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State of the literature on the economic impacts of climate change in the United States

Abstract: This paper discusses the current literature on impacts and adaptation costs at the sectoral level. The focus is primarily the US, but includes examples on international applications that highlight key differences or other relevant demonstrations of method and data use. The paper provides an overall framework that addresses the components of economic impacts, including definitions of impacts, adaptation costs, and residual damages. The paper then focuses on understanding the current breadth and depth of the literature that exists to characterize what we know about economic sectors studied in the recent literature (agriculture, coastal resources, water resources, infrastructure, health, crime, energy, labor productivity, and ecosystems), how the methodologies differ, what the gaps and challenges are, and offers a sense of the impacts at the US national level. A new generation of impact studies, including the U.S. EPA's ongoing Climate Impacts and Risk Analysis (CIRA) project; the new Intergovernmental Panel on Climate Change (IPCC) AR5 Working Group II report; the U.S. National Climate Assessment; and the Risky Business Project led by the Next Generation Foundation, provide the motivation for this review. These efforts, taken together, have advanced the state of US economic impact assessment work along two critical frontiers, both of which support benefit-cost analyses of climate change: assessment of the risk and economic consequences of extreme climatic events; and assessment of ecosystem effects. Yet, the latest work also highlights gaps in the lack of comprehensive sectoral coverage; more complete incorporation of adaptation opportunities in impact assessment; and critical cross- and multi-sectoral effects that remain poorly understood.

Keywords: adaptation; climate change; economic impacts; economic sectors.

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1 Introduction

The need for clarity regarding the impacts of climate change and the potential for cost-effective adaptation action has been recently sharpened as the Obama Administration has begun to pursue implementation of the Climate Change Action Plan. Some of the best known aspects of this plan have included increases in vehicle fuel efficiency standards and controls on greenhouse gas (GHG) emissions from new and existing electric power plants (Executive Office of the President, 2013). However, the plan also acknowledges that even aggressive GHG mitigation action will not be sufficient to avoid negative impacts of a changing climate, and notes the need to identify the impacts of climate change on the US economy, and to take adaptation action to lessen those impacts. Information on the economic impacts of climate change and on the costs and benefits of adaptation are essential to understanding the economic benefits of mitigation policies, and to identifying priority sectors for adaptive action. In addition, state and local governments are beginning to use impact and adaptation cost estimates to support climate impact response plans (U.S. Global Change Research Program, 2014), as are some businesses (America's Energy Coast, America's Wetlands Foundation, & Entergy Corporation, 2010; Gordon, 2014).

Despite growing interest in estimates of the economic costs of climate change and the costs and benefits of adaptation, the extent to which this information is available systematically remains limited. For a few sectors, there are multiple lines of evidence supporting many estimates of impacts, but for most sectors, estimates are sparse or of uneven quality (Revesz et al., 2014). Even less is known about adaptation costs (Chambwera et al., 2014; Sussman et al., 2013). The lack of readily accessible estimates, and concerns that the available estimates may cover only a subset of important impact categories, may be why benefit-cost analyses (BCAs) are currently used only rarely to support adaptation planning efforts (Chambwera et al., 2014).

Two new efforts have been launched to examine economic impacts at the sector level, to assess the extent to which adaptive action can reduce impacts, and to inform policy on the potentially largest, most immediate, and most uncertain economic impacts: 1) A series of papers that have emerged from the U.S. EPA's Climate Impacts and Risk Analysis (CIRA) program; and 2) the "Risky Business: The Economic Risks of Climate Change in the US" report, which assesses US economic impacts of climate change (with a focus audience of business leaders) and was developed by a group of academics and consulting firms coordinated by Next Generation, a nonprofit organization (Gordon, 2014).

This paper discusses the results of these two efforts in the context of the broader body of literature on the economic impacts of climate change. The

CIRA program is ongoing but includes several sectoral analysis results that have already been published as part of a special issue of *Climatic Change*. The CIRA research and analysis program includes a focus on improving existing sectoral economic studies, while also adding new primary literature to improve sectoral coverage of impacts, consistent with the overall goal of providing insights on the economic benefits of GHG mitigation policies in reducing impacts, in a consistent and comprehensive way for the nation as a whole.

The Risky Business Project is also focused on the US, but interprets rather than adds to the primary literature on impacts. The main focus of the work is to develop sectoral damage functions to apply in a risk-based framework to assess the costs of inaction in a business-as-usual GHG scenario; i.e., the originators of the Risky Business Project attempt to provide a probabilistic picture of economic impacts, reflecting the business risk analysis paradigm that ought to be familiar to business leaders. Notably, the Risky Business team puts sectoral estimates into a welfare economic framework that is built around a computable general equilibrium (CGE) assessment of the US economy – a currently incomplete component of the authors' work (but with the potential, as the literature progresses, to ultimately provide estimates of the welfare costs of climate change for the US, at least within the market impacts realm). Both efforts provide the first national quantitative estimates of economic impacts for some sectors, with CIRA doing so as a result of new primary literature, and the Risky Business Project doing so by interpreting sub-national scale literature for application in its national framework.

This paper focuses on national-scale estimates, and excludes results from individual studies, even those at a national scale, that are not part of the broader CIRA and Risky Business initiatives. The intent is not to provide a complete synthesis of all of the literature on economic impacts in the US. Rather, this paper focuses on enhancing understanding of the most important sectoral effects in the US, which is best accomplished by reviewing and comparing sectoral results from within programs that have a common analytic framework and climate scenario specification.

The literature on economic impacts continues to grow, and there are significant new studies that are not covered here. Some of these studies provide important insights. For example, a recent US Department of Agriculture study addresses heat stress effects on dairy production (looking at this effect in more detail than prior studies) and assesses national economic implications, including effects on prices (Key, Sneeringer, & Marquardt, 2014). As discussed later, this category of effects is sometimes excluded from agriculture sector studies; the inclusion of these effects combined with a welfare economic framework that explicitly estimates partial equilibrium consumer and producer surplus effects, makes this an important new study. Nonetheless, a good argument can be made that the CIRA or Risky Business initiatives at least partially reflect this effect. As noted above by providing a consistent framework applied across multiple sectors, these initiatives also have potential to generate meaningful general equilibrium estimates of economic impact.

The need to update the type of review presented in this paper on an ongoing basis is already clear; for example, the National Center for Atmospheric Research recently embarked on a new program to estimate the Benefits of Reducing Anthropogenic Climate Change (BRACE),[1] which when completed will undoubtedly merit consideration alongside the work reviewed here. Nonetheless, the near simultaneous release of the results of these two broad, multi-sector efforts provides an important opportunity to comment on the overall state of the literature, and offers direction for further research that is needed to improve comprehensiveness and critically important estimates of meaningful multi-sectoral and secondary effects of climate change on the US economy.

The paper begins by providing a framework for considering impacts and adaptation potential, derived primarily from an IPCC chapter on the economics of adaptation. The framework is designed mostly to help readers less familiar with climate change economic impact methodology better interpret the review that follows. The main body of the paper provides a review and summary of economic impact and adaptation results by sector for the US, and the paper concludes with discussion of the three key gaps and challenges for researchers to provide a more comprehensive picture of economic impacts and adaptation costs for the US.

2 A framework for understanding impact and adaptation assessment

A basic framework for defining the economic impacts of climate change, adaptation, and residual impacts derives from IPCC work. The term "impacts" represents the effects of climate change on natural and human systems. Depending on the consideration of adaptation, we can also distinguish between potential impacts and residual impacts – the former are all impacts that may occur as a result of a projected change in climate, without considering adaptation, and the latter are impacts of climate change that might persist after adaptation takes place.

Adaptation must also be clearly defined. According to IPCC, adaptation is an adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.

1 See https://chsp.ucar.edu/brace

Types of adaptation include anticipatory, autonomous, and planned adaptation – defined respectively as adaptation that takes place before impacts of climate change are observed (or proactive adaptation); adaptation that does not constitute a conscious response to climatic stimuli but is triggered by ecological changes in human systems (or spontaneous adaptation); and adaptation that is the result of a deliberate policy decision, based on an awareness that conditions have changed or are about to change and that action is required to return to, maintain, or achieve a desired state (see appendix I: glossary in IPCC, 2007).

The relationship between potential economic impacts of climate change, adaptation cost, and residual impacts also belies an economic logic, as described in the IPCC AR5 WGII chapter on the Economics of Adaptation (2014, Chambwera et al. 2014). Figure 1 reproduces figure 17.2 from that chapter. On the vertical axis of both panels is the impact of climate change – at the top of the vertical axis is the expected potential impact for a particular sector and locale. The horizontal axis shows the cost of adaptation. The curve therefore represents the tradeoff between investment in adaptation and tolerance of climate impacts. The left panel illustrates a situation where adaptation could be fully effective in relieving impacts – but also illustrates a theoretical optimal balance between these alternatives which takes advantage of the relatively cost-effective adaptation possible in the steep part of the curve to the upper left, while avoiding the relatively expensive adaptation in the shallow part of the curve. The result is a reduction in potential impacts (shown in light blue on the vertical axis), and residual impacts that could be deemed too expensive to address (shown in red on the left axis).

The right panel of Figure 1 illustrates a more nuanced and perhaps realistic situation, where technological limits are a constraint in fully adapting to climate change – this circumstance lifts the tradeoff curve above the horizontal axis, suggesting that residual impacts are a function not only of choices made to achieve cost effectiveness, but also technological limits. As the graphic illustrates, it is also quite possible that “what we will do” in adaptation space is further constrained by such factors as implementation difficulties. The point is that several factors are likely to contribute to constrained adaptation, adding to the uncertainty of an impacts calculation that incorporates adaptation (since we are not sure what ultimately will be done to adapt). As a result, it remains useful to provide policy makers not only estimates of adaptation costs, but also of the costs of impacts, and the assumed or estimated relationship between the two. These concepts are referred to below in each of the sector-specific summaries in the next section of the paper.

As noted by several authors, the literature currently does not reflect an accepted set of methodological tenets for impact and adaptation studies (Chambwera et al., 2014; Revesz et al., 2014). If the state of adaptation and impact

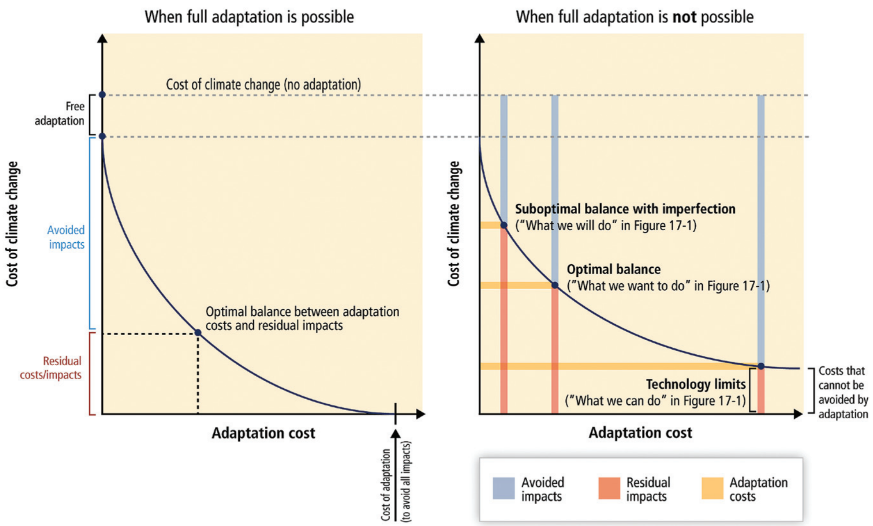

Figure 1 Framework for optimizing the balance between economic impacts of climate change, cost of adaptation, and residual impacts.
Graphical representation of link between the cost of adaptation (on the x-axis) and the impacts and residual impacts climate change (on the y-axis). The left panel represents a case where full adaptation is possible, while the right panel represents a case in which there are unavoidable residual costs. The top of the graphic shows that some adaptations are costless. The right panel, at the bottom, conveys the concept of unavoidable residual impacts, which result from the technological limits of adaptation. Other limits of adaptation result from economic concerns (the "optimal balance" reflects a balance of costs and benefits of adaptation), and from failure to learn or poor information (the "suboptimal balance"). Most studies reviewed in this paper consider the full costs of climate, absent adaptation. Some econometric studies consider autonomous adaptation as reflected in historical climate adaptations, which may or may not be free. A few simulation studies (e.g., Neumann, Hudgens, Herter, & Martinich, 2010) assess optimal adaptation as well use a benefit-cost framework that balances impacts with the costs and benefits of adaptations.
Source: Chambwera et al. (2014, figure 17.2).

science were further advanced, it might be possible to develop a tradeoff curve such as that illustrated in Figure 1, or a marginal cost of adaptation step function might be developed for each sector and locale, akin to the marginal abatement cost curves for mitigation policy (McKinsey & Company, 2009). This review does highlight some instances where marginal adaptation cost curves have been developed and/or incorporated in modeling impacts and adaptation tradeoffs, mainly in the coastal and agricultural sectors (e.g., see Ahouissoussi, Neumann, & Srivastava, 2014; Neumann et al. 2010 for coastal; Sutton, Srivastava, & Neumann, 2013 for agriculture). IPCC WGII (2014) has made a recent attempt to lay out some elementary best practices, identifying four principles that characterize the best impact/adaptation studies (see Text Box 1) but more is needed in this area to establish further a benchmark for the execution of these studies.

Finally, in reviewing recent literature that informs our understanding of impacts and adaptation costs in the US, it is important to distinguish between two broad classes of economic applications: 1) Studies and methods designed to inform an adaptation planner's decision-making, and 2) studies and methods designed to inform a GHG emissions mitigation regulator's point of view. These contrasting viewpoints have been also characterized as "bottom-up" and "top-down" approaches (Agrawala, Bosello, Carraro, de Cian, & Lanzi, 2011),

Text Box 1 Desirable characteristics of impact/adaptation studies.

The IPCC Working Group II report includes a chapter called Economics of Adaptation, which includes a statement of desirable characteristics of adaptation studies that incorporate economic analysis (Chambwera et al., 2014). The four characteristics identified in the chapter are:

- A broad representation of climate stressors, including both gradual change and extreme events, spanning multiple future outcomes (e.g., a range of individual climate model forecasts and GHG emissions scenarios). Consideration of multiple outcomes reflects forecasting uncertainty and can help to ensure the adaptation rankings that result from the analysis are robust across a range of future outcomes (Agrawala et al., 2011; Lempert & Kalra, 2009).
- Representation of a wide variety of alternative adaptation responses (e.g., in the agriculture sector, consideration of changes in crop varieties and farmer education to ensure the varieties are grown with the best available know-how). Depending on the context, a single adaptation response with variation in dimension may be useful (e.g., varying the height of a levee or the capacity of a dam spillway) (Fankhauser, 2010; Fankhauser et al., 1999; World Bank, 2010).
- Rigorous economic analysis of costs and benefits, which ideally includes consideration of market, nonmarket, and socially contingent implications (Watkiss, 2011); one-time and replacement capital and ongoing recurring costs; and costs of residual damages after an adaptation response is implemented (World Bank, 2010).
- A strong focus on adaptation decision making, including a clear exposition of the form of adaptation decision making that is implied in the study, and consideration of both climate and non-climate sources of uncertainty (Lempert et al., 2006).

While these characteristics are focused on adaptation studies, the principles apply equally well to impact studies For impact studies, however, the following additional characteristic might also be specified: Transparent estimation of a no-climate-change baseline, which reflects uncertainty in socioeconomic parameters, and a with-climate-change, no-adaptation impacts scenario to clarify the "risks of inaction" in response to climate stressors. The established baseline should reflect market, nonmarket, and socially contingent effects where possible.

Source: Chambwera et al. (2014).

although it is also important to identify that the difference in perspective of the two types of studies subtly changes the nature of the economic problem to be solved as well. The adaptation planner is the perspective established in Figure 1 – the problem faced is choosing a specific adaptation program that best balances the tradeoff between the costs of adapting and the costs of inaction (i.e., climate damages or potential impacts). The mitigation planner is interested in a different tradeoff: between the costs of taking GHG emissions mitigation action and the benefits of avoiding climate change. The levels of adaptation assumed or modeled as optimal, however, are also relevant to the mitigation planner because adaptation and mitigation represent the portfolio of responses to climate change, each of which entails economic costs. The current consensus reflects a need to take both adaptation and mitigation action, suggesting that sectoral economic impact analyses designed to inform mitigation policy might most usefully provide at least two types of estimates, one that reflects no adaptation action (the pure risks of inaction), and one that reflects cost-effective adaptation (with the costs of such adaptation actions also reflected as part of damages). This is an important characteristic of the studies reviewed below; unfortunately few studies currently provide such a rich set of results to support mitigation policy.

3 Review of sectoral impact and adaptation estimates

The general conceptual framework for impacts and adaptation established in the prior section applies to the review of sectoral impact and adaptation estimates presented in this section. With some exceptions for selected sectors, the CIRA and Risky Business estimates reviewed below both provide estimates of impacts of a business-as-usual, no-GHG-reduction scenario for the continental US, absent planned adaptation but incorporating reactive, autonomous adaptation. In other words, they include adaptive actions that are likely to be taken in response to climate change as it unfolds, but exclude adaptation that would require active planning and investment, such as new infrastructure or changes in the location of economic activity. The two efforts assess impacts in different ways, however, which are largely reflected in the CIRA effort's greater emphasis on simulation modeling of impacts, and the Risky Business Project's emphasis on econometric estimates.

Differences between econometric and simulation approaches are best explained through examples for agriculture sector impact analyses. Econometric studies generally examine the link between climate variables and physical or economic output based on historical cross-sectional, time series, or panel data to infer the effects of climate across space or time. Within the econometric category, there are Ricardian studies (which relate to land values, or to profitability, (e.g., Deschênes & Greenstone, 2007; Mendelsohn, Nordhaus, & Shaw, 1994) and more generic correlational approaches (e.g., Schlenker, Hanemann, & Fisher, 2005) that link temperature and precipitation to agricultural crop yields. The key advantage of an econometric approach is reliance on real-world data; the econometric approach does not require the analyst to simulate all impact and adaptation mechanisms, only to establish that there is a robust relationship between a climate stressor and the outcome of interest. The key disadvantage is that the statistical estimation can be challenging and sometimes subject to multiple interpretations (Schlenker et al., 2005).

The simulation approach traces costs and benefits of adaptation strategies through mechanisms of interest, something not possible with an econometric approach, typically through a series of climate, biophysical, behavioral response, and economic components. In the agricultural context, these are typically crop yield models, coupled with economic simulations of the US economy (see the suite of agricultural studies in Mendelsohn & Neumann, 1999; for an international context simulation model, see Sutton, Srivastava, & Neumann, 2013). The richness of US data supports sophisticated analyses of climate change/climate impact links, as well as the benefit and cost consequences of adaptation choices, and at least theoretically can consider other factors that might influence or constrain options, such as agricultural policies and nonmarket values.

The sectors reviewed reflect those that are believed to be sensitive and potentially vulnerable to climate change, starting from as early as U.S. EPA (1989). These sectors will undoubtedly be expanded over time. For example, the IPCC Working Group II chapter 10 considers effects on manufacturing, mining, tourism and recreation, finance and insurance, and other sectors not addressed here, although some experience climate change impacts only through indirect or secondary effects mechanisms. Further, as pointed out in Sussman, Weaver, and Grambsch (2014), some of the impacts that are compelling to the general public – loss of charismatic species, threats to endangered historical or cultural monuments, displacement of livelihoods and disruptions to ways of life – are the most difficult to estimate, and so little literature exists to estimate the value of these changes. The literature in the US on these other sectors remains relatively thin, a conclusion buttressed by the choices made in the CIRA and Risky Business efforts, which both seek to focus on the sectors most directly affected by climate change, but also more readily quantified.

3.1 Agricultural resources

Probably owing to agriculture's obvious sensitivity to climate, the agriculture sector, including livestock, is among the best studied for climate change impacts. Farmers have been sensitive to and, usually, responsive to climate variability and change for many years. As a result, an assumption of a no-adaptation scenario, reflecting a "myopic farmer" with little capacity for autonomous adaptation, is difficult to justify. A key difficulty in the agriculture sector, however, is the extent to which it is possible to understand the limits of adaptive capacity in the face of fundamental changes in structure of the weather (Schlenker, Roberts, & Lobell, 2013), for example, the likelihood of a higher variability of daily rainfall, where annual precipitation can increase but rainfall comes in a small number of very intense events (Zhang et al., 2007).

Both the CIRA and Risky Business efforts quantify agricultural impacts, CIRA through a simulation approach and Risky Business through an econometric analysis, coupled with an input-output model. CIRA incorporates both crop yield and economic effects, incorporating adaptation at both the farm level (through changes in cropping patterns, timing, and inputs) and at the market level (reflecting a broader optimization of domestic agricultural economic activity to maximize the sum of consumer and producer surplus, with the option of agricultural trade to backstop the dynamic balancing of supply and demand). The CIRA agriculture sector methodology has been established, but the results, unfortunately, remain in process at press time.

The Risky Business initiative authors employ statistical studies that, using econometric techniques, isolate the effect of temperature and rainfall on crop yields (Schlenker & Roberts, 2009). Those results are then linked to a study of adaptation (Burke & Emerick, 2013) that employs a similar econometric approach to measure rates of agricultural adaptation. The result is a crop yield effect, focusing on four major US crops (maize, wheat, oilseeds, and cotton). Risky Business finds that a central case GHG emissions scenario RCP 4.5 results in a median yield penalty of 0.6% in 2020–2039; rising to 0.9% by mid-century and 3.4% by end century (2080–2099). Higher emissions scenarios (RCP 8.5) roughly triple this effect, and increase the yield penalty to 15.3% by end century. The Risky Business analyses incorporate an estimate of carbon fertilization in their main findings, but also explore the impact of this factor – absent carbon fertilization, the median yield penalty for RCP 4.5 increases to 4.1%, 8.4%, and 14.4% for the three 21st-century projection periods, with a corresponding reduction in the probability of a positive effect of climate change on agricultural yields.

These crop yield effects, both direct costs and direct benefits, are valued using an input-output approach based on the IMPLAN model (see Table 1 for

Table 1 Summary of recent US climate change impact economic estimates.

Sector	GHG emissions and adaptation action scenario	CIRA results*	Risky business results**	Comments
Agriculture	Business-as-usual, full adaptation (as reflected in econometric study)	In progress	– 2020 to 2039: –$2.5 to $3.5 billion – 2040 to 2059: –$3.6 to $7.8 billion – 2080 to 2099: –$3.9 to +$24	Risky Business estimates are annual. Negative values represent benefits of climate change. Carbon fertilization effects included in these estimates
Coastal Resources	Business-as-usual, full adaptation (as reflected in simulated site-specific BCA)	$990 billion in cumulative impacts through 2100	Not estimated	CIRA estimate discounted at 3% to 2015. CIRA estimate reflects effects of sea level rise and storm surge together
	Business-as-usual, no adaptation	Over $4 trillion cumulative impacts through 2100	– 2050: $66 billion to $106 billion – 2100: $238 billion to $507 billion – 5% chance that annual storm surge damages grow by $42 to $108 billion	Risky Business estimate is cumulative through target year. CIRA estimate uses 3% discount rate
Water Resources	Business-as-usual, no adaptation	– 2050: –$0.5 to $2.5 billion annually – 2100: $6.5 to over $100 billion annually	Not estimated	Annual estimates reported here are undiscounted, and are estimates for the reported year
	GHG mitigation scenario	2100: –$3.8 to $16 billion annually	Not estimated	
Infrastructure	Business-as-usual	$260 billion cumulative impacts through 2100	Not estimated	Discounted at 3%

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(**Table 1** Continued)

Sector	GHG emissions and adaptation action scenario	CIRA results*	Risky business results**	Comments
Health	Business-as-usual	Heat stress mortality quantified but not monetized	– 2040 to 2059: –$24 billion to +$160 billion (median estimate of +$67 billion) – 2080 to 2099: +$93 to +$536 billion	Risky Business results for high emissions scenario, RCP 8.5, for heat stress mortality
Crime	Business-as-usual	No study	– 2020 to 2039: $90 million to $2.6 billion annually – 2040 to 2059: $1.7 to $5.2 billion – 2080 to 2099: $5.3 to $11 billion	Estimates are for high emissions scenario RCP 8.5, and are annual averages for the period reported
Energy	Business-as-usual	1.7 to 8.3% increase in cumulative power system costs through 2050	– $0.5 to $12 billion on average by 2020 to 2039 – $8 to $30 billion by 2040–2059 – $33 to $89 billion by 2080–2099	CIRA estimate discounted at 3%. Risky Business estimate is annual for RCP 8.5 emissions scenario
Labor Supply	Business-as-usual	In progress	– 2020 to 2039: –$0.5 to +$22 billion – 2040 to 2059:+$11 to +$53 billion – 2080 to 2099: +$45 to +$156 billion	Estimates are annual for RCP 8.5
Ecological – coral reefs	Difference between business as usual and GHG mitigation scenario	– Coral reefs: $18 billion (95% CI of $9 to 26 billion) – Fire response: $7.3 to $9.2 billion – Recreational fishing: $0.3 to $1.0 billion	Not estimated	Ecological effects estimates are cumulative through 2100. Discounted 3% rate

*CIRA estimates from various sources, see text.

**Risky Business estimates from Houser et al. (2014). Estimates for Risky Business are undiscounted.

a summary of results). Change in yields for the RCP 8.5 scenario range from an average annual direct cost of −\$2.5 billion (i.e., a \$2.5 billion benefit) to \$3.5 billion by 2020–2039; −\$3.6 to +\$7.8 billion by 2040–2059, and −\$3.9 to +\$24 to billion by 2080–2099. As noted in the report, these are relatively modest impacts in the context of the US economy, perhaps in part because they reflect a carbon fertilization assumption. They remain in the same order of magnitude, however, as many prior estimates of the impact of climate change on agricultural sector economic production (e.g., Robert Mendelsohn & Neumann, 1999).

The importance of the treatment of carbon fertilization on estimates of agricultural impacts cannot be understated, but the effect of CO_2 increase on crop growth is still under debate. Many experiments have been done, most under laboratory conditions. However, crops in field conditions usually are grown in dense populations where they compete for space and light. Under field conditions, crop plants also are likely to respond as a community rather than individual plants, wherein light (solar radiation) becomes a limiting factor for growth. Under these conditions, elevated CO_2 cannot promote horizontal expansion and greater light capture (Bazzaz & Sombroek, 1996). Scaling current knowledge to farmers' fields and even further to regional scales, including predicting the CO_2 levels beyond which saturation may occur, remains a challenge (Tubiello, Soussana, & Howden, 2007). Nonetheless, it is unambiguous that higher CO_2 levels allow plant stomata to open less, leading to less moisture loss in plants to evapotranspiration, a critical factor in plants adapting to hotter, drier climates. A second factor, the effect of climate change on ozone levels, has not yet been adequately accounted for in these studies. It is clear that the potential negative effect of elevated ozone may be substantial for crop yields (Fishman et al., 2010).

Another key issue involves integrating water resource availability for irrigated production – is a need to take into account the effect of climate irrigation demand (increases) and on overall water supply (can increase or decrease overall, but most critical is supply during key phenological periods when water is needed). Some regional scale studies have been conducted, outside the US, that consider factors such as competition for water from non-agricultural sectors, priorities during drought periods, and the future adequacy of storage to support irrigation (Ahouissoussi et al., 2014; Sutton et al., 2013), but this approach has not yet been applied in US analyses.

3.2 Coastal resources

The national scale impacts of sea level rise on US coastal resources have been studied since at least the late 1980s (see Park, Trehan, Mausel, & Howe, 1989;

Titus et al., 1991; U.S. EPA, 1989; Yohe, 1990), but more recently analyses have included the joint effects of sea level rise and storm surge, first using physical measures (Frumhoff, McCarthy, Melillo, Moser, & Wuebbles, 2007; Lin, Emanuel, Oppenheimer, & Vanmarcke, 2012), and then very recently using economic measures (Kirshen, Merrill, Slovinsky, & Richardson, 2012), including for the full US coast (Neumann et al., 2014a,b). Impacts include losses of at-risk assets to flooding and inundation (property, infrastructure); indirect effects in the form of business interruption and diversion of capital; social disruption; and health (mortality during floods, illness and injury from flood damage). All of these impact categories apply where no adaptation action is taken. Adaptation action involving protective structures, beach nourishment, elevation and flood proofing of structures, and even managed retreat/relocation, has long been known to be very cost effective (Neumann, Yohe, Nicholls, & Manion, 2001; Yohe & Schlesinger, 1998). Each of these adaptation measures entail cost, and the efficacy of each has been called into question, not to mention the task of evaluating efficiency as the optimal measure in any given location; nonetheless a broad literature finds that these measures are good investments in risk mitigation, with life-cycle costs usually less than the potential damages (see Moser et al., 2014 for a recent review). As a result, most contemporary estimates of the impacts on coastal resources provide estimates of impacts, net of adaptation action (Neumann et al., 2010; Yohe, Knee, & Kirshen, 2011; Yohe, Neumann, Marshall, & Ameden, 1996).

Both the CIRA and Risky Business efforts report estimates of impacts and adaptation costs for sea level rise and storm surge. The CIRA work reports that a business-as-usual scenario results in $990 billion in cumulative impacts through 2100 (2005$ discounted at 3% to 2015), net of cost-effective adaptation action (see Table 1 for a summary of results). Interestingly, a policy to mitigate GHGs is estimated to reduce those estimates by only $84–$100 billion, reflecting the fact that oceans incorporate a great deal of warming inertia, and reversing sea level rise is therefore difficult and likely to take longer than the typical time horizon of these types of studies (2100). Other recent work using the same CIRA model and scenarios (Waldhoff et al., 2014) also provides an estimate of impacts with no adaptation. For the business-as-usual scenario noted above, the estimate is over $4 trillion (cumulative, discounted through 2100), more than a factor of four higher than the "with-adaptation" results. This finding buttresses the conclusion noted above that adaptation is very cost effective for this sector.

The Risky Business Project notes that by 2050, between $66 billion and $106 billion of existing coastal property will likely be below sea level by 2050, rising to $238 billion to $507 billion by 2100 – these estimates exclude adaptation action. In addition, the study estimates there is a 1 in 20 chance that average annual losses from hurricanes and coastal storms along the Atlantic and Gulf coasts will

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grow by $42 billion owing only to the effect of sea level rise – that is, the effect that a higher sea amplifies the damage of the current profile of storm surge risk. Potential changes in hurricane activity associated with climate change, however, could increase this estimate to $108 billion annually (Gordon, 2014; Houser et al., 2014).

Analyses of sea level rise impacts are clearly dependent on the scenarios of sea level rise that drive the economic models. A key difference between the CIRA and Risky Business analyses derives from assumptions about the likelihood of dynamic ice sheet melting in Greenland and West Antarctica. For the subset of CIRA analyses that exclude dynamic ice sheet melting, results are comparable to the Risky Business analysis but the CIRA analysis which incorporates dynamic ice sheet melting projections yields the higher estimates cited above.

Other impact categories not yet adequately addressed in the latest coastal impacts literature are the links with social vulnerability (Martinich, Neumann, Ludwig, & Jantarasami, 2013), and a series of indirect effects of impacts on the diversion of resources from productive to defensive capital (such as sea walls and beach nourishment); and the value and importance of ecosystem effects, particularly on coastal wetlands. In addition, recent events, such as Hurricane Sandy, have inflicted such devastating effects (Abel, Bram, Deitz, & Orr, 2012) that some analysts believe that the US may be poorly adapted to current coastal risks. Such a large current "adaptation deficit" calls into question assumptions of cost-effective adaptation in the future, which would imply an adaptation learning capacity and pace that may be unrealistic. Research on this topic is ongoing, but one speculation is that individuals systematically underestimate the probability and severity of recurring natural risks, particularly without strong financial signals to the contrary, such as higher property value insurance rates that reflect growing risks to coastal property (Kunreuther & Michel-Kerjan, 2009). These concerns may be behind the choice of the Risky Business Project to focus on quantifying coastal property value at risk of loss, rather than impacts net of adaptation.

3.3 Water resources

Recent droughts in the US, including the nearly country-wide drought in 2012 and the one ongoing in California, have led to greater awareness that climate change could put water resource use at risk. The water resource impacts of climate change are more complicated than drought alone: too much water over too short a period results in flooding, too little and there is drought, and water available far away from water demand locations is of little value to humans without a substantial infrastructure to move the water. National-scale water resource modeling therefore requires a collection of technical capabilities that reflect the reality of water management, while remaining computationally tractable and reliable at the levels of temporal and spatial scale employed. As a result, there is currently not a single national-scale model available to comprehensively estimate impacts of climate change.

The CIRA analysis provides a reasonably comprehensive assessment, based on five existing, peer-reviewed models that estimate impacts on major parts of the water resource sector (Strzepek et al., 2014). These include hydrologic variables (runoff), hydro-climatic metrics (drought indicators), water management indicators (water stress), damages from severe floods, and economic welfare (consumer and producer surplus). Results from the flooding and economic welfare analyses are most relevant for this review. These results show substantial welfare decreases for basins in the South Gulf area, due to low flow effects on ecological resources, and basins in the Lower Colorado, California, and Pacific Northwest areas due to decreases in hydropower generation resulting from regional drying. The magnitude of the negative impacts of these four areas dominates over the minor positive and negative impacts in other areas of the country, where forecasts of increased precipitation lead to increases in runoff (water volume in rivers). The net welfare effects are very sensitive to the climate model used – the primary model results show a welfare increase of $0.5 billion per year in 2050, but by 2100, the model estimates decreases in welfare of $6.5 billion per year. Results for other climate models show decreases in welfare of from $15.0 billion to over $100 billion per year by 2100 (see Table 1 for a summary of effects). GHG mitigation policy has a substantial effect in reducing impacts and increasing economic welfare, $3.3 billion per year in 2050 and $9.4 billion per year by 2100 for the preferred model, and $14.5 billion to $84 billion per year in 2100 for alternative models.

The economic supply and demand model does not estimate capital expenses for new infrastructure or welfare losses due to flooding – a separate flooding damages model (Wobus, Lawson, Jones, Smith, & Martinich, 2014) finds that climate change increases flooding losses for 10 of the 18 major basins in the lower 48 states in 2100, and mitigation yields an overall increase in welfare on the order of $2.5 billion dollars per year by 2100.

These economic welfare and flooding model results reflect an underlying estimate of a large increase in mean annual runoff, although it is not uniform across the US. The runoff models indicate drying in the Southwest, wetting in the northeastern and southeastern US, and substantial wetting in the central areas of the country. The drought model also shows negative effects of climate change, but an “extreme-reducing” benefit from GHG mitigation.

Two key remaining challenges in water resource analyses are fully reflecting the influence of infrastructure’s effects on impacts, and integrating the results

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of the water resources analyses in other sectoral analyses (irrigated agriculture, energy cooling, and aquatic ecosystem analyses). The Risky Business analysis did not include a separate water resource estimate, noting that there currently is no econometric model available to estimate effects (although the CIRA flooding analysis does employ an econometric approach). The report does stress the importance of the intersectoral nature of water resources – and one could interpret the Risky Business agricultural analysis as incorporating some measure of irrigation water availability, to the extent that is indirectly reflected in the climate/crop yield relationships they employ. The CIRA analysis, being a simulation approach, notes more explicitly the need to adequately reflect infrastructure's influence on water, and the economic model did incorporate a limit on hydropower production in wet years to acknowledge that current hydropower infrastructure capacities limit the ability to generate additional hydropower in wet years (electric grid integration issues may also be a constraint). The more important point may be that changes in infrastructure capacities and perhaps operating rules, particularly for hydropower and flood control, may constitute an important source of adaptive capacity that has not been explored in economic analyses to date.

3.4 Infrastructure

Adaptation studies in the infrastructure sector are most common for roads, but the CIRA analyses also addressed impacts to bridges and urban drainage. The key analytic issues had been, until recently, of a primary nature: assembling useful geocoded inventories of potentially vulnerable infrastructure resources and networks, and then parameterizing climate stressor/response relationships from the engineering literature (Transportation Research Board, 2008). The latter typically represent a new transformation of existing information on the sensitivity of infrastructure to existing climate variability. One of the first studies to overcome the inventory issue is Larsen et al. (2008), a simulation modeling approach that assumed perfect foresight and that focused on Alaskan infrastructure, which relied on rules of thumb for the stressor-response component. Larsen did, however, provide some key insights about the benefits of adaptation, showing substantial net gains from investing in adaptation, particularly in modifying and optimizing capital replacement and maintenance cycles.

The CIRA studies rely mainly on this simulation approach (see Chinowsky, Price, & Neumann, 2013 for roads; Neumann et al., 2014b for urban drainage; Wright et al., 2012 for bridges). The results, summarized in Neumann et al. (2014b), suggest that roads and bridges may be particularly vulnerable and worth further study. The three infrastructure models differ in their approach and report impacts and adaptation costs on different time scales, but all four rely on a common fundamental structure: identify vulnerable infrastructure from the capital stock, develop a stressor-response relationship to estimate impacts, and identify and apply cost-effective adaptation measures to reflect the net results of reasonable adaptation responses to stressors. Cumulative impacts (discounted at 3%) total about $260 billion, with $160 billion from bridges, and $80 billion from roads, and $20 billion from urban drainage (see Table 1 for a summary). The time profile varies substantially, however, with most effects to bridges occurring before 2050, and most effects for roads occurring after 2050. Mitigation policy is effective in reducing these impacts (by $85 billion discounted), having a somewhat greater effect for roads than for bridges. The results also suggest that adaptation strategies are important and likely to be costly, but also that adaptation plans for infrastructure sectors ideally require advance planning and optimization for a broad range of future climates.

The remaining challenges for infrastructure analyses include moving beyond the simplified perfect foresight models to incorporate more realistic learning and baseline road maintenance norms; generating an econometric literature as a cross-check on these simulation approaches; "knock on" secondary damages associated with productivity losses following infrastructure failure; and addressing extreme events. Econometric approaches could start with a cross-sectional method, for instance, that relates spatial differences in temperature and precipitation regimes with construction costs and/or specifications. A key challenge with an econometric approach for US public infrastructure is that it is currently not built to optimize revenue returns – without tolls, there is no revenue stream, only a service stream that is not quantified. This may be one reason the Risky Business Project did not attempt an infrastructure analysis.

3.5 Health

The health costs of adapting to climate change are based on expected impacts through vector-, water-, and food-borne diseases; exacerbation of air pollution and associated health effects; thermal stress caused by heat waves; and negative impacts of malnutrition (e.g., effects on the agriculture sector that might raise local prices or limit availability of food or at least more nutritious food). Quantitative estimates of these impacts are characterized by a high level of uncertainty, arising not only from a lack of knowledge about the increased risks of individual health outcomes but also because of changing baseline conditions (baseline risks are expected to fall over time) and changes in demographic make-up of areas with a potentially elevated risk (Ebi et al., 2008).

US estimates in this sector have focused on heat stress mortality – both CIRA and Risky Business provide new estimates, but both focus on quantifying mortality without valuation. The CIRA study applies city-specific mortality relationships for extremely hot and cold temperatures for 33 metropolitan statistical areas in the US to develop mortality projections for historical and potential future climates (Mills et al., 2014a), under the theory that decreases in extreme cold mortality might partially compensate for increases in extreme heat mortality as climates warm. The results indicate the extreme hot-day effect dominates. Using a fixed population, the study finds that between about 2000 and 2700 net additional mortalities would result in 2050 in the 33 city domains (accounting for about a third of the current US population), and between 7500 and 12,500 by 2100 (a different assumption using a higher temperature threshold for mortality reduces the 2100 estimates to between 3200 and 5900 additional mortalities). If projections of population increases are used, the estimates jump to 2700 and 12,500 in 2050 and 2100. GHG mitigation has a substantial effect on these results, as does an estimate of the effects of adaptation. The authors do note that their estimates are less than those suggested by other recent studies that employ synoptic rather than threshold methods, for example, Greene et al. (2011).

The Risky Business analysis also estimates net mortality changes for both cold and heat stress, for multiple age categories and across the full US, based on two econometric method studies that estimate the marginal effect of heat and cold stress (as a net effect): Deschênes & Greenstone (2011) and Barreca, Clay, Deschenes, Greenstone, and Shapiro (2013). The results for the central case GHG emissions scenario RCP 4.5 indicate a likely range of changes in death rates per 100,000 of –3.3 to 2.3 in 2020–2039; rising to –3.2 to 4.0 by mid-century and –2.5 to 5.9 by end century (2080–2099). These ranges include the finding that the median effect of climate change is to reduce death rates, on net, until late century. The higher emissions scenario (RCP 8.5), however, yields a death rate increase at the median of 1.5, 2.8, and 3.7 deaths per 100,000 for the early, mid-, and late-century periods.

Lost mortality is not valued in the CIRA published paper (Mills et al., 2014), but valuation of mortality effects in the "Risky Business" report (Gordon, 2014) is based on both the value of lost labor (a "human capital" approach) and a value of statistical life (VSL) measure. Recent federal government Regulatory Impact Analyses have used VSLs in the range of $6 to 7.9 million, and the "Risky Business" report uses the high end of this range. The result is average annual nationwide mortality costs under RCP 8.5 of −$24 billion to +$160 billion (median estimate of +$67 billion) by 2040–2059. For the late-century period the estimate grows to +$93 to +$536 billion, more than twice as high as the market costs of climate-driven mortality, as summarized in Table 1. The lost labor market costs are about half the costs using the VSL method. Note that VSL values might also reasonably be increased to account for the effects of income increases over time, as some federal agencies already do, including the U.S. EPA.

3.6 Crime

The Risky Business Project includes a new econometrically estimated impact estimate for the link between climate change and crime. The mechanism underlying this correlational link is poorly understood, but three main hypotheses have been explored: 1) that individual criminal behavior is determined by rational decisions about the costs and benefits of certain actions, and that weather factors into the probability of committing a crime without getting caught; 2) that temperature affects aggression levels, and loss of control and heightened propensity to commit criminal acts; and that 3) the frequency of criminal acts is determined in part by opportunity, and certain climate conditions allow for increased social interaction.

The new estimates focus on the marginal effect of daily maximum temperatures on violent crime and property crime, using two studies: Ranson (2014) examines county-level monthly crime rates during 1960–2009, and Jacob, Lefgren, & Moretti (2007) examine jurisdiction-level weekly crime rates during 1995–2001. The authors of both studies find that crime generally could increase as early as 2020–2039 and the range of likely changes is unambiguously positive by mid-century for all scenarios. In RCP 8.5, for example, they estimate violent crime is likely to increase 0.6–2.1% by mid-century and 1.9–4.5% by late-century. Property crime impacts tend to be substantially smaller in percentage terms (e.g., late-century rates for the RCP 8.5 scenario could rise 0.4–1%). The authors explain that property crime does not increase as strongly as violent crime because the impact function for property crime is nonlinear and flattens at temperatures higher than 55°F, while the impact function for violent crime continues to increase even at high temperatures. Projected changes are smaller in magnitude for RCP 4.5.

The Risky Business report authors assess the direct costs of the climate-driven increase in violent and property crime using both avoided cost and stated preference estimates for specific types of violent and property crimes. As shown in Table 1, the total US change in direct property and violent annual crime costs for RCP 8.5 is $90 million to $2.6 billion on average by 2020–2039, $1.7 to $5.2 billion by 2040–2059, and $5.3–$11 billion by 2080–2099. This puts the effects of crime roughly equal to effects on commodity crop production.

3.7 Energy

The energy sector has been studied for many years, but it is important to distinguish effects of mitigation activities on energy production, and the effects of climate change on energy demand and supply. The former represents a critically important area of study, but it is generally less important for understanding direct impacts of climate change stress. Perhaps the first comprehensive estimates of climate effects on energy were completed as part of the Mendelsohn and Neumann (1999) multi-sector study – the energy study in that suite of analyses focused on the effects of climate change on the net change in space heating and cooling demand, and therefore consumer and commercial expenditures on energy for this purpose. This econometric study has been further refined and buttressed by other studies, also largely econometric, but a new suite of studies completed for CIRA applies three simulation approaches focused on temperature effects on electricity demand, and largely confirms the finding of this early work.

The CIRA analysis (McFarland et al., 2014) applies a common set of temperature projections to three well-established models of the US electric power sector:

- Global Change Assessment Model (GCAM-USA): a detailed, service-based building energy model for the 50 states;
- Regional Electricity Deployment System Model (ReEDS): a deterministic, myopic, optimization model of the deployment of electric power generation technologies and transmission infrastructure for the contiguous US; and
- Integrated Planning Model (IPM®): a dispatch and capacity planning model used by the public and private sectors to inform business and policy decisions.

The models forecast changes in electricity demand as a function of changes in heating and cooling degree-days (HDD/CDDs) – measures that relate each day's temperatures to the demand for energy needed to heat and cool buildings – and other technical and calibration parameters.

Rising temperatures will increase electricity demands for cooling, but decrease demand for heating (to the extent electricity is used for this purpose). Results for the three models show that closely aligned trends of falling HDDs and rising CDDs. As a result of these changes, electricity demand across the country is projected to increase under the reference scenario by 1.5–6.5% by 2050, compared to a control scenario with today's climate (i.e., no warming). The study uses the change in system cost to produce electricity as the key metric of economic impact for this sector, and finds that meeting this additional demand in the reference case raises power system costs by 1.7–8.3% across the models (cumulative costs discounted at 3% from 2015 to 2050). The study also looks at the costs of meeting the Policy 3.7 GHG-emissions reduction target, and finds these costs are nearly as large as the costs of meeting the additional electricity demand for warming that results in the reference scenario.

The Risky Business study assesses changes in energy demand using econometrically derived estimates of percentage change in energy expenditures. As shown in Table 1, at the national level, they found that future changes in temperature increases average annual energy expenditures under RCP 8.5 by \$0.5 to \$12 billion on average by 2020 to 2039, \$8 to \$30 billion by 2040 to 2059, and \$33 to \$89 billion by 2080 to 2099. These estimates are much larger than the early econometrically derived estimates, and it is not clear why.

3.8 Labor supply

Effects of climate change on labor supply have only recently been studied, although the conceptual links between climate change workers' ability to remain productive are intuitive, which are, essentially, that there is an optimal environmental condition for worker activity in outdoor settings, and sub-optimal conditions can affect workers' ability to perform tasks, which in turn can affect overall labor productivity. Even small changes in labor productivity can have a significant effect on overall economic output.

The Risky Business study incorporates estimates of Graff Zivin and Neidell (2014), which provide a basis for estimating impact functions for individuals working in high- and low-risk industries, i.e., industries where individuals are likely and unlikely, respectively, to be strongly exposed to unregulated temperatures. The study concludes that temperature has a threshold effect – that is, that there is very little influence on labor supply until very high daily maximum temperatures are reached – and these high temperature conditions cause individuals to be able to supply less labor. The Risky Business study authors found that median estimates for high-risk labor supply generally decline by mid-century, and the range of likely changes are clearly negative by late-century for all scenarios (e.g., in RCP 8.5, high-risk labor declines by 0.22–0.86% by mid-century and by 0.81–2.3% by late-century). Effects on low-risk labor supply are more modest.

Valuation of these effects is estimated using 2011 IMPLAN input-output tables by geographic area. Changes in labor productivity from the impact function calculations are assumed to translate linearly to changes in value-added for the relevant labor sectors. National results suggest that the average annual direct labor productivity costs (high risk and low risk combined) under RCP 8.5 are −\$0.5 billion (i.e., a \$0.5 billion benefit) to +\$22 billion by 2020–2039, +\$11 to +\$53 billion by 2040–2059, and +\$45 to +\$156 billion by 2080–2099. See Table 1 for a summary. These relatively large estimates – roughly an order of magnitude

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larger than the nation-wide agricultural impacts in the same Risky Business study – have yet to be confirmed by other studies, but this first national effort suggests that this line of study should be important to pursue in future work.

3.9 Ecological resources

The coverage of ecosystem impacts from climate change has improved dramatically in the last 10 years, but remains largely focused on a set of ecosystem effects that are both readily quantified and amenable to monetization – but which can hardly be considered a representative slice of the full range of ecosystem effects that could have economic meaning in the US. Marine and ocean-based ecosystems are one area where work has started. The CIRA analysis includes a study of coral reefs that translates changes in sea-surface temperature to estimates of coral coverage, and then values the losses using willingness-to-pay (WTP) estimates for recreational use of reefs. The approach is applied to three regions: Florida, Puerto Rico, and Hawaii and results are reported as benefits of a mitigation policy. The greatest recreational benefits (i.e., reduced damages under the mitigation scenario compared to a reference scenario) are in Hawaii, with an average net present value (3% discount rate) of ~$17 billion (95% CI of $9–26 billion); comparable values for Florida (~$1.3 billion; 95% CI of $0.7–2.0 billion) and Puerto Rico (~$0.4 million, 95% CI of $0.2–0.5 million) are lower.

CIRA also includes a study that quantifies and monetizes projected impacts on terrestrial ecosystem carbon storage and areas burned by wildfires, using the MC1 dynamic global vegetation model (Mills et al., 2014b). The results indicate that climate change has the potential to substantially increase wildfire risk, but the paper reports only the reduction in area burned that could be achieved by a mitigation policy. The primary model shows cumulative reductions of 122 million hectares between 2011 and 2100, implying avoided cumulative fire response costs of $9.2 billion (discounted); the two alternative climate models show smaller benefits, of 84–91 million burned hectares avoided and an associated cost reduction of $7.3–$7.8 billion, as summarized in Table 1.

Finally, the CIRA study includes an assessment of freshwater recreational fishing. Climate change should have negative effects on cold-water fishing opportunities, and positive effects on at least some warm-water fishing. The results of the study indicate that the net recreational fishing days for a climate change scenario is projected to increase from 2011 to 2050 by approximately 1,500,000 days, but then decline in 2100 to approximately the same level as 2000. But valuation of these changes reflects higher values for cold-water fishing trips relative to warm-water fishing trips. The net present value (NPV) of benefits of a mitigation policy are ~$1 billion for cold-water fishing alone, but decline to approximately $300 million when gains in other types of fishing are considered. As the CIRA papers note, however, the quantified economic benefits are associated solely with widely measured recreational uses, so are a subset of the total economic and societal benefits we might expect to be associated with projected future declines in freshwater fisheries and coral reefs.

4 Discussion: key gaps and challenges

As this review shows, both the quality and comprehensiveness of recent economic estimates of the impacts of climate change in the US is increasing, but much work remains on both fronts. Table 2 attempts to summarize the review, with reference to gaps and challenges identified for each of the sectors addressed in this paper. Thinking more comprehensively about the state of the impacts and adaptation literature, however, three key cross-cutting gaps and challenges remain and involve treatment of a broader range of climate stressors, improving sectoral coverage, and expanding the range and type of effects categories.

4.1 Climate stressors

Most of the estimates reviewed above, not to mention those developed since the ground-breaking 1989 EPA Report to Congress, focus on gradual changes in temperature and precipitation. Techniques for assessing these effects have certainly improved over that time, but both recent climate science and recent climatic events (e.g., the 2012 drought and Hurricane Sandy, to name two) suggest that future impact assessments must focus more attention on extreme events. The CIRA and Risky Business studies together begin to make progress in this area, with nationwide treatment of storm surge and wildfire events, and new estimates for one type of seasonal flood and high rainfall events that overwhelm urban drainage systems, but even these events are only incompletely assessed. For example, while the coastal analyses reflect changes in storm surge associated with changes in hurricane patterns and intensity, they only partially reflect wind damage from these storms. With an improved climate science base – and an unfortunate series of recent extreme events to serve as roadmaps for economic effect chains or econometric studies – it is critical that economists focus on enhancing comprehensiveness of US estimates in this dimension.

Table 2 Summary of sectoral review.

Sector	Coverage and key gaps	Key gaps	Key sources of uncertainty	Results reflect multiple lines of evidence?
Agriculture and Forestry	– Commercial production of most cereal crops – Commercial timber	High-value fruits and vegetables excluded from most studies	– Assumptions about carbon fertilization about plant growth – Level of autonomous adaptation by farmers	Yes – multiple econometric and simulation studies, in multiple settings and scales, refined over many years of study
Coastal Resources	Coastal property and some infrastructure, as affected by sea level rise and periodic storm surge	– Most public infrastructure excluded – Wetlands and other coastal ecosystems – Indirect effects (such as business interruption)	– Sea level rise inputs (particularly assumptions about dynamic ice sheet melting) – Level of autonomous adaptation by property owners	Yes – multiple studies refined over many years of study
Water Resources	Hydropower, commercial irrigation, municipal water supply	– Flooding at hourly to daily scale – Aquatic ecosystem effects	– Interactions with other sectors (e.g., agriculture and hydropower energy) – Future water allocation regimes	No – study is largely confined to simulation studies, some of which do not yet consider the effects of water infrastructure on outcomes
Infrastructure	Roads, bridges, urban drainage, coastal infrastructure, some port infrastructure	– Electric transmission and distribution networks (susceptible to wind damage and extreme heat transmission losses) – Rail networks	– Relatively simplistic stressor-response relationships – Interactive effects with other sectors (e.g., coastal property, energy network reliability)	No – new area of study, each category of infrastructure is characterized by only a handful of studies

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(**Table 2** Continued)

Sector	Coverage and key gaps	Key gaps	Key sources of uncertainty	Results reflect multiple lines of evidence?
Energy	Electric energy (demand-and-supply effects)	Oil and gas exploration	– Interaction of mitigation policy compliance and impact estimation – Assumption of relatively stable profile of energy demand and supply structure in the future	Yes – multiple econometric and simulation studies (simulation studies relatively new)
Health	Heat stress mortality	– Most vector-borne diseases – Nutrition effects linked to agricultural production effects – Mental health – Extreme event mortality	– Success in limiting vector-borne disease in recent history limits ability to model future vector-borne risks – Many health effects have indirect causative chains	– Yes – for heat stress effects – No – for other effects
Crime	Property crime, violent crime	New area – gaps not yet well clarified	Causative chains not well understood – only econometric studies to date	No – relatively new area of study
Ecosystems	Forests, coral reefs, freshwater fisheries	– Most coastal ecosystems – Many terrestrial ecosystems – Most freshwater aquatic ecosystems	Impacts from multiple stressors, where climate changes may present a “tipping point”	No – relatively new area of study, typically only a handful of studies for each ecosystem type
Labor Productivity	“High-risk” outdoor worker productivity	Indirect effects on labor productivity (e.g., through morbidity effects or extreme events)	Econometric simulations may not capture most important or robust climatic stressors	No – first national study in 2014

4.2 Sectors

In this review it is clear that some sectors have a wide range of existing and high-quality estimates, conducted over a long period of time; for these sectors (e.g., agriculture and forestry, coastal resources, energy, health, and perhaps water resources) the research base is sufficient to critique the literature and identify key issues for improvement. For other sectors we have only a few estimates (e.g., infrastructure, ecosystems, crime, labor, productivity). In this second category, the sector is either incompletely addressed (ecosystems are largely a sample of convenience), impact estimates are reliant on only one thread of evidence or study type (crime), or both (infrastructure). There also remain a class of effects that are simply not yet addressed,which include the effects of increased ambient ozone on health and ecosystems (and even managed ecosystems such as agriculture and forestry), nutrition effects, water quality impacts, thermal cooling effects for electric power plants, and a broad class of non-market effects. Tools exist to address these effects, and the push for improved comprehensiveness in the economic realm needs to remain strong to keep up with our improved understanding of climate science and physical effects of climate change.

4.3 Effects categories

Most of the economic impact estimates reviewed here reflect direct effects of climate change on economic assets or production. A broad class of indirect effects, however, is largely ignored, even in the better studied sectors. Effects of coastal storms, for example, include not just property value losses but also business interruption and long-term capital losses that are omitted in the current set of estimates.

The Risky Business approach to macro-economic effects, however, holds promise as a useful next step. It applies a new macroeconomic model of the US economy (RHG-MUSE) that processes the direct costs and benefits of the climate-driven changes in agricultural production, labor productivity, mortality, energy costs, and coastal property loss. The model then utilizes adjustments in the form of substitution in response to changes in prices, or changes in capital stock or labor supply, to effectively reduce (or in some cases, amplify) the direct costs. For example, the impact of damaged coastal capital stock in a given year affects economic growth in subsequent years.

On net, the macroeconomic effects captured in RHG-MUSE reduce the overall cost of the direct climate impacts integrated into the model, but since they represent only a subset of the overall costs, this finding cannot yet be considered robust. What is especially encouraging is that RHG-MUSE has been designed as a flexible, readily updated tool: as existing studies (such as the new CIRA estimates) and new analyses are developed, the model's direct cost and benefit inputs can be updated. With the current set of inputs, the RCP 8.5, late-century results suggest a combined effect of direct costs of 0.8–3.5% of GDP nationwide, and a macroeconomically processed effect of 0.8–1.9%. More thinking is needed to incorporate effects such as premature mortality – however the late century estimates of direct mortality costs include lifetime earnings lost after 2100, while the macroeconomic estimates do not. This approach deserves further attention as a means for incorporating health impacts, and might benefit from the U.S. EPA (2011) analysis of air pollution effects, which also incorporated both mortality and morbidity effects in a CGE model.

One of the most important omissions, perhaps, is the broad range of intersectoral effects. The water sector provides perhaps the best examples: water is used to produce energy (through hydropower and thermal cooling), and energy is used as part of the water system (for example to pump irrigation groundwater). Neither the water for energy nor energy for water effects are captured in these estimates to date. A good first start would be to incorporate changes in water availability as a constraint on irrigated agricultural production. This is a difficult task but feasible with intersectoral work employing current modeling frameworks. Initial studies also suggest that cooling water intake temperature and supply volumes need to be considered as a potential constraint on electric power production capacity. It would be most useful to conduct a broad series of intersectoral "pilot studies" at the local or regional scale to learn what might be the most economically important intersectoral effects to capture in the next wave of national-scale studies.

Economists may aspire to be able to conduct BCAs of climate change mitigation policies – those that do presumably would like to be assured that the estimates of economic benefit that would be applied are both of high quality and comprehensive. Recent work, addressed in this paper, provide some assurance that estimates of economic benefits are improving, but the discussion makes it clear that these estimates do not yet provide comprehensive coverage. As other papers in this issue make clear, there remain other important economic challenges in conducting a traditional BCA for a potentially globally disruptive economic stressor that occurs over multiple generations and many years. Further, there appears to be no sense of agreement on such critical issues as how to consider the role of how technological, demographic, and even preference change over time. The need is just as great for better economic impact (and adaptation) estimates to support other economic paradigms, such as integrated assessment models, social cost of carbon calculations, risk management frameworks, or robust decision-making approaches. None of these can be conducted without continuous improvement in the economic impacts discipline. In this light, the recent additions to this economic literature ought to be viewed in a favorable light, and further progress encouraged.

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