Change 2014: Mitigation of Climate Change. *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, ... and J.C. Minx, Eds. New York, NY: Cambridge University Press.
- 3 United Nations Framework Convention on Climate Change. 2013. Report of the Conference of the Parties on its nineteenth session, held in Warsaw from November 11-23, 2013. Part one: Proceedings. FCCC/CP/2013/10.
- 4 CIRA uses sectoral impact models driven by consistent climate and socioeconomic scenarios to analyze both physical impacts and economic damages of climate change at national and regional scales in the U.S. This unique multi-model design allows for 'apples-to-apples' comparisons of impacts and benefits of global GHG mitigation across sectors, but is not comprehensive in scope. The impact estimates presented in this report are consistent with the key findings of the U.S. Global Change Research Program's Third National Climate Assessment. See Section H of the Technical Appendix for this report for a more detailed comparison of key findings.
- 5 The Social Cost of Carbon (SCC) is a metric that estimates the economic value of impacts associated with the global emission of one ton of carbon dioxide (CO₂) or, conversely, the economic benefit of avoiding or reducing one ton of CO₂ (in dollars per ton of CO₂ in a given year). Unlike CIRA, the SCC draws from models of anticipated climate change impacts and benefits across the entire globe, not just for the U.S. The SCC has already been applied to estimate the global economic benefits of CO₂ emission reductions from certain U.S. regulations, but it does not provide explicit information about how the actual physical impacts in specific sectors of the U.S. may change over time and space. For more information, see: U.S. Interagency Working Group on the Social Cost of Carbon. 2013. Technical support document: Technical update of the social cost of carbon for regulatory impact analysis under Executive Order 12866.
- 6 The CIRA project estimates the benefits to the U.S. of global action on climate change. Importantly, the costs of GHG mitigation are not assessed in the project. As such, the analysis presented in the report does not constitute a cost-benefit assessment of climate policy. The costs of reducing GHG emissions have been well examined in the scientific literature (see references below), where recent assessments have used multiple economic models to investigate the sensitivity of costs to policy design, assumptions about the availability of low carbon-emitting energy technologies, socioeconomic and demographic changes, and other important sources of uncertainty. The one instance in the CIRA project where mitigation costs are considered is in the electricity sector (see Electricity section for details). For that sector, the impact of climate change on costs to the U.S. electric power system is estimated along with the costs associated with GHG emission reductions in that sector. See: Fawcett, A., L. Clarke, and J. Weyant. 2013. Introduction to EMF 24. *The Energy Journal*. DOI:10.5547/01956574.35.S11.1; White House Council of Economic Advisors. 2014. The Cost of Delaying Action to Stem Climate Change. Executive Office of the President of the United States; CCSP. 2007. Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations (Part A) and Review of Integrated Scenario Development and Application (Part B). *A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research*. Clarke, L., J. Edmonds, J. Jacoby, H. Pitcher, J. Reilly, R. Richels, ... and M. Webster (Authors). Washington, DC: Department of Energy; Kriegler, E., J.P. Weyant, G.J. Blanford, V. Krey, L. Clarke, J. Edmonds, ... and D.P. van Vuuren. 2013. The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. *Climatic Change*. DOI:10.1007/s10584-013-0953-7; and Kriegler, E., K. Riahi, N. Bauer, V.J. Schwanitz, N. Petermann, V. Bosetti, ... and O. Edenhofer. 2015. Making or breaking climate targets: the AMPERE study on staged accession scenarios for climate policy. *Technological Forecast and Social Change*. DOI:10.1016/j.techfore.2013.09.021; *Energy Economics*. Volume 31, Supplement 2, Pages S63-S306 (2009). International, U.S. and E.U. Climate Change Control Scenarios: Results from EMF 22. Edited by Leon Clarke, Christoph Böhringer and Tom F. Rutherford.
- 7 Example of co-benefit literature: IPCC. 2014. Climate Change 2014: Mitigation of Climate Change. *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, ... and J.C. Minx, Eds. New York, NY: Cambridge University Press.

SUMMARY OF KEY FINDINGS

- 1 This section draws upon conclusions described in the overview paper for the CIRA special issue: Waldhoff, S., J. Martinich, M. Sarofim, B. DeAngelo, J. McFarland, L. Jantarasami, K. Shouse, A. Crimmins, S. Ohrel, and J. Li. 2014. Overview of the Special Issue: A multi-model framework to achieve consistent evaluation of climate change impacts in the United States. *Climatic Change*. DOI:10.1007/s10584-014-1206-0.
- 2 Changes in extreme weather events across the CIRA scenarios are discussed in more detail in: Monier, E. and X. Gao. 2014. Climate change impacts on extreme events in the United States: an uncertainty analysis. *Climatic Change*. DOI:10.1007/s10584-013-1048-1.
- 3 See, for example: 1) Ciscar, J.-C., A. Iglesias, L. Feyen, L. Szabó, D. Van Regemorter, B. Amelung, ... and A. Soria. 2011. Physical and economic consequences of climate change in Europe. *Proc Natl Acad Sci USA*. DOI:10.1073/pnas.1011612108; 2) Frumhoff, P.C., J.J. McCarthy, J.M. Melillo, S.C. Moser, and D.J. Wuebbles. 2007. Confronting climate change in the U.S. Northeast: science, impacts, and solutions. Report of the Northeast Climate Impacts Assessment. Cambridge, MA: Union of Concerned Scientists; and 3) Hayhoe, K., D. Cayan, C.B. Field, P.C. Frumhoff, E.P. Maurer, N.L. Miller, ... and J.H. Verville. 2004. Emissions pathways, climate change, and impacts on California. *Proc Natl Acad Sci USA*. DOI:10.1073/pnas.0404500101.
- 4 Throughout the report, future benefits—i.e., the annual time series of avoided costs—are discounted at a 3% rate to reflect their value in the present day, which is defined as the year 2015 in this report. In short, discounting provides an equal basis to compare the value of benefits (and costs) that occur in different time periods. The discount rate itself reflects the trade-off between consumption today and consumption tomorrow, meaning that with a positive discount rate, benefits that occur today are worth more than they would be tomorrow. A higher discount rate implies a greater preference for present-day consumption and a lower present value of future damages. A lower discount rate implies a greater value on future damages. That is, the present value of future damages calculated at a 5% rate will be lower than those calculated using a 3% rate. There are many ways to select a discount rate and little consensus about which discount rate is most appropriate, particularly when assessing benefits that span multiple generations. Therefore, we selected 3%, a commonly employed rate in the climate impacts and benefits literature. This rate was also used to calculate two of the U.S. Government's four Social Cost of Carbon estimates (including the central value), which estimate climate damages that occur over long time horizons. In particular, the U.S. Government review found that it was consistent with estimates provided in the economics literature and noted that 3% roughly corresponds to the after-tax riskless interest rate. For a detailed discussion on discount rate selection, please see the Social Cost of Carbon Technical Support Document, available at <http://www.epa.gov/oms/climate/regulations/scc-tsd.pdf>.

CIRA FRAMEWORK

- 1 Martinich, J., J. Reilly, S. Waldhoff, M. Sarofim, and J. McFarland, Eds. 2015. Special Issue on "A Multi-Model Framework to Achieve Consistent Evaluation of Climate Change Impacts in the United States." *Climatic Change*.
- 2 Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds. 2014. Climate Change Impacts in the United States: The Third National Climate Assessment. Appendix 5: Scenarios and Models. U.S. Global Change Research Program. DOI:10.7930/J0Z31WJ2.
- 3 While beyond the scope of this report, analyses of the adequacy of current GHG mitigation efforts, at domestic and global scales, relative to the magnitude of climate change risks are described in the assessment literature. See, for example: 1) Jacoby, H. D., A. C. Janetos, R. Birdsey, J. Buizer, K. Calvin, F. de la Chesnaye, ... and J. West. 2014. Ch. 27: Mitigation. *Climate Change Impacts in the United States: The Third National*

- Climate Assessment*, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program. DOI:10.7930/J0C8276J; and 2) IPCC. 2014. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, ... and J.C. Minx, Eds. New York, NY: Cambridge University Press.
- 4 A third emissions scenario was applied in most CIRA sectoral analyses, as described and presented in the research papers supporting the project. In 2100, this scenario, called Policy 4.5 in the CIRA project, achieves a radiative forcing of approximately 4.2 W/m² with an atmospheric GHG concentration of 600 ppm (CO₂ equivalent). This radiative forcing value reflects GHG radiative forcing (i.e., not including aerosols) and uses a baseline of 1750 (both of which are necessary adjustments for comparing to the IPCC RCPs), therefore making it slightly different than the value reported previously in the CIRA literature (4.5 W/m²).
 - 5 Paltsev, S., J.M. Reilly, H.D. Jacoby, R.S. Eckaus, J. McFarland, M. Sarofim, M. Asadoorian, and M. Babiker. 2005. The MIT Emissions Prediction and Policy Analysis (EPPA) model: version 4. Report 125, MIT Joint Program on the Science and Policy of Global Change. <http://globalchange.mit.edu/publications>.
 - 6 By 2100 (using a baseline of 1750), the CIRA Reference scenario has a total radiative forcing of 9.8 W/m², which appears considerably larger than RCP 8.5. However, the contrast is primarily due to differences in how forcing is calculated by different GCMs used in developing those scenarios. The IGSM radiation code was derived from the GISS climate model, and therefore when calculating radiative forcing due to increased concentrations in the IGSM, forcing functions fit to the GISS code were used rather than the more common approach of using simplified equations, such as those defined in IPCC's Third Assessment Report. Using these simplified equations, total radiative forcing for the CIRA Reference is 8.6 W/m², and 3.2 W/m² for the Mitigation scenario. Other differences between the IGSM scenarios and the RCPs are due to differences in anthropogenic emissions, natural emissions responses to warming, and atmospheric chemistry.
 - 7 Paltsev, S., E. Monier, J. Scott, A. Sokolov, and J. Reilly. 2013. Integrated economic and climate projections for impact assessment. *Climatic Change*. DOI:10.1007/s10584-013-0892-3. We also note that the Reference scenario is calibrated using historic GHG emissions through 2010; see Paltsev et al. (2013) for more information.
 - 8 Paltsev, S., E. Monier, J. Scott, A. Sokolov, and J. Reilly. 2013. Integrated economic and climate projections for impact assessment. *Climatic Change*. DOI:10.1007/s10584-013-0892-3.
 - 9 Radiative forcing (including CO₂, CH₄, N₂O, PFCs, SF₆, HFCs, CFCs and HCFCs) for the Reference and Mitigation scenarios (see Paltsev et al. 2013), compared to the four RCPs (data from Meinshausen et al. 2011). The negative forcing effects of aerosols are not included. See: Meinshausen, M., S. J. Smith, K. V. Calvin, J. S. Daniel, M. L. T. Kainuma, J.-F. Lamarque, ... and D. van Vuuren. 2011. The RCP Greenhouse Gas Concentrations and their Extension from 1765 to 2300. *Climatic Change*. DOI:10.1007/s10584-011-0156-z.
 - 10 Please see the literature underlying the CIRA project for information on post-processing and bias-correction of climate outputs for use in the sector analyses.
 - 11 Monier, E., X. Gao, J.R. Scott, A.P. Sokolov, and C.A. Schlosser. 2014. A framework for modeling uncertainty in regional climate change. *Climatic Change*. DOI:10.1007/s10584-014-1112-5.
 - 12 Adaptive actions modeled in the sectoral analyses of this report should not be interpreted as recommendations of these particular strategies.
 - 13 Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, ... and R. Somerville. 2014. Chapter 2: Our Changing Climate. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J.M. Melillo, R.C. Richmond, and G. W. Yohe, Eds. U.S. Global Change Research Program. DOI:10.7930/J0KW5CXT.
 - 14 The U.S. Global Change Research Program's National Climate Assessment (NCA) results are reported for the RCP 8.5 scenario, using a range (5th-95th percentile) of results from a suite of climate models, adjusted to match the same baseline period used for the IGSM-CAM model. The NCA also presents results from the older SRES models: the A2 scenario from SRES was projected to warm by 5-8°F by 2100.
 - 15 Future climate change depends on the response of the global climate system to rising GHG concentrations (i.e., how much temperatures will rise in response to a given increase in atmospheric CO₂). Assumptions about this relationship are referred to as climate sensitivity.
 - 16 IPCC. 2014. Summary for Policymakers. In: *Climate Change 2014, Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, ... and J.C. Minx, Eds. New York, NY.
 - 17 IPCC. 2013. Summary for Policymakers. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, ... and P.M. Midgley, Eds. New York, NY.
 - 18 The estimate of warming from the historical period (0.65°C) used in Figure 1 of the Temperature Projections section is slightly less than the IPCC's estimate of 0.85°C because the former utilizes a 30-yr average (1980-2009) to represent the current period.
 - 19 Warming from the historical period (0.65°C) comparing 1880-1909 to 1980-2009 was calculated using the NOAA Global Historical Climatology Network GHCN-3 dataset of Global Land and Ocean Temperature Anomalies (available at http://www.ncdc.noaa.gov/cag/time-series/global/globe/land_ocean/yttd/12/1880-2014.csv). Combined with this historical warming, the 2°C target (relative to preindustrial) is equivalent to a warming of 2.43°F (relative to the 1980-2009 baseline period), as shown in Figure 1 of the Temperature Projections section. This value is consistent with the average of the last two decades of the century (2081-2100) for the CIRA Mitigation scenario: 2.23°F.
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 - 22 The CIRA sea level rise scenarios are at the high end of projected sea level rise rates for similar scenarios based on recent publications (Horton et al. 2014, Kopp et al. 2014). However, we also note that the effect of GHG mitigation on reducing the increase in future sea level was found to be larger in these studies. The use of a smaller sea level rise would likely lead to a decrease in total damages, but a larger reduction in sea level rise due to the Mitigation scenario would likely yield larger economic benefits than those presented in this report. See: 1) Horton, B.J., S. Rahmstorf, S.E. Engelhart, and A.C. Kemp. 2014. Expert assessment of sea-level rise by AD 2100 and AD 2300. *Quaternary Science Reviews*. DOI:10.1016/j.quascirev.2013.11.002; and 2) Kopp, R.E., R.M. Horton, C.M. Little, J.X. Mitrovica, M. Oppenheimer, D.J. Rasmussen, B.H. Strauss, and C. Tebaldi. 2014. Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future*. DOI:10.1002/2014EF000239.
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 - 27 Paltsev, S., E. Monier, J. Scott, A. Sokolov, and J. Reilly. 2013. Integrated economic and climate projections for impact assessment. *Climatic Change*. DOI:10.1007/s10584-013-0892-3.
 - 28 For each scenario, a site-specific, fixed annual rate of land subsidence or uplift is estimated, which combines with the SLR scenario to yield site-specific relative sea level rise. Historical vertical land movement is based on annual average measurements from National Oceanic and Atmospheric Administration (NOAA) tide gauge data from 68 sites with at least 25 years of continuous measurements and linear interpolation of subsidence rates for all cells that lie between the selected sites. An estimated 1.7 mm/year is subtracted from the tide gauge annual average to account for the component of relative sea level rise that is accounted for by 20th century sea level change, yielding the site-specific subsidence/uplift rate.
 - 29 The CIRA approach for calculating relative sea level rise assumes that the difference in rate between global and relative sea level change will continue into the future. Because some physical processes (e.g., changes in differential ocean heating) will likely change in the future at rates different from what is reflected in historical tide gauge data, the CIRA approach does not capture all of these dynamics. For more information, see: Neumann, J., D. Hudgens, J. Herter, and J. Martinich. 2010. The Economics of Adaptation along Developed Coastlines. *Wiley Interdisciplinary Reviews: Climate Change*. DOI:10.1002/wcc.90.
 - 30 Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, ... and R. Somerville. 2014. Appendix 3: Climate Science Supplement. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J.M. Melillo, T.C. Richmond, and G.W. Yohe, Eds., U.S. Global Research Program. DOI:10.7930/J0KS6PHH.
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 - 32 Monier, E., X. Gao, J.R. Scott, A.P. Sokolov, and C.A. Schlosser. 2014. A framework for modeling uncertainty in regional climate change. *Climatic Change*. DOI:10.1007/s10584-014-1112-5.

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- 34 All three CIRA emissions scenarios contain the same level of global and U.S. population change over time.
- 35 For each emissions scenario, values represent the ensemble mean of the five IGSM-CAM initializations using a climate sensitivity of 3°C.
- 36 IPCC. 2013. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, ... and P.M. Midgley, Eds. New York, NY: Cambridge University Press.
- 37 A climate sensitivity of 6°C is considered “low probability” when considering feedbacks expected over the next century. However, there is literature suggesting that slower feedbacks involving ice sheet and vegetation changes can lead to higher “Earth System Sensitivity” on timescales of several centuries, such that a sensitivity of 6°C will have a higher probability on these longer timescales. Additional feedbacks including methane and carbon cycles are not included in the climate sensitivity definition.
- 38 Mapped values represent the ensemble mean of the five IGSM-CAM initializations with different climate sensitivities under the Reference scenario.
- 39 All five maps assume a climate sensitivity of 3°C under the Reference scenario.
- 40 A method by which the average change produced by running a climate model is combined with the specific geographic pattern of change calculated from a different model in order to approximate the result that would be produced by the second model.
- 41 Please refer to: 1) Monier, E., X. Gao, J.R. Scott, A.P. Sokolov, and C.A. Schlosser. 2014. A framework for modeling uncertainty in regional climate change. *Climatic Change*. DOI: 10.1007/s10584-014-1112-5; and 2) Flato, G., J. Marotzke, B. Abiodun, P. Braconnot, S.C. Chou, W. Collins, ... and M. Rummukainen. 2013. Evaluation of Climate Models. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley, Eds. New York, NY: Cambridge University Press.
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- 43 This section draws upon conclusions described in the overview paper for the CIRA special issue: Waldhoff, S., J. Martinich, M. Sarofim, B. DeAngelo, J. McFarland, L. Jan-tarasami, 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.
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SECTORS Health

- 1 The economic estimates described throughout this report are presented in constant 2014 dollars. The literature underlying the CIRA project presents results primarily in 2005 dollars. This should be noted when comparing the results presented in this report with those in the CIRA literature. Dollar years were adjusted using the U.S. Bureau of Economic Analysis’ Implicit Price Deflators for Gross Domestic Product. Source: U.S. Bureau of Economic Analysis, Table 1.1.9 Implicit Price Deflators for Gross Domestic Product, March 27, 2015, <http://www.bea.gov/national/index.htm>.
- 2 Throughout the report, future benefits—i.e., the annual time series of avoided costs—are discounted at a 3% rate to reflect their value in the present day, which is defined as the year 2015 in this report. In short, discounting provides an equal basis to compare the value of benefits (and costs) that occur in different time periods. The discount rate itself reflects the trade-off between consumption today and consumption tomorrow,



- meaning that with a positive discount rate, benefits that occur today are worth more than they would be tomorrow. A higher discount rate implies a greater preference for present-day consumption and a lower present value of future damages. A lower discount rate implies a greater value on future damages. That is, the present value of future damages calculated at a 5% rate will be lower than those calculated using a 3% rate. There are many ways to select a discount rate and little consensus about which discount rate is most appropriate, particularly when assessing benefits that span generations. Therefore, we selected 3%, a commonly employed rate in the climate impacts and benefits literature. This rate was also used to calculate two of the U.S. Government’s four Social Cost of Carbon estimates (including the central value), which estimate climate damages that occur over long time horizons. In particular, the U.S. Government review found that it was consistent with estimates provided in the economics literature and noted that 3% roughly corresponds to the after-tax riskless interest rate. For a detailed discussion on discount rate selection, please see the Social Cost of Carbon Technical Support Document, available at <http://www.epa.gov/oms/climate/regulations/scc-tds.pdf>.
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- 11 For comparison, the current national 8-hour daily maximum ozone standard is 75 parts per billion: primary and secondary standard in the form of annual fourth-highest daily maximum 8-hour concentration averaged over 3 years.
- 12 Changes in ozone and PM_{2.5} concentrations in the Risks of Inaction section and in Figures 1 and 2 are not population-weighted.
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 - 15 An additional mortality valuation approach using years of life saved is provided in Garcia-Menendez et al. (2015).
 - 16 Reductions in PM_{2.5} largely drive the change in mortality. However, the contribution of ozone pollution to these estimates increases towards the end of the century and accounts for 40% of the projected life years saved by 2100. See Garcia-Menendez et al. (2015) for more information.
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 - 19 Fine particulate matter constituents analyzed include sulfate, elemental carbon, organic aerosol and ammonium nitrate.
 - 20 Changes in mortality are estimated by applying the differences in daily-maximum 8-hour ozone (8-hr-max ozone) between May and September and daily average PM_{2.5} to the concentration response functions.
 - 21 At the time of this report's release, the U.S. Environmental Protection Agency's Guidelines for Preparing Economic Analyses report recommends a VSL of \$7.9 million (2008\$), based on 1990 incomes. To create a VSL using 2014\$ and based on 2010 incomes, the standard value was adjusted for inflation using BEA implicit price inflator for gross domestic product and for income growth adjustment based on a method described in the user manual of EPA's BenMAP model (pg. 109). The resulting value, \$9.45 million for 2010 (2014\$), was adjusted to future years by assuming an elasticity of VSL to GDP per capita of 0.4. Projections of GDP and population for the CIRA Reference scenario were employed. Using this approach, the VSL in 2050 is estimated at \$12.53 million and \$16.39 million in 2100. Finally, we note that the VSL values used in this report differ slightly from those used in Garcia-Menendez et al. (2015), which therefore affects the valuation estimates reported in each. Sources: 1) U.S. Environmental Protection Agency. 2014. Guidelines for Preparing Economic Analyses. National Center for Environmental Economics. [http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0568-52.pdf/\\$file/EE-0568-52.pdf](http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0568-52.pdf/$file/EE-0568-52.pdf); 2) U.S. Bureau of Economic Analysis, Table 1.1.9 Implicit Price Deflators for Gross Domestic Product, March 27, 2015, <http://www.bea.gov/national/index.htm>; and 3) U.S. Environmental Protection Agency. 2012. BenMAP Users Manual. Office of Air Quality Planning and Standards.
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 - 39 Bureau of Labor Statistics, Quarterly Census of Employment and Wages, data accessible at <http://www.bls.gov/cew/>. High-risk workers were defined as those employed in agriculture, forestry, and fishing; hunting, mining, and construction; and manufacturing, transportation, and utilities industries.
 - 40 Bureau of Labor Statistics, Quarterly Census of Employment and Wages, data accessible at <http://www.bls.gov/cew/>. Average wage (\$23.02) calculated using high-risk labor categories only, as the majority of extreme temperature impacts on labor hours occur in these industries.
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- 29 The CIRA sea level rise scenarios are at the high end of projected sea level rise rates for similar scenarios based on recent publications (Horton et al. 2014, Kopp et al. 2014). However, we also note that the effect of GHG mitigation on reducing the increase in future sea level was found to be proportionally larger in these studies. The use of smaller sea level rise rates would likely lead to a decrease in total damages, but a larger reduction in sea level rise due to the Mitigation scenario compared to the Reference would likely yield larger economic benefits than those presented in this report. See: 1) Horton, B.J., S. Rahmstorf, S.E. Engelhart, and A.C. Kemp. 2014. Expert assessment



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Electricity

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

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- 9 A wetter future climate, as projected under the IGSM-CAM for many crop-growing parts of the U.S., will tend to reduce water stress such that some yields may increase even with higher temperatures. In the EPIC modeling, irrigated crops are assumed to be able to meet their water needs regardless of climate change effects on precipitation, so a wetter/hotter climate scenario just increases their temperature stress without reducing their water stress. This tends to make impacts on rainfed crops more negative than for irrigated yields. In addition, the ability of climate models to simulate precipitation as severe storms or as heavy rainfall rather than frequent drizzle is an emerging area of research in the climate modeling community. As such, the results presented here should be interpreted with acknowledgement of this uncertainty.
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- 11 The EPIC simulations assume that crops can be irrigated at a level that eliminates water stress. A particular concern for climate change is that in areas where the need for irrigation is greatest due to reduction in precipitation, the supply of water for irrigation will also be reduced. To fully consider this risk requires integration of crop modeling with hydrologic modeling for projections of future water supply, which was not modeled in this biophysical crop yield analysis.
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also be reduced. To fully consider this risk requires integration of crop modeling with hydrologic modeling for projections of future water supply, which was not modeled in this biophysical crop yield analysis.

- 18 The analysis uses climate projections from all five initializations of the IGSM-CAM. Given the sensitivity of the EPIC and MC1 models to natural variability, the use of the five initializations of the IGSM-CAM climate model, each of which has an equally plausible future climate, aids in understanding and constraining the potential magnitude of crop and vegetation changes in the future. Please refer to the Levels of Certainty section of this report for more information.
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- 24 Consumer and producer surplus are used to estimate impacts on total economic welfare. Consumer surplus is the monetary gain obtained by consumers because they are able to purchase a product for a price that is less than the highest price that they would be willing to pay. Producer surplus or producers' surplus is the amount that producers benefit by selling at a market price that is higher than the least that they would be willing to sell for.
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- 27 FASOM has perfect foresight of future climate change effects, and thus can optimize near term land owner behavior. The model also simulates changes in agricultural and forestry commodities beyond those modeled in EPIC (9 crops) and MC1 (hard and softwoods).
- 28 This analysis does not reflect climate change impacts on international forests and agriculture, which would also affect relative returns to different uses of land and trade patterns and therefore affect land use decisions. Also, numerous uncertainties remain regarding issues such as future changes in crop technology, energy policy, and other interactions that could affect market outcomes.

Endnotes



- 29 FASOM-GHG is optimized to maximize consumer and producer surplus in the base, but re-adjusts production and consumption patterns to re-optimize in response to changes in potential yields.
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- 37 Comprised of the following Geographic Area Coordination Center regions: Northern Rockies, Rocky Mountain, Southwest, Eastern Great Basin, Western Great Basin, Northwest, California North, and California South.
- 38 Percent changes calculated by comparing acres burned under the Reference scenario at the end of the century (average of 2085-2114) compared to the historic baseline (average of 2000-2009).
- 39 Fuel management costs are estimated at \$15 billion under the Reference and \$12 billion under the Mitigation scenario through 2100 (average across all IGSM-CAM initializations, 2014\$, discounted at 3%), corresponding to avoided costs (benefits) of \$3.4 billion under the Mitigation scenario.
- 40 Fuel management costs were not estimated using the MIROC climate model.
- 41 The CIRA results simulated in the MC1 vegetation model suggest a substantial change to the wildfire regime we experience today. For example, unmitigated climate change is projected to increase area burned by wildfire annually by approximately 45% in California by the end of the century, 64% in the Mountain West, and 95% in the Northwest. Given the sensitivity of the MC1 climate model to natural variability, the use of the five initializations of the IGSM-CAM climate model, each of which has an equally plausible future climate, aids in understanding and constraining the potential magnitude of vegetation changes in the future.
- 42 Because the IGSM-CAM projects a wetter future for a majority of the nation, pattern-scaled output from two additional climate models were simulated in MC1 to encompass a broader range of possible climate futures. While all three sets of climate projections show increases in the area burned by wildfire compared to the historic period, only the IGSM-CAM and MIROC climate model results are presented in this report. For an in-depth discussion of the results, see: Mills, D., R. Jones, K. Carney, A. St Juliana, R. Ready, A. Crimmins, ... and E. Monier. 2014. Quantifying and Monetizing Potential Climate Change Policy Impacts on Terrestrial Ecosystem Carbon Storage and Wildfires in the United States. *Climatic Change*. DOI:10.1007/s10584-014-1118-z.
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CONCLUSION

- 1 The few efforts to date that have estimated multi-sector impacts in a consistent framework include the European Commission's PESETA project (<http://peseta.jrc.ec.europa.eu>), and the Risky Business Initiative (<http://riskybusiness.org>), a project focusing on economic risks in the U.S. Integrated assessment models, such as FUND (<http://fund-model.org>), are also being used to estimate the multi-sector social costs of GHG emissions.
- 2 The use of a climate model that generates a relatively higher amount of future precipitation may strongly influence results in a particular sector. For example, inland flooding damages may be larger under these wetter projections compared to those under a drier model. This same sensitivity of sectoral results to the choice of climate model could affect a different part of the water sector in complementary ways, such that drought damages could be smaller compared to those under a drier model.



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