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Overview of the special issue: a multi-model framework to achieve consistent evaluation of climate change impacts in the United States

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1 Introduction

Understanding the risks of the physical impacts and economic damages associated with different levels of future climate change is essential to informing policy decisions designed to address these risks. Proposed policies to mitigate greenhouse gases (GHGs) have generally been focused around specific temperature or emissions targets, such as limiting global average temperature change to 2 °C above preindustrial levels (IPCC 2014) or reducing GHG emissions to 80 % below 2005 levels by 2050 (White House 2013). Many analyses of the potential costs of these proposals have been conducted (US Environmental Protection Agency 2010; US Energy Information Administration 2009). However, the benefits of GHG mitigation – the reduced or avoided damages due to the policy – have not been as thoroughly analyzed.

The Climate Change Impacts and Risk Analysis (CIRA) project was initiated as an on-going project to estimate the benefits of GHG mitigation,[1] and to complement the well-developed capacity to model the costs of climate policies. The first phase of the CIRA project is the modeling exercise presented in this Special Issue entitled "A Multi-Model Framework to

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[1] The CIRA project is being led by the US Environmental Protection Agency's Climate Change Division, with significant contributions from a number of collaborators, as identified in the papers of this Special Issue.

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Achieve Consistent Evaluation of Climate Change Impacts in the United States." This effort focuses on two primary goals: first, to assess the degree to which global GHG mitigation may avoid or reduce climate change-related risks and damages[2] in the United States (US) compared to a future without mitigation policy; and second, to clearly articulate and analyze several key sources of uncertainty in estimating these benefits.

To achieve these goals, CIRA estimates climate change impacts and damages, including changes in risks associated with key sources of uncertainty, for multiple sectors in the US under a business as usual future and two global GHG emissions mitigation scenarios.[3] This multi-model framework enables development of consistent estimates of the benefits of climate change policy across these multiple impacts sectors. As described in more detail below, this framework builds upon existing research, and advances the climate change impacts literature through: 1) the development and use of internally consistent climate policy and no-policy scenarios; 2) the quantification of both the physical and economic impacts of GHG mitigation across multiple sectors, time periods, and US regions; and 3) the systematic exploration of multiple sources of uncertainty in modeling the benefits of GHG mitigation policies.[4]

This paper describes the design of the analytical framework used in the CIRA project and introduces and summarizes the remaining 10 papers in this Special Issue. This paper is organized as follows. Section 2 outlines the components necessary for developing comprehensive estimates of the benefits of a climate change policy and the contributions/advancements of the framework used in CIRA. Section 3 describes the specific methods and models used in this exercise, and briefly introduces the subsequent papers of this Special Issue. Section 4 summarizes previous multi-sectoral impacts analyses to place the CIRA modeling exercise within the context of the larger impacts literature. Section 5 presents a brief synthesis of CIRA results included in this Special Issue, and discusses common themes across the sectoral findings. Section 6 concludes and presents directions for potential future research.

2 Modeling the benefits of climate change policy

An ideal modeling framework for estimating the benefits of a GHG emissions mitigation policy would include four primary components. First, the benefits of mitigation would be assessed as the difference between the impacts in futures with and without the policy, using scenarios with consistent climatic, socioeconomic, and technological assumptions. Second, although a full accounting of all impacts may never be achieved, the benefits estimates should

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[2] As used herein, the term "damages" refers to the net economic effect of the physical impacts of climate change and "benefits" to the change in damages across scenarios. This analysis does not presuppose that damage estimates will be negative and allows for beneficial impacts due to climate change.

[3] The focus of this exercise is on impacts and risks from climate change in the US. The GHG mitigation scenarios used here are not associated with a specific policy, and are assumed to be achieved through global efforts to mitigate GHGs. The resulting impacts changes are independent of where emissions mitigation occurs.

[4] The CIRA analyses differ in key ways from the tools currently used to characterize the benefits of GHG mitigation, namely the Social Cost of Carbon (SCC) and comprehensive scientific assessments. First, the CIRA analyses do not serve the same analytical purpose nor use the same methodology as the SCC, a metric that estimates the economic value of impacts associated with small changes in emissions in a given year. The SCC is meant to be comprehensive, and includes a wide range of anticipated climate benefits, which are aggregated into one economic estimate (e.g., dollars per ton in a given year). The SCC is often used to incorporate the economic benefits of small CO_2 emission reductions in benefit cost analyses (US Interagency Working Group on the Social Cost of Carbon 2013). Second, CIRA is not intended to be a comprehensive scientific assessment of the breadth of the impacts literature, such as those conducted by the IPCC (2014) and USGCRP (Melillo et al. 2014).

represent the depth and breadth of potential climate change impacts, both across and within sectors. Third, the key sources of uncertainty over the range of impacts should be explicitly modeled and characterized. Finally, the ideal modeling framework would represent interactions among impacts sectors and regions and feedbacks with the economic and climate systems. The CIRA project was initiated to improve benefits modeling consistent with these ideals. The modeling exercise presented in this Special Issue represents the first stage of this project, and were designed to incorporate several of these components as a step toward this ideal framework.

2.1 Scenarios

Anthropogenic GHG emissions, and the resulting climate change impacts and damages, depend on future socioeconomic development pathways (population, economic growth, and technological change). A wide range of socioeconomic, emissions, and climate scenarios has been used to estimate climate change impacts and damages in the literature.[5] This breadth of scenarios is beneficial for conveying ranges of climate change impacts in multiple potential futures. However, there needs to be caution in the extent to which this range of impacts information serves as a basis for calculating the benefits of policy, because the estimates may vary for reasons unrelated to climate (e.g., underlying population assumptions). To create a set of impacts estimates with consistent underlying assumptions, the CIRA modeling exercise used three socioeconomic and emissions scenarios with climate projections based on these scenarios, as inputs for all sectoral impact models. The CIRA socioeconomic scenarios consist of a reference (no climate policy) and two global mitigation policy scenarios. The difference in impacts and damages between the policy and reference scenarios can thus be interpreted as the benefits of the policy with comparable results across models and sectors.

2.2 Multiple impacts and depth of analysis

Recent science assessments (IPCC 2014; Melillo et al. 2014) make it clear that climate change will result in far ranging impacts that are important to the health and welfare of people in the US and all world regions. Therefore the goal of any analysis to quantify and value the physical and economic benefits of GHG mitigation across sectors should be to reasonably estimate and account for as many impacts as possible. The CIRA project was designed to quantify the climate change impacts and damages in the US using high-resolution climate projections in a large number of detailed, bottom-up sectoral impact models. In addition to exploring structural uncertainties in sectoral models, this design enables in-depth analysis across regions, sectors, and time. Further, the role of adaptation can be effectively modeled at a sectoral level to explore the potential for risk reduction and to quantify the costs associated with these adaptive actions.

2.3 Uncertainty

A number of sources of uncertainty cause variability across estimates of sectoral impacts and damages, and the resulting benefits of GHG mitigation. These include future socioeconomic development pathways, the sensitivity of the climate to changes in atmospheric GHG

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[5] Because future development trajectories are uncertain, a wide range of future socioeconomic and emissions scenarios have been developed (e.g., IS92, SRES, EMF 22) to examine the potential effects of development pathways on emissions, impacts, and mitigation potential.

concentrations, the spatial and temporal distribution of climate changes, potential climate catastrophes, and threshold responses. Estimates will also vary due to differences stemming from model structure, parameterization,[6] or assumptions about the effectiveness of adaptation. The CIRA modeling exercise was designed to communicate the benefits of GHG mitigation in light of key sources of uncertainty. Under the three CIRA emission pathways, sectoral impacts and damages were estimated, where feasible, using climate outputs based on four levels of climate sensitivity. As further described in Section 3, the effect of natural variability was explored using different initializing conditions of the climate model, and the role of variability across climate models was examined using pattern scaling. Finally, the variability in sectoral impacts estimates was studied, where feasible, with the use of multiple sectoral impact models.

2.4 Integration

Finally, an ideal modeling framework would include the potential interactions across sectors or regions (e.g., competing water demands in the energy, agriculture, and municipal sectors), and feedbacks from climate change impacts back into the economy and the climate system (e.g., reduced labor productivity due to heat-related morbidity; increased CO_2 emissions from forest fires resulting from climate changes). Integrated assessment (IA) modeling, which is designed to jointly model the economic, energy, land use, and climate systems, is in the infancy of incorporating such interactions and feedbacks. Though research and development in these areas continues, and given current modeling capabilities, this CIRA exercise focused on exploring the effects of consistent scenarios and uncertainties, as described above. While integration across sectors and the incorporation of impacts into broader economic frameworks were not the focus of this first phase of the CIRA project, future efforts will begin to address these important issues.

3 The CIRA methodology

3.1 Overview

The CIRA modeling exercise, as shown in Fig. 1, was designed to enable consistent comparison of impacts and damages across many sectors in the US. To accomplish this, two IA models and 15 sectoral models, encompassing five broad impacts sectors (water resources, electric power, infrastructure, human health, and ecosystems), were employed in this first phase of CIRA.

As noted above, three internally consistent socioeconomic and climate scenarios were used to estimate the benefits of global GHG mitigation targets: a reference scenario and two policy scenarios (Fig. 1). These socioeconomic scenarios were used by two IA models to explore the effects of model uncertainty in the resulting emissions, concentration, and climate outputs. The resulting GHG emissions data from each of the three scenarios were used as inputs to climate models, which were tuned to four different climate sensitivities for each scenario. Each of the sectoral models used the harmonized socioeconomic and climate data to estimate climate

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[6] Models are built to simulate aspects of the real world, and as such, each may be structured and parameterized differently. It is beyond the scope of this paper to review variability and uncertainty across multiple model types, but model intercomparison exercises such as the Coupled Model Intercomparison Project 5 (Taylor et al. 2012), Inter-Sectoral Impact Modeling Intercomparison Project (Warszawski et al. 2014), and the Energy Modeling Forum exercises (emf.stanford.edu) have and will continue to provide insights about the relative importance of uncertainty sources.

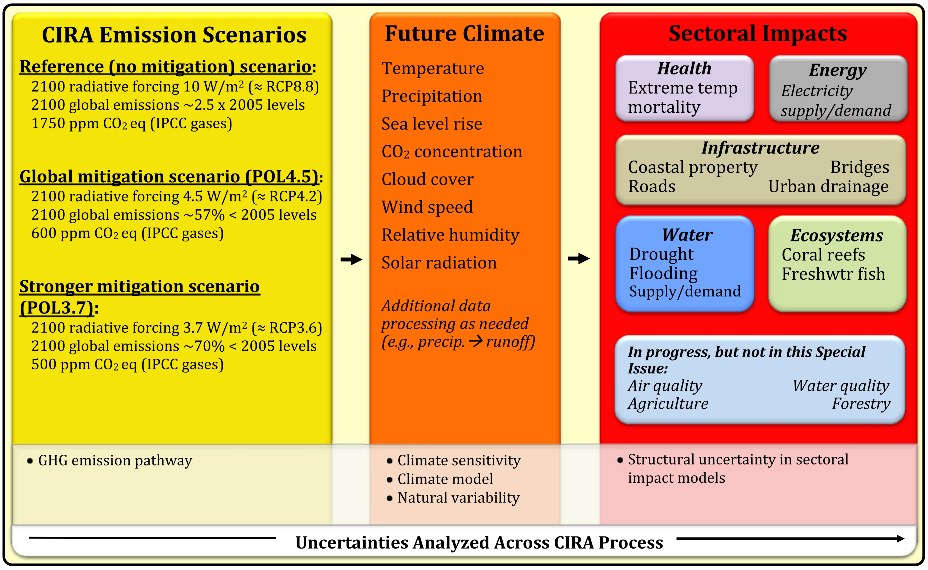

Fig. 1 The flow of inputs and outputs in the three main phases of the CIRA framework: emission and socioeconomic scenario development, climate projection, and impacts and benefits estimation

change impacts and the benefits of GHG mitigation. The flow from IA emission scenarios to climate models to sectoral impact models is currently one directional in the project, i.e., climate change does not affect the original emission scenarios and damages in the sectoral models do not affect emissions or the degree of climate change itself.

3.2 Emission scenarios

The second paper of this Special Issue (Paltsev et al. 2013) describes the generation of the CIRA socioeconomic and emission scenarios. The Massachusetts Institute of Technology's Joint Program on the Science and Policy of Global Change produced the CIRA scenarios for population, GDP, emissions, concentrations, and a number of climate metrics using the Integrated Global System Model (IGSM) framework, an IA model that couples a human activity model with an earth system model of intermediate complexity. Three consistent socioeconomic and emission projections form the base scenarios analyzed across the sectoral impact models: a reference (REF) with no explicit climate policy (total radiative forcing (RF) of 10.0 W/m^2 at the end of the century),[7] a policy scenario that achieves a RF target of 4.5 W/m^2 in 2100 (POL 4.5), and a more stringent policy scenario that stabilizes RF at

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[7] Under the REF scenario, the global mean surface air temperature anomaly in 2100 compared to the 1980–2009 baseline is slightly larger than 5 °C. The CIRA REF scenario has a higher RF and global temperature anomaly in 2100 compared to representative concentration pathway (RCP) 8.5 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 RF 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 RF is: 8.8 W/m^2 for the REF; 4.2 W/m^2 for the Policy 4.5 scenario; and 3.6 W/m^2 for the Policy 3.7 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.

3.7 W/m^2 in 2100 (POL 3.7). The differences in the damages between the REF and policy scenarios are interpreted as the benefits of the policy.

The human activity component of the IGSM, the Emissions Predictions and Policy Analysis (EPPA) model, was harmonized with the gross domestic product (GDP) and population projections from the US Energy Information Administration's Annual Energy Outlook (US Energy Information Administration 2011) through 2035 to produce the REF scenario. By 2100, the US population under the REF reaches 514 million, US GDP per capita is (2005)$144,000, and global atmospheric CO_2 concentrations reach 830 ppm.[8]

Global climate change metrics, such as atmospheric GHG concentrations and temperature change, were generated within the IGSM framework and can be viewed in Table OR-1 of Online Resource 1. In order to explore a range of potential climate outcomes for each of the three scenarios, the IGSM was tuned to four different equilibrium climate sensitivities 2.0, 3.0, 4.5, and 6.0 °C – to represent uncertainty around the physical response of the climate system to RF changes. The 12 resulting simulations form the core scenarios for the exploration of uncertainty in the CIRA project. Figure OR-1 of Online Resource 1 shows the temperature trajectories for these scenarios, with comparisons to the IPCC RCP and SRES scenarios.

To gain insight into differences in emissions and climate that may result from different model structures, another IA model, the Global Change Assessment Model (GCAM) developed at the Pacific Northwest National Laboratory's Joint Global Change Research Institute, was harmonized with the REF population and GDP outputs from EPPA. To harmonize the two GHG mitigation scenarios, the IA models were constrained to achieve the same RF targets. Harmonizing specific inputs for the two models allows a clearer comparison of the differences in estimates of projected emissions, concentrations, and climate that can arise due to model structural uncertainty, rather than underlying baseline scenarios (see Table OR-1 of Online Resource 1).[9] Using GCAM to analyze these 12 core scenarios, the third paper of this Special Issue (Calvin et al. 2014) focuses on the interactions between climate sensitivity, carbon cycle sensitivity, and the level of emissions mitigation effort required to meet the defined RF targets (POL 4.5 and POL 3.7). The paper explores the effect of the capacity of the terrestrial system to store carbon on the cost of achieving RF targets. They find that the carbon price required to meet a radiative forcing target is greater at higher climate sensitivities, due to the reduced the ability of the terrestrial system to store carbon at the higher temperatures and the resulting increase in CO_2 concentrations for a given level of emissions. They conclude that a higher sensitivity simultaneously raises both the cost of mitigation and the expected temperature change for a given RF target.

3.3 Projecting future climate

The fourth paper of this Special Issue presents the CIRA approach for projecting future regional climate change, and assesses the relative importance of several sources of uncertainty

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[8] Population projections do not change across the reference and policy scenarios. However, the integrated structure of the IGSM captures the economic costs of the climate policies, though not the economic damages associated with climate change impacts (thus economic growth is not affected by the level of damages associated with different climate sensitivities). Economic growth is therefore slightly lower in the policy scenarios than in the REF. In 2050, US GDP/cap for the REF, POL 4.5, and POL 3.7 are (in 2005 dollars) $86,000, $80,000, and $78,000, respectively.

[9] IA models are parameterized over many input assumptions (e.g. labor productivity, technological development, emissions factors). In CIRA only the population and GDP inputs have been harmonized so differences in outputs should not be interpreted as resulting only from different model structures.

pertinent to climate change impacts analyses (Monier et al. 2014). Regional climate projections are obtained through a two-pronged method. First, the authors use the IGSM-CAM framework (Monier et al. 2013), which links the IGSM to the NCAR Community Atmospheric Model (CAM), providing a dynamical downscaling of the IGSM climate projections. The climate sensitivity in CAM is changed through a cloud radiative adjustment method described in Sokolov and Monier (2012). Each of the 12 core scenarios is run with five different initial conditions of the GCM to assess the uncertainties associated with natural variability. Secondly, the authors use a pattern-scaling method (Schlosser et al. 2013) to statistically downscale the IGSM climate projections and thus assess the structural uncertainty associated with the regional patterns of change of different general circulation models (GCM). The pattern scaling method is applied to the 12 core scenarios with the patterns of three IPCC AR4 climate models along with the IPCC AR4 multi-model ensemble mean. [10] The pattern scaling method generally enables the development of projections that are consistent with climate conditions from different GCMs without undertaking computationally expensive model runs, while also maintaining consistency of climate sensitivity with the original IGSM model. [11]

3.4 Estimating impacts across sectors

The impact sectors presented in this Special Issue include water resources, electricity demand and supply, infrastructure, mortality from extreme temperatures, and ecosystems. Table 1 describes the contents of the sixth through eleventh[12] papers of this Special Issue, which present impact and damage estimates for the CIRA emission scenarios using 15 different sectoral models. The sectoral impacts analyzed in the papers of this Special Issue were chosen based on the following criteria: the existence of sufficient data to support the methodologies; availability of modeling applications that could be applied in the CIRA framework; sufficient understanding of the impact of climate change to support the modeling; and the economic or iconic significance of impacts and damages in the sector to the US. Although many important climate change impacts are not covered in this Special Issue, the coverage of sectoral impacts will expand and deepen in future work within the CIRA project.[13]

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[10] Analyzing the large number of simulations produced by the full combination of uncertainty parameters in the sectoral models would be unwieldy for many of the sectoral impacts models in terms of the effort necessary to run all of these scenarios (IGSM-CAM: 3 scenarios X 4 sensitivities X 5 initializing conditions=60 scenarios; IGSM-pattern scaling: 3 scenarios X 4 sensitivities X 4 patterns=48 scenarios). For this reason, a subset of runs was chosen to ensure that all models presented in this Special Issue include a core group of simulations. This base set includes the REF scenario at climate sensitivities of 3.0° and 6.0 °C (chosen to inform both on the "most likely" climate sensitivities and questions related to risks of higher than expected levels of climate change), and the POL 4.5 and POL 3.7 scenarios at a climate sensitivity of 3.0 °C, all for the first IGSM-CAM initializing condition.

[11] Given the importance of climate model uncertainty, the use of results from multiple GCMs was considered for this exercise. However, it was decided to focus on the results from IGSM-CAM primarily because the use of MIT's IGSM framework enables development of climate projections that are consistent with the socioeconomic and emissions scenarios, and the exploration of a number of key sources of uncertainty beyond what would be available in GCM archives. To address variability and structural uncertainty across climate models, simplified representations of GCM patterns were employed.

[12] The fifth paper of this Special Issue, Monier and Gao (2014), estimates changes in climate extremes in the US, and is described in Section 5 of this paper.

[13] At the time of publication of this overview paper, analyses on agriculture, forestry, air quality, water quality, and thermo-electric cooling were underway, but were not completed in time for inclusion in the Special Issue.

Table 1 Description of the sectoral impact models, key impact metrics, and scope of the analyses included in the Special Issue

Impact Sector and Special Issue Paper Reference	Impact Estimated and Model Name (where applicable)	Description of Analysis
Water Resources (Strzepek et al. 2014)	Change in drought risk using several indices of drought.	Estimated for the 99 Assessment Subregions of the Water Resource Regions of the contiguous US.
	Water supply and demand optimization and allocation	Spatial-equilibrium simulation of the water balance for each of the 99 Assessment Subregions, with results aggregated to the Water Resource Regions of the contiguous US.
	Change in domestic water scarcity in the Global Change Assessment Model (GCAM)	Estimation of water scarcity index based on major water demand components for each of the Water Resource Regions of the contiguous US.
	Precipitation-based flooding damages	Inland damages calculated for the Water Resource Regions of the contiguous US.
Electric Power Sector (McFarland et al., Submitted for publication in this special issue)	Change in electricity demand and supply using the Integrated Planning Model (IPM), the state-level GCAM model (GCAM-USA), and the Regional Energy Deployment System (ReEDS)	Estimation of changes in electricity demand, supply mix, and system costs from ambient air temperature changes for the contiguous US with results aggregated to six regions.
Infrastructure (Neumann et al. 2014)	Property loss and property protection expenditures using the National Coastal Property Model (NCPM)	Sea level rise risks to coastal development, in terms of costs associated with lost property or protection measures, are estimated for the contiguous US.
	Vulnerable road infrastructure, with repair costs	Includes temperature and precipitation effects on paved (rutting & cracking damages) and unpaved (erosion) roads, and assumes that adaptation measures (e.g., resealing, regrading) will be implemented to maintain the current level of service.
	Bridges vulnerable to flooding, with retrofit costs (proactive and reactive to vulnerability)	Estimates change in maximum daily precipitation and peak flow for 100-year flood. Results include both numbers of bridges affected in the contiguous US and the incremental climate-driven maintenance costs. Does not include damages due to storm surge.
	Urban storm water capacity exceedance and cost estimation of management response measures	Based on modeling in 19 major US cities of changes in the 10-year, 24-h storm, consistent with the design criteria for most urban drainage infrastructure.
Human Health (Mills et al.2014b)	Extreme temperature mortality	Based on modeling of extreme heat and cold mortality in 33 US cities.
Ecosystems (Lane et al. 2014, Mills et al. 2014a)	Change in coral reef cover using the Coral Mortality and Bleaching Output (COMBO) model, with recreation use valuation	Coral reefs in S. Florida, Puerto Rico, and Hawaii are analyzed.

Table 1 (continued)

Impact Sector and Special Issue Paper Reference	Impact Estimated and Model Name (where applicable)	Description of Analysis
	Change in suitable habitat for freshwater fish, with impacts to recreational fishing	Estimates thermal and precipitation based changes in suitable habitat for cold, warm, and rough fish species types. Economic estimates are based on freshwater recreational fishing days.
	Wildfire incidence and suppression costs using the MC1 Dynamic Global Vegetation Model	Estimated for the contiguous US at 0.5° × 0.5° resolution and aggregated to the USFS Geographic Area Coordination Center fire regions.
	Terrestrial carbon sequestration using the MC1 Dynamic Global Vegetation Model, with valuation using the social cost of carbon	Estimated for the contiguous US at 0.5° × 0.5° resolution and aggregated to the USFS Geographic Area Coordination Center fire regions.

4 CIRA within the context of existing impacts analyses

A large body of research has examined climate change impacts over many regions, though fewer studies provide direct quantification and valuation of damages, and even fewer efforts examine multiple impact sectors in a consistent framework. The methods of a select group of studies that have quantified physical and/or economic impacts of climate change at various spatial and temporal scales are summarized in Table 2 in order to place the CIRA project in the context of the wider body of impacts research. This table summarizes the unique features, analytic approach, and coverage for each of these prior analyses.

Previous work has analyzed climate change impacts at a global scale (Arnell et al. 2013; Warszawski et al. 2014), in the US (Mendelsohn and Neumann 1999; Frumhoff et al. 2007; Jorgenson et al. 2004), for individual US regions (Hayhoe et al. 2004), or in other world regions (Ciscar et al. 2011). In general, most of these efforts have not been developed for the purpose of examining the difference in climate change damages between no-policy and policy scenarios, nor the uncertainties around these estimates. The CIRA project was designed to address the specific challenges described in Section 2 and offers the following advancements in one framework, whereas previous effort may have only achieved a subset of these: 1) the use of scenarios with consistent socioeconomic drivers that enable the quantification of the benefits of GHG mitigation; 2) the exploration of multiple sources of uncertainty in the analytical chain; 3) highly-detailed, bottom-up modeling of sectoral impacts with a spatial and temporal richness to effectively communicate risk; 4) the disaggregation of separate impacts within a single sector to provide a diversity of information (e.g., analyzing drought, flood, and water supply/demand impacts within the water sector); and 5) estimating the economic value of impacts in addition to quantifying physical effects.

5 Key findings across sectors and synthesis of results

Looking across the results of the sectoral impacts analyses presented in this Special Issue, several common themes emerge. These themes are briefly discussed here, with specific findings described in Table 3 and the papers of this Issue. Caution should be taken when interpreting Table 3, as the monetized estimates should not be aggregated to represent a total

Table 2 Comparison of selected multi-sectoral climate change impacts studies

Study	Socioeconomic and Emission Scenarios	Analytical Approach			Coverage				
		Climate Models	Static/ Dynamic*	Top down/ bottom up	Uncertainties analyzed	Spatial	Temporal	Sectoral	Physical/ Economic
Mendelsohn and Neumann (1999)	Incremental increases in temperature, precipitation, and sea level	A few GCMs used in a subset of the sectors	Dynamic	Bottom up	Climate sensitivity, climate model	United States	2060, with additional years for some sectors	Seven sectors: agriculture, forestry, water, coastal development, energy, commercial fishing, outdoor recreation	Physical impacts and economic damages
Hayhoe et al. (2004)	SRES A1FI SRES B1	Two climate models	Static	Bottom up	Climate model	California	2035 and 2085	Four sectors: heat mortality, alpine/ subalpine forest cover, snowpack, streamflow	Physical impacts
Jorgenson et al. (2004)	Incremental increases in temperature, precipitation, and sea level	Ensemble of 15 model patterns	Dynamic	Top down based on response functions	Climate model pattern	United States	Annual time steps through 2100	Agriculture, forestry, electricity demand, water supply, coastal property, labor supply	Economic damages
Frumhoff et al. (2007)	SRES A1FI SRES B1	Ensemble of three climate models	Static	Bottom up	Climate model	United States	30 year averages centered on 2025, 2055, and 2085	Coastal impacts, forestry, agriculture, winter recreation, human health	Physical impacts
			Static	Bottom up			2020s and 2080s		

Table 2 (continued)

Study	Socioeconomic and Emission Scenarios	Analytical Approach			Coverage				
		Climate Models	Static/ Dynamic*	Top down/ bottom up	Uncertainties analyzed	Spatial	Temporal	Sectoral	Physical/ Economic
Ciscar et al. (2011)	SRES A2 SRES B2	One global and two regional climate models			Sectoral-level uncertainties modeled	European Union		Five sectors plus CGE model of the economy	Physical impacts and economic damages
Arnell et al. (2013)	SRES A1FI, and SRES A1B with four emissions pathways combining peak in 2016 or 2030 with reductions of 2 or 5 %/year	Pattern scaling for seven GCMs	Dynamic in some sectors	Bottom up	Emissions, climate model	Global	2030, 2050, 2080 and 2100	Six sectors: water stress, drought in cropland, river flooding, crop suitablity/yield, coastal flooding, energy demand	Physical impacts
Warszawski et al. (2014)	4 RCPs with SSP2	Five climate models from the CMIP5 archive	Dynamic	Bottom up	Emissions, climate model, structural uncertainty in sectoral models	Global, with key regional areas of analysis	Varies by sectoral analysis	Agriculture, water, biomes, health (malaria), coastal infrastructure	Physical impacts with economic damages for some sectors
Ciscar et al. (2014)	A1B, E1 and RCP8.5, along with a 2 °C stabilization scenario	Combination of global and regional climate models	Static	Bottom up	Emissions, climate model, sectoral-level uncertainties	European Union	2020s and 2080s, with some sectors reporting at additional timesteps	Ten sectors, plus CGE model of the economy	Physical impacts and economic damages

Table 2 (continued)

Study	Socioeconomic and Emission Scenarios	Analytical Approach			Coverage				
		Climate Models	Static/ Dynamic*	Top down/ bottom up	Uncertainties analyzed	Spatial	Temporal	Sectoral	Physical/ Economic
CIRA, as described in this Special Issue	CIRA Reference and radiative forcing targets in 2100 of 4.5 W/m^2 and 3.7 W/m^2	One GCM, plus scaling of 17 model patterns	Dynamic	Bottom up	Emissions, mitigation effort, climate sensitivity, climate model, natural variability, structural uncertainty in sectoral models	United States	Varies by sectoral model - some annual, others at key time steps (e.g., 2050, 2100)	Five sectors (water resources, infrastructure, energy, human health, ecosystems) with subsector impacts (e.g., drought, floods)	Physical impacts and economic damages

* Refers to the whether impacts are estimated in a future where socioeconomic variables are changing over time.

Table 3 Synthesis of sectoral impact results, physical and monetary benefits of GHG mitigation (REF-POL3.7), in 2050 and 2100

Sector and Special Issue Paper Reference	Impact	Benefits of GHG Mitigation (POL 3.7 – REF)*				Notes †^
		2050		2100		
		Physical	Monetary † (2005)$B	Physical	Monetary † (2005)$B	
Water Resources (Strzepek et al. 2014)	Drought risk	35 % less severe droughts	Not estimated	44 % less severe droughts	Not estimated	Effect of mitigation on percentage occurrence of severe Palmer Drought Severity Index droughts over 30-year era centered on 2050 or 2100.
	Water supply and demand	NA	3.3	NA	9.4	Hydro-economic, spatial equilibrium simulation of primary water uses, including irrigation, municipal & domestic, commercial & industrial, hydropower, and maintenance of minimum flows.
	Water scarcity	Reduction in scarcity index of 5 %	Not estimated	Increase in scarcity index of 12 %	Not estimated	Numbers represent changes in US Water Scarcity Index, defined as ratio of total water demand to total amount of runoff in each basin, from the 2005 base using runoff-weighted average of in-basin changes.
	Flooding damages	NA	0.2	NA	2.5	Changes in flooding damages based on econometric analysis; therefore no physical metrics were estimated.
		% Reduction in demand	Reduction in system cost			System costs include capital, operations and maintenance, and fuel, and only refer to the supply-side costs.
Electric Power Sector ‡ (McFarland et al., Submitted for publication in this special issue)	Electricity demand & supply	4.0	29.3	NA	Not estimated	Estimated in IPM. Cumulative benefits from 2015–2050 are $141B.
		1.1	8.7	NA	Not estimated	Estimated in GCAM-USA. Cumulative benefits from 2015–2050 are $51B.
		1.4	12.8	NA	Not estimated	Estimated in ReEDS. Cumulative benefits from 2015–2050 are $147B.
	Coastal development	200 fewer ha. of inundated land	1.0	15,000 fewer ha. of inundated land	10	Physical effect based on 20-year avg. of area at risk (2031–2050 for 2050 and 2081–2100 for 2100). SLR estimates include dynamic ice sheet melting. Storm surge impacts not included. Cumulative benefits through 2100 are $6B.

Table 3 (continued)

Sector and Special Issue Paper Reference	Impact	Benefits of GHG Mitigation (POL 3.7 – REF)*				Notes †^
		2050		2100		
		Physical	Monetary † (2005)$B	Physical	Monetary † (2005)$B	
Infrastructure (Neumann et al. 2014)	Roads	1.4 % reduction in maint. costs	2.0	4.5 % reduction in maint. costs	6.0	Estimates represent road maintenance costs to maintain current level of service. Cumulative benefits through 2100 are $44B.
	Bridges	1,000 fewer bridges	0.4	2,200 fewer bridges	0.1	Physical change represents # of fewer bridges at risk of peak flow damage. Economic estimates for repair in advance of damage calculated using avg. of costs prior to that date. Cumulative benefits through 2100 are $33B.
	Urban drainage infrastructure	4.3 % less capacity exceedance	0.3	10.3 % less capacity exceedance	0.6	Based on modeling of 19 large US cities. Physical change represents weighted avg. capacity exceedance avoided relative to baseline capacity, using baseline capacity as weights. Economic estimates represent costs of water management measures.
Human Health (Mills et al. 2014b)	Extreme temp. mortality	2,000 fewer deaths	22	11,800 fewer deaths	170	Based on modeling of 33 MSAs accounting for about 1/3rd of US population. An analogue city approach reduces 2100 benefits to 4,000 fewer deaths. A VSL of (2005)$8.87 million for 2010 is used, adjusted to 2100 by assuming an elasticity of VSL to GDP per capita of 0.4.
	Coral reefs	Avoided loss of 45 % of initial percent Hawaiian coral cover	1.3	Avoided loss of 38 % of initial percent Hawaiian coral cover	1.1	Coral cover change calculated by subtracting target (2050 or 2100) year value under each scenario from initial avg. HI coral cover starting value of 38.4 %. Recreational values, for reefs in FL, Puerto Rico, and HI, represent average of 2045–2055 for 2050 and 2090–2100 for 2100. Cumulative benefits (three regions) through 2100 are $19.1B.

Table 3 (continued)

Sector and Special Issue Paper Reference	Impact	Benefits of GHG Mitigation (POL 3.7 – REF)*				Notes †^
		2050		2100		
		Physical	Monetary † (2005)$B	Physical	Monetary † (2005)$B	
Ecosystems (Lane et al. 2014, Mills et al. 2014a)	Freshwater fish	67,000 fewer ha. of coldwater fish habitat loss	(0.003)	144,000 fewer ha. of coldwater fish habitat loss	0.08	Monetized estimates of recreational value represent all fish guilds, some of which show expansions of suitable habitat in a warmer climate – thus explaining slight disbenefits in 2050.
	Wildfire	891,000 fewer ha. burned	0.1	3.2 million fewer ha. burned	1.2	2050 and 2100 estimates based on avg. of 2045–2054 and 2095–2104 period, respectively. Avg. of 5 initial conditions for each scenario run through the IGSM-CAM. Economic estimates represent suppression costs. Cumulative benefits through 2100 are $9.24B.
	Terrestrial carbon storage	80,000 fewer metric tons of carbon stored	(19)	30,000 fewer metric tons of carbon stored	(11)	2050 and 2100 estimates based on avg. of 2045–2054 and 2095–2104 period, respectively. Avg. of 5 initial conditions in IGSM-CAM per scenario. Monetized using the social cost of carbon. Cumulative benefits through 2100 are ($7.62B).

* POL 3.7 run in the IGSM-CAM with climate sensitivity of 3 °C

† Monetized impacts in 2050 and 2100 are listed in billions of undiscounted $2005 USD. Economic disbenefits are shown in parentheses. Cumulative streams of benefits presented in the Notes column are discounted at 3 %

^ Monetized estimates should not be aggregated, as many important impacts are not estimated here

‡ Consistent with the design of the CIRA project and the other results presented here, these results show the estimated benefits to the electric power sector due to the reduction in demand and systems costs due to the lower temperatures under POL 3.7, compared to the REF. McFarland et al. (Submitted for publication in this special issue) also present an analysis that includes the costs to the electric sector of implementing the policy

benefits estimate. Such a conclusion would be inappropriate for three reasons. First, a large number of important impacts are not included at this time (e.g., impacts on agriculture, air quality), therefore any summed total would be incomplete and an underestimate. Second, the sectoral models report a mix of cost types —ranging from welfare estimates (e.g., recreation loss and other nonmarket sectors) to expenditure accounting (i.e., direct rather than social costs)—that may not be strictly additive. Finally, potential feedbacks and interactions across sectors, such as the effects of drought on electric generating capacity, are not accounted for here, so these values would not reflect the true costs of climate change or benefits from GHG emissions mitigation policies.

5.1 GHG mitigation provides both monetary and risk-reduction benefits

In most sectors, global GHG mitigation prevents or reduces adverse impacts in the US throughout the 21st century compared to the REF. These physical and monetized benefits of GHG mitigation can be seen in Table 3 for the years 2050 and 2100. Note that the monetary impacts of those snapshot years span several orders of magnitude across the sectors. Human health, electric power, and coastal development comprise the sectors with the largest benefits of GHG mitigation, ranging from 10 to almost 200 billion dollars per year. Though some sectoral models estimate only small or moderate benefits from the GHG mitigation scenarios and a few estimate disbenefits in some periods, results like those seen in the health sector (extreme temperature mortality) show large cumulative benefits of GHG mitigation by the end of this century.

Further, Monier and Gao (2014) analyze the incidence of extreme weather events across the US (e.g., extreme hot and cold days and extreme precipitation events) for a range of uncertainties, including policy target, climate sensitivity, and natural variability.[14] They find that GHG mitigation has a larger effect on reducing the incidence of extreme temperature and precipitation events in 2100, compared to the REF, than either climate sensitivity or natural variability. Even for the highest climate sensitivity considered, the GHG mitigation scenarios drastically reduce the increases in extreme weather events through the century.

5.2 Benefits of mitigation increase over time

Due to minimal differences in climate outcomes between the three emissions scenarios before 2040, as described in (Paltsev et al. 2013), the avoided impacts of climate change due to GHG mitigation policies do not show large differences from the REF until mid-century. For example, increasing benefits of GHG mitigation over time are shown in Mills et al. (2014b), where the deaths in 2050 and 2100 from extreme temperature are, respectively, 2,000 and 11,700 fewer under the Policy 3.7 scenario, compared to the REF. This lag in the realization of GHG mitigation benefits suggests that the long-term effects of climate change (i.e., beyond mid-century) can be strongly influenced by near-term policy choices. Due to the time needed for policies to have a strong effect on emissions and the relatively slow response of the climate to changes in emissions, many of the CIRA analyses demonstrate that delaying action will increase significant and costly impacts in the future.

5.3 Adaptation can reduce net overall costs

In addition to estimating impacts, many of the sectoral models in the CIRA framework quantify the economic costs associated with adapting to these changes (see Table OR-2 in Online Resource 1 for

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[14] Natural variability is simulated in IGSM-CAM by altering the initial conditions of the climate model.

additional detail on the treatment of adaptation in each sectoral model and analysis). Although GHG mitigation is estimated to provide benefits across most sectors compared to the REF, results for some sectors also show that there are cost-effective adaptation measures that can substantially reduce impacts under all scenarios, including the REF. For example, results using the National Coastal Property Model (Neumann et al. 2014) indicate that cumulative, discounted (3 %) sea level rise damages to coastal development under the REF scenario with no adaptation are (2005)$1.5 trillion through 2100, with estimates increasing to over $4 trillion when storm surge effects are included. When cost-effective adaptation along the coast is included, total discounted damages under the REF fall to $207 billion ($690 billion including storm surge effects), with the majority of those damages coming from capital and operations/maintenance required to protect development.

5.4 Spatial and temporal scale are important

Given the objectives of the CIRA project to estimate the US benefits of global mitigation, it is important to note that aggregating nation-wide impacts and damages can miss important regional scale impacts, as their importance may be obscured, or even canceled out, when compiled into broader-scale trends. These large regional changes are certainly relevant on a local/regional scale and should thus be presented in addition to national estimates. As an example, Mills et al. (2014a) estimate climate change impacts on all vegetative wildfires in the continental US and find that changes in burned area of the Southeast and Rocky Mountain regions will have very large regional effects, and are, in fact, the primary drivers of national trends.

6 Summary and future directions

The CIRA project establishes a new framework for dynamic analysis of potential climate change impacts and damages in the US. The methodology allows the results to be directly interpreted as the potential benefits to specific sectors of the US associated with global-scale actions to mitigate GHG emissions. The analytical design offers a number of advantages, particularly consistency in the implementation of socioeconomic and climate change scenarios across a wide range of sectoral impact and damage models, analysis of multiple policy targets, and exploration of the changes in the risk of impacts across multiple sources of uncertainty. The results from coordinated impacts analyses like CIRA are important for communicating potential GHG mitigation policy benefits in terms of avoided or reduced risks to human health, welfare, and the environment.

Although the CIRA framework was developed to promote consistency across scenarios and multiple impact sectors, and explore the role of uncertainty in the estimation of the benefits of GHG mitigation, there are limitations to what could be realistically included and meaningfully interpreted. Several of the most important limitations include:

- *Coverage*: Analyses of several important impact sectors (e.g., agriculture, forestry, air quality, water quality) were not completed in time for this Special Issue. Certain impact sectors would also benefit from deeper coverage (e.g., human health effects other than extreme temperature mortality, and water resource constraints on energy systems). Geographic coverage of the US is not complete in every sector analysis (e.g., Alaska and US territories). Finally, it is worth repeating that the CIRA project does not examine impacts and damages occurring outside of US borders, which, aside from their own relevance for policy-making, could in

turn affect the US through, for example, changes in world food production and migration.
- *Interactions*: This first phase of the CIRA project is not designed to explore interactions across impact sectors. Thus, the sectoral modeling results presented in this Special Issue have the potential to miss many important and potentially unforeseen effects.
- *Feedbacks*: Similarly, potential feedbacks from climate change impacts to the climate system (e.g., GHG emissions from forest fires) and from sectoral damages to the economy are not included in these modeling results. The initial approach taken in CIRA is intended to be a first step, modeling a one-way path from the socioeconomics, to the climate, to impacts, with consistent inputs across multiple models.
- *Scenarios*: As mentioned earlier, most of the CIRA sectoral analyses presented in this Special Issue did not run the full suite of 60 IGSM-CAM and 48 IGSM pattern scaling climate scenarios. Completing these additional runs would further characterize the range of future risks. Further, socioeconomic and technology parameters are explored as drivers of future emission scenarios is limited, as only one set of future population and GDP projections and the resulting emissions
- *Climate Projections*: Although a number of important uncertainty sources are explored in the CIRA framework for climate projection, the use of additional GCMs could provide further fidelity to the impacts estimated in the Special Issue.

With full acknowledgement of the importance of these limitations, they are deferred to future work. Potential future research directions under the CIRA project include: 1) the incorporation of additional impacts in the framework; 2) the use of additional RF targets to explore the effect of more marginal reductions in GHGs; and, in the longer-term, 3) exploration of the interactions across sectoral impacts and feedbacks from damages to the broader economy in a general equilibrium economic framework.

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