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Climate damages and adaptation potential across diverse sectors of the United States

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There is a growing capability to project the impacts and economic effects of climate change across multiple sectors. This information is needed to inform decisions regarding the diversity and magnitude of future climate impacts and explore how mitigation and adaptation actions might affect these risks. Here, we summarize results from sectoral impact models applied within a consistent modelling framework to project how climate change will affect 22 impact sectors of the United States, including effects on human health, infrastructure and agriculture. The results show complex patterns of projected changes across the country, with damages in some sectors (for example, labour, extreme temperature mortality and coastal property) estimated to range in the hundreds of billions of US dollars annually by the end of the century under high emissions. Inclusion of a large number of sectors shows that there are no regions that escape some mix of adverse impacts. Lower emissions, and adaptation in relevant sectors, would result in substantial economic benefits.

Earth's climate is now changing faster than at any point in human history, and the resulting impacts to society and the environment are increasingly visible across the United States. As warming accelerates, options exist for reducing the risks Americans face, and decisions made in the near-term will determine the rate, magnitude and impact of future changes[1]. To help inform these decisions, estimates are needed regarding the physical and economic implications of climate change across a range of sectors, along with spatially explicit projections of how mitigation and adaptation actions can avoid or reduce these impacts[2]. While the estimation of mitigation costs[3,4] and the adequacy of current mitigation actions[5,6] have been well described elsewhere in the literature, multi-sector studies projecting the effects of mitigation and adaptation on the United States have been limited until recently.

In the past five years, the science and economics of estimating future climate change impacts have advanced considerably. These advances have enabled several frontier research initiatives to improve the understanding and quantification of climate impacts in the United States[7–9]. A more recent study[10] constructs spatially explicit, probabilistic estimates of economic damages in the United States from climate change across six sectors. Primarily using empirically grounded econometric approaches applied at a county level across the contiguous United States (CONUS), the authors derive damage functions linking global mean temperature change to both market and non-market impacts. At a global scale, several modelling frameworks[11–13] have quantified potential damages across multiple sectors, particularly with regards to agriculture, coastal flooding and water resources. Altogether, these coordinated frameworks, each of which involves many collaborators and models, have substantially advanced the characterization of physical and economic risks. However, important uncertainties and gaps remain.

Here, we quantify potential physical and economic damages of climate change to 22 sectors (for example, air quality, labour and roads) in the United States using a consistent set of climate and socioeconomic scenarios and assumptions (Table 1). This coordinated modelling project, involving a large number of teams under the second modelling phase of the Climate Change Impacts and Risk Analysis (CIRA) project[14], was developed to provide technical input to the Fourth National Climate Assessment (NCA4) of the United States Global Change Research Program (USGCRP). Using scenarios, projections and assumptions consistent with those developed for NCA4 and reflecting one of the newest statistical downscaling techniques, a large number of sector-specific impact models are used to simulate future changes in climate impacts across the CONUS, with several analyses also covering Alaska, Hawaii and Puerto Rico (Supplementary Table 3).

The predominant use of process-based modelling in this framework offers several advantages, including the ability to dynamically simulate responses to climatic and environmental conditions that are outside, or rarely observed in, the historic period. This is an important factor when modelling across long time frames and for impacts that have empirical data constraints or no known historical analogue (for example, agricultural productivity under high temperatures and atmospheric carbon dioxide concentrations)[15,16]. In addition, process-based models are capable of simulating impacts with high levels of local-scale complexity and nonlinear interactions, such as air chemistry and hydrologic modelling, which are difficult to adequately represent through econometric analysis. Finally, process-based models offer the capability to simulate the effects of biophysical, behavioural or technological adaptations on reducing climate damages, as is done for a number of sectors in this framework (Table 1). However, process-based models come with their own challenges, including the need for extensive parameterization, calibration and validation (see the underlying literature referenced in Table 1 and Supplementary Table 3 for discussions of individual sectoral model calibration and validation, including the uncertainty involved with these processes), which can be constrained by the availability of temporally and spatially resolved historic datasets. Furthermore, some process-based models have large computational demands, which often limit the extent to which multiple uncertainty sources can be explored. These parameterization and computational demands can also constrain resources to analyse structural uncertainty through the use of multiple sectoral models, which has been shown to be important for impacts analysis[17].

For each sectoral model shown in Table 1, inputs from ten climate projections are used, built using two forcing scenarios

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Table 1 | Descriptions of sectoral impact analyses

Sector[a]	Summary of approach, key physical metrics and valuation	Adaptation simulated
Health		
Air quality[25]	Temperature effects on future ozone concentrations and the resulting number of premature deaths are economically valued with the income-adjusted value of a statistical life (VSL)	None
Aeroallergens[26]	Change in oak pollen season length, exposure to pollen concentrations and the resulting number of asthma-related emergency department visit is economically valued via cost per visit	None
Extreme temperature mortality[27]	The number of premature deaths on projected population attributable to extreme hot and cold temperatures (in 49 major cities only) is economically valued with the income-adjusted VSL	Adjustment of mortality thresholds to include higher levels of capacity[b]
Labour[28]	Lost labour supply hours due to changes in hot and cold temperature, including extreme temperatures, are economically valued via lost wages scaled by economic growth	None, other than those adaptations represented in the observed period
West Nile virus[29]	The impact of temperature on the number of West Nile neuroinvasive disease cases is economically valued with the income-adjusted VSL and hospitalization costs	None
Harmful algal blooms[30]	Change in the occurrence and severity of cyanobacterial harmful algal blooms is economically valued by lost consumer surplus from the number of reservoir recreational visits	None
Infrastructure		
Roads[31]	The vulnerability of current paved, unpaved and gravel roads to future changes in temperature, precipitation and freeze–thaw cycles is economically valued by costs of repair or rehabilitation	Reactive or proactive repair or rehabilitation costs to maintain level of service
Bridges[32]	The vulnerability of current non-coastal bridges to future changes in peak water flow is economically valued by costs of repair or rehabilitation	Costs of proactive maintenance and repairs to maintain level of service
Rail[33]	The vulnerability of the current Class I rail network (passenger and freight, volume scaled by change in economic growth) to changes in temperature is economically valued by costs of delays and sensor installation	Reactive costs of reduced speed and traffic to railroad companies and to public, and proactive adaptation costs to install sensors
Alaska infrastructure[34]	The vulnerability of current roads, buildings, airports, railroads and pipelines to changes in permafrost thaw, freeze–thaw cycles, precipitation and precipitation-induced flooding is economically valued by costs of repairs, rehabilitation or reconstruction	Reactive and proactive adaptation expenditures to maintain level of service
Urban drainage[35]	Change in volume within the current urban drainage network (in 100 major cities only) due to changes in rainfall intensity and runoff is economically valued by costs of best management practices/offsets (for example, bioswales)	Proactive adaptation costs to implement stormwater best management practices
Coastal property[36]	The vulnerability of current on-shore property to sea-level rise and storm surge is economically valued by abandoned property values (scaled by changes in economic growth) and costs of protective adaptations	Abandonment, property elevation, beach nourishment and seawall construction
Electricity		
Electricity demand and supply[37]	Changes in electricity demand (based on projected population and economic growth) and supply (including hydropower generation) in response to changes in temperature and flow are economically valued by system costs (capital, operations and maintenance, and fuel costs)	Changes in cooling and heating demands for residences and buildings

Continued

Table 1 | Descriptions of sectoral impact analyses (Continued)

Sector[a]	Summary of approach, key physical metrics and valuation	Adaptation simulated
Water resources		
Inland flooding[38]	Changes in the frequency of 100-year riverine flooding events are economically valued via damages to current assets located in floodplains (for example, buildings)	None
Water quality[39,40]	Changes in river, lake and reservoir water quality based on modelling of temperature, dissolved oxygen, total nitrogen and total phosphorus are economically valued by willingness-to-pay estimates for offsetting changes in the water quality index	Water allocated to different sectors on the basis of available supply
Municipal and industrial water supply[41]	Changes in water supply to meet municipal indoor, municipal outdoor and industrial water demands (based on projected population) are economically valued by changes in consumer welfare	Water allocated to different sectors based on available supply
Winter recreation[42]	The impact of changes in snowpack on recreation visits for downhill skiing and snowboarding, cross-country skiing and snowmobiling is economically valued by lost recreation (lift ticket and entry prices)	Snow-making included as a response
Agriculture		
Agriculture[43]	Impacts of changing climate conditions on yields of major US crops (for example, corn, soybean, wheat, alfalfa hay and cotton) are economically valued by change in producer, processor and consumer welfare	Landowners change crop mix, production practices and land allocation in response to yield changes
Ecosystems		
Coral reefs[44]	Percentage change in shallow coral reef cover is economically valued by lost recreational value of visitors	Autonomous adaptation by coral types
Shellfish[45]	Effects of ocean acidification on growth rates of oysters, scallops, geoducks, quahogs and clams, with subsequent effects on shellfish supply, are economically valued by change in consumer welfare	Consumers switch shellfish purchases on the basis of changes in price/supply
Freshwater fish[46,47]	Change in the spatial distribution of suitable habitat for coldwater, warmwater and rough fish species inhabiting rivers and streams is economically valued by lost recreational value to anglers	Anglers shift target fish guilds on the basis of proximity and willingness to travel
Wildfire[48-50]	Change in terrestrial ecosystem vegetative cover and acres burned on non-agricultural, undeveloped lands is economically valued by change in wildfire response costs	None

[a] See Supplementary Table 3 for expanded information and additional references on each sectoral model. [b] A sensitivity analysis was conducted using assumptions that approximated higher physiological adaptation and increased availability of air-conditioning by setting the threshold temperature for extreme heat days equal to the observed threshold values for Dallas, Texas, the second warmest city in the analysis.

(representative concentration pathways, or RCP8.5 and RCP4.5) in five general circulation models (GCMs) that are statistically downscaled and bias-corrected, and chosen to reasonably cover the range of temperature and precipitation outcomes in the CONUS observed across the entire ensemble from the Coupled Model Intercomparison Project 5 (CMIP5; see Supplementary Section 2)[18]. Our modelling framework evaluates the effects of increasing population and economic growth over time, while preserving the ability to isolate climate-driven changes under this dynamic socioeconomic scenario.

Regional distribution of impacts

Synthesis of impacts across sectors reveals highly complex patterns, with each region projected to experience a unique mix of physical and economic effects. Figure 1 shows 16 sectors with spatially resolved impacts across the CONUS; 6 sectors are not shown due to the impact area falling outside the CONUS (that is, coral reefs and Alaska infrastructure), the impacts not being spatially resolved below the NCA4 regional level, as they were simulated as part of a national market (that is, agriculture and shellfish), or because of other constraints on spatial display (that is, roads and urban drainage); see Supplementary Tables 4–8 for national and NCA4 regional estimates of all sectors.

The inclusion of 22 sectors in this broader analysis demonstrates the compounding effect of multiple climate impacts, an important feature not observed in single-sector analyses. Understanding where multiple risks are projected to occur can also identify areas where risks in one sector may lead to weakened adaptive capacity in another, which could result in greater impacts than projected, or even cascading failures. For example, the inclusion of location-specific water supply in the electricity demand and supply analysis, to account for constraints on water availability for thermo-electric cooling, results in increased vulnerability to the electric power system through higher system costs (see Supplementary Table 9). While the current work includes inter-sectoral connections between the agriculture, water and electric power system models, the project framework generally fails to capture other important interactive effects between sectors. While fully interactive modelling of all sectors in a single integrated assessment framework could provide insight beyond what is reported here, such platforms are not yet capable of quantifying such a large number of sectoral impacts at high temporal and spatial resolutions.

Previous research[10] suggests that southern states of the CONUS, where large adverse impacts are projected in labour, extreme temperature mortality, energy and coastal sectors, will experience the

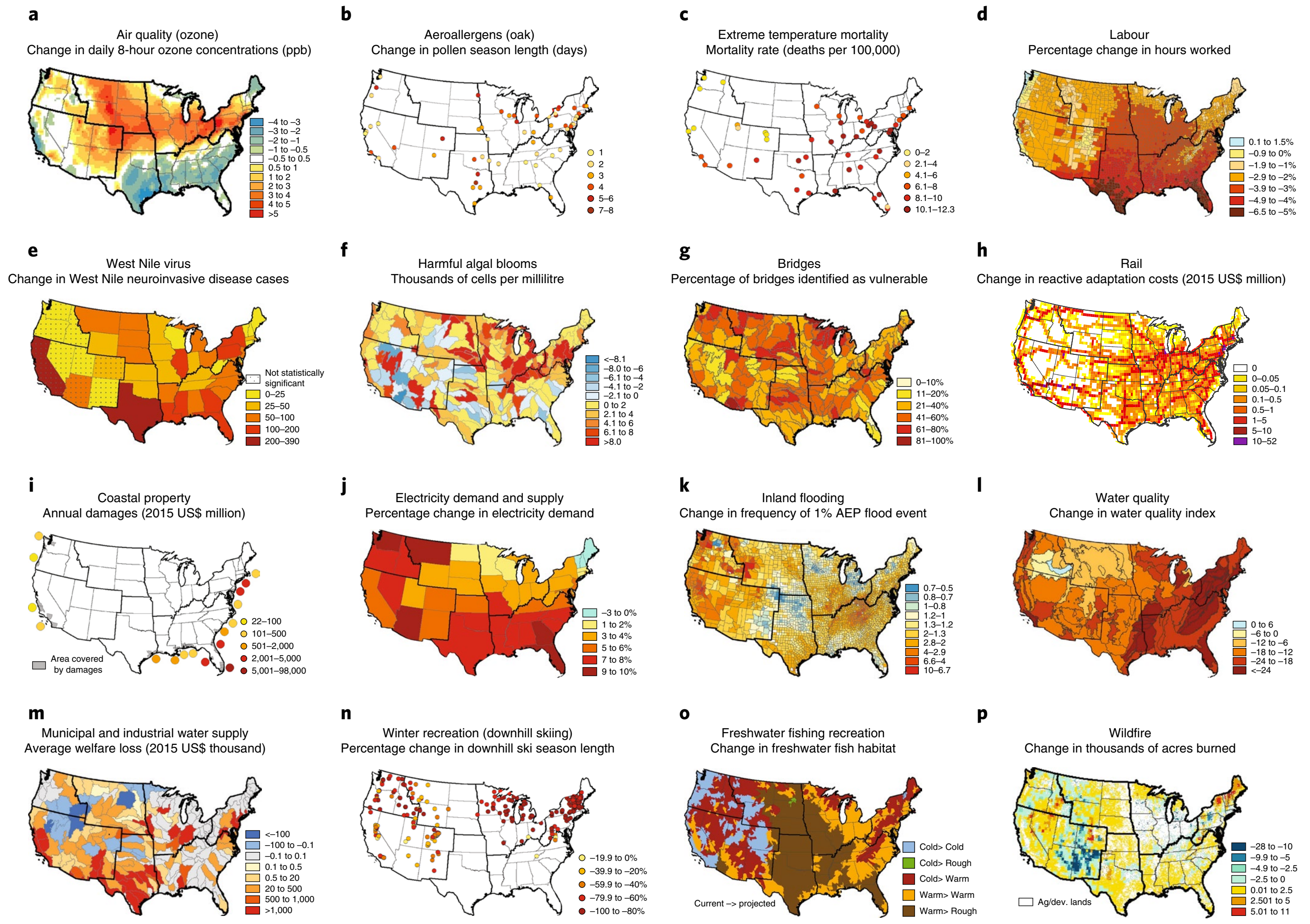

Fig. 1 | Geographic distribution of select projected climate impacts. a–p, Annual impacts projected under RCP8.5 in 2090 (5-GCM average unless otherwise noted) for change in summer-average maximum daily 8-h ozone concentrations (ppb) from the 1995–2005 reference period under the CCSM4 climate model alone (**a**), change in oak pollen season length (days) from the 1994–2010 reference period (**b**), net premature mortality rate (deaths per 100,000 people) from extremely hot and cold days in 49 cities from the 1989–2000 reference period (**c**), percentage change in hours worked in high-risk industries from the 2003–2007 reference period, normalized by the high-risk working population by county (**d**), change in West Nile neuroinvasive disease cases by state from the 1986–2005 reference period (**e**), change in waterbody surface cyanobacteria (thousands of cells per millilitre) for a low-growth scenario relative to a control (no-climate) scenario aggregated to 4-digit hydrologic unit codes (HUCs) (**f**), percentage of bridges identified as vulnerable (immediate repair needed to maintain level of service) due to incremental effects of climate change aggregated to 4-digit HUCs (**g**), change in reactive adaptation costs (delays due to reduced speed and traffic) to the Class I rail system from the 1950–2013 reference period (**h**), damages to coastal property from sea-level rise and storm surge for 17 multi-county areas (chosen as examples) assuming no adaptation (**i**), percentage change in state-level electricity demand from the Global Change Assessment Model relative to a control scenario without climate change (**j**), change in the frequency of the 2010 baseline (2001–2020) 1% annual exceedance probability (AEP) (or `100-year') flood event (such that a value of 2 represents a doubling in the frequency of a 100-year flood event) (**k**), change in the water quality index under the HAWQS biophysical model relative to the 1986–2005 reference period aggregated from the 8-digit HUC level to the level-III ecoregions, weighted by area (see Supplementary Fig. 9 for US Basins model results) (**l**), welfare loss from impacts on municipal and industrial water supply, aggregated to the 4-four-digit HUC scale (**m**), percentage change in downhill ski season length from the 1986–2005 reference period at 247 modelled locations (**n**), change in freshwater fish habitat (8-digit HUC scale) from the 2011 reference year under only the CCSM4 climate model (**o**), change in acres burned (all vegetation types) from the 1986–2005 reference period (agricultural and developed lands removed) aggregated to ½ degree cell resolution (**p**). The differences in the reference periods are due to constraints unique to each sectoral impact model.

greatest economic damages of climate change, while northern states will experience lesser damages or even benefits of climate change for these sectors. Our analysis found similar spatial patterns of high economic damages in southern regions for these four sectors, as well as for the West Nile virus, inland flooding and urban drainage sectors (see Supplementary Tables 7 and 8). However, inclusion of additional sectors not considered by the previous work shows that there are no regions that escape some form of adverse physical climate impact (see Fig. 1 and Supplementary Table 6). For example, the Northeast, Northern Plains and Midwest are projected to experience disproportionately larger increases in 8-h maximum ozone concentrations (air quality) and oak pollen season lengths (aeroallergens; Fig. 1), resulting in hundreds of future excess annual ozone-related premature deaths and asthma-related emergency department visits (Supplementary Table 6). Potentially compounding health impacts of reduced air quality, longer pollen seasons and extreme heat highlight an important vulnerability in the Midwest and Northeast. The Northwest and Northern Plains are projected to experience high increases in electricity demand and the frequency of exposure to 100-year flood events relative to southern regions

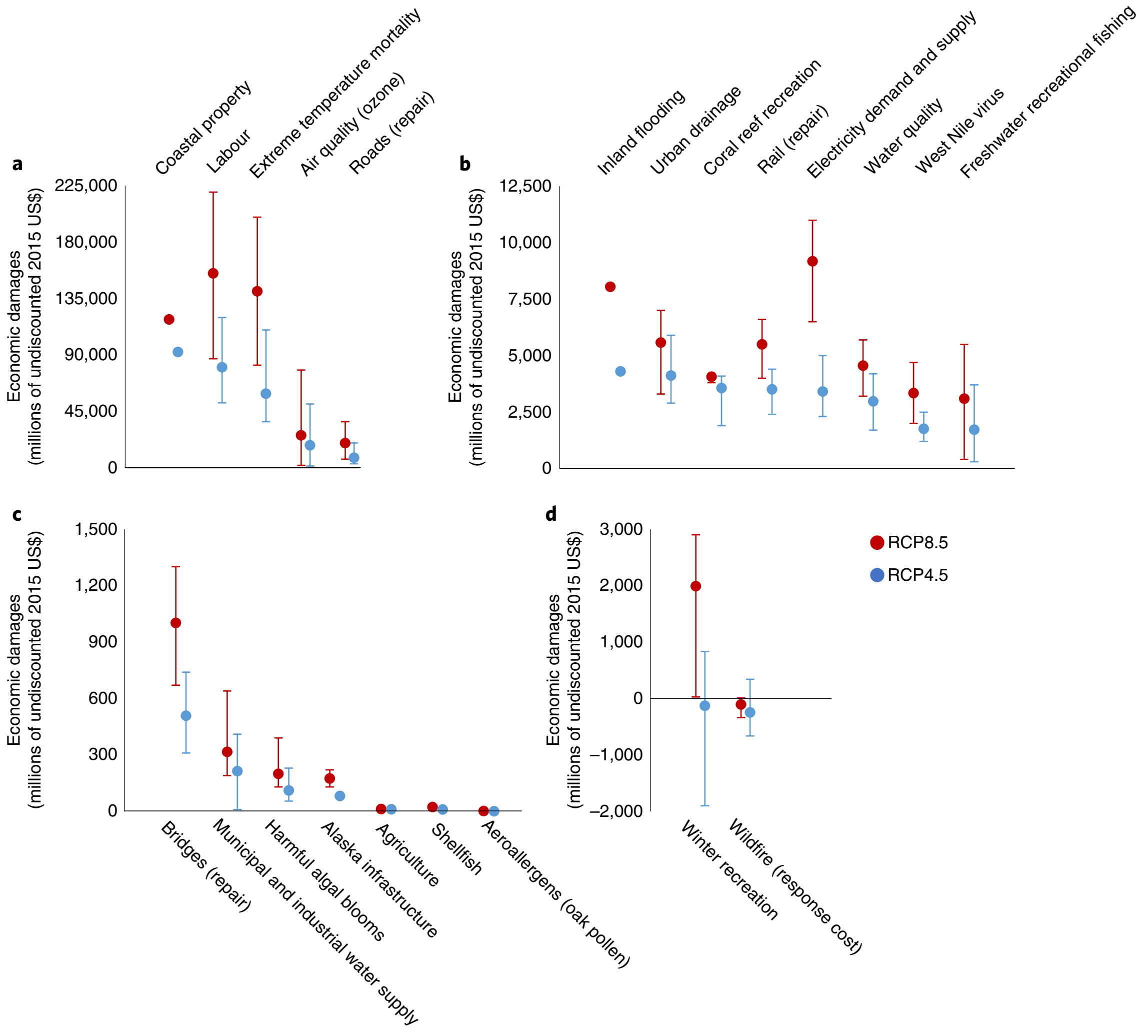

Fig. 2 | Annual economic damages from climate change under two mitigation scenarios. a–d, Mean estimates of annual climate change damages in millions of undiscounted 2015 US dollars for RCP8.5 and RCP4.5 in 2090. The four graphs are on different scales to capture the range of impacts. Note that **d** includes negative damages (benefits). Unless noted, the upper and lower bounds are based on values across the climate models. The data underlying this graphic can be found in Supplementary Table 5. For coastal property, costs with no adaptation are shown. The upper/lower bounds are not shown from the probability-based sea-level projections. For air quality, mean and upper/lower bounds are shown based on confidence intervals from the BenMAP-CE model. For inland flooding, GCM-specific results were not derived as part of the analysis. For electricity demand and supply, the results are from the Global Change Assessment Model power sector model alone. For water quality, range and mean values based on combined results from US Basins and HAWQS are shown.

(Fig. 1); these northern regions are also projected to incur damages to iconic or culturally significant resources, such as the loss of recreational opportunities for winter recreation or freshwater fishing for highly prized coldwater species (Supplementary Table 6). While not the largest source of economic damages, such recreational impacts can be very important to local economies that rely on these activities. See Supplementary Section 3.2 for additional comparisons to sectoral results from previous studies.

Many impacts are projected to be greater in the eastern half of the United States than in the western half (for example, rail and coastal property; Fig. 1). For water quality, both sector models used project larger impacts to eastern states (see Supplementary Fig. 9). This geographic pattern is in part due to larger population densities and urban areas in these regions. However, the lack of duplicate infrastructure may also make rail, road and bridge delays or closures for repair more significant to residents in some western states, as there are fewer alternative transportation routes. Vulnerability associated with this lack of infrastructure redundancy is particularly meaningful in Alaska, where road flooding associated with increased precipitation is projected to be the largest source of reactive repair costs. By including a large number of sectors, a complex geographic pattern of damages emerges, with each region projected to experience a different mix of physical and economic impacts of climate change.

Effect of mitigation in reducing damages

Substantial reductions in global greenhouse gas (GHG) emissions would reduce climate change impacts in the United States (Fig. 2). Projected physical and economic damages are larger under RCP8.5 than under RCP4.5 across all 22 sectors and both time periods, with only 1 exception (urban drainage adaptation costs in 2050; see Supplementary Table 5). Damages associated with extreme weather, such as extreme temperature, heavy precipitation, drought and storm surge events, are substantially reduced under RCP4.5. For example, more than twice as many 100-year riverine inland flooding events are projected across the CONUS under RCP8.5 compared to RCP4.5 by the end of the century (see

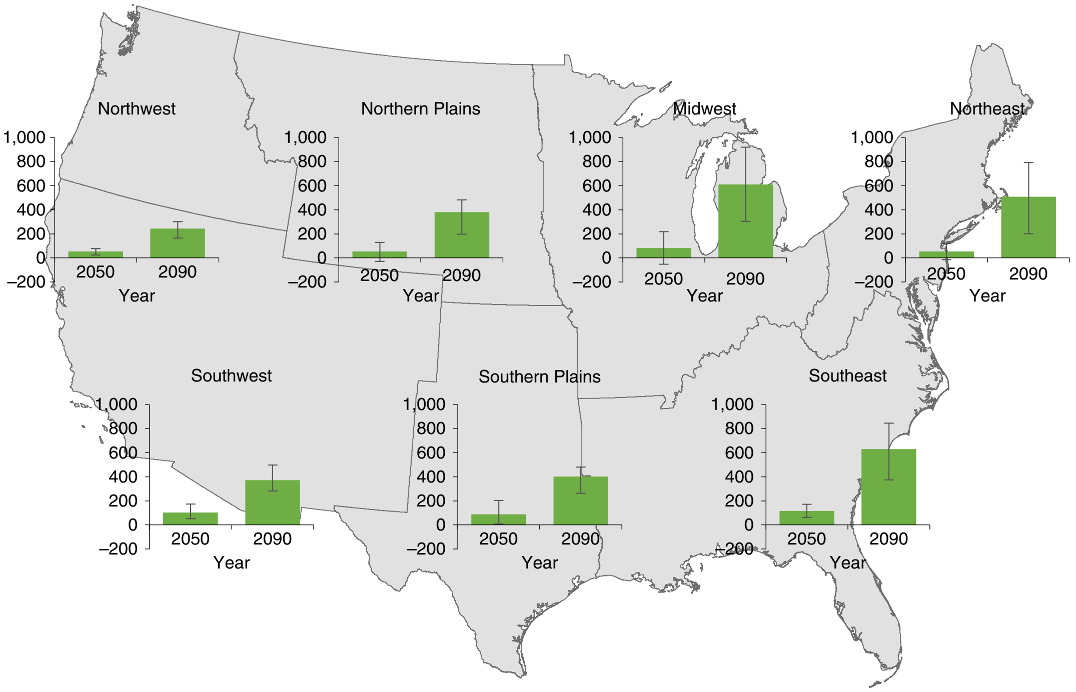

Fig. 3 | Projected regional economic effects of global climate mitigation. Estimated annual, per capita economic effects of global GHG mitigation (RCP8.5 minus RCP4.5 in undiscounted 2015 US$) in 2050 and 2090 for 20 sectors of the United States (the agriculture and shellfish sectors are excluded because they use national market models; see Supplementary Table 5 for those values). Positive numbers represent benefits, or avoided damages, due to climate mitigation. The upper and lower bounds are based on values across the climate models (see Fig. 2 for exceptions). See Supplementary Tables 7 and 8 for additional data.

Supplementary Fig. 10), resulting in avoided costs of approximately US$4 billion per year (Fig. 2).

Avoided damages (RCP8.5 minus RCP4.5) under each sector range across several orders of magnitude, from millions to tens of billions of US dollars in annual benefits by the end of the century (see Supplementary Table 5). These avoided damages are projected to increase over time, and the range of potential damages is generally narrowed under RCP4.5 compared to RCP8.5 (Fig. 2). Extreme temperature mortality, labour, coastal property and roads are the sectors projected to have the largest avoided damages under RCP4.5, in the range of US$12 billion to US$82 billion each year; air quality and electricity demand and supply are each projected to see savings under RCP4.5 of more than US$5 billion each year (see Supplementary Table 5 and Supplementary Fig. 11 for projected changes in electricity demand from two electric power sector models and time periods). Importantly, projected impacts are only partially quantified or valued in many sectors. For example, the air quality analysis did not include changes to fine particulates and other non-ozone air pollutants. Therefore, the damages reported in Fig. 2 and Supplementary Table 5 are probably underestimates of the actual climate impacts that would occur under any given scenario.

The sum of projected regional, annual per capita effects of global GHG mitigation for 20 sectors is large (Fig. 3), particularly in 2090. Despite each region experiencing a complex mix of different sectoral impacts with varying associated economic damages, the benefits of mitigation are relatively similar across regions on a per capita basis. Smaller estimated benefits in the Northwest and Northern Plains compared to the eastern regions are explained by small to no projected regional damages in some of the sectors with the highest national economic impacts (for example, labour and coastal property), and artefacts of methodological limitations. For example, none of the 49 cities in the extreme temperature mortality analysis is located in the Northern Plains, and the 3 cities located in the Northwest were too cool in the historic baseline to derive heat mortality response functions, leading to underestimates of the change in future mortality in those cities under a warming climate.

Risk reduction through adaptation

The explicit evaluation of adaptation impacts in multi-sector climate impact modelling frameworks has been limited[19], with the concurrent effects of adaptation and mitigation being considered only in select sectors, such as agriculture[20]. Adaptation options can vary depending on the sector, the timing of implementation and other factors. Importantly, adaptation is not as relevant in many sectors (for example, harmful algal blooms).

Within the CIRA2.0 framework, the sector-by-sector modelling of adaptation takes different forms (Table 1 and Supplementary Section 3.3). We illustrate specific sector-level adaptations and their economic implications for three sectors where adaptation is understood to be an effective response: coastal property, roads and rail. The coastal property analysis quantifies damages from sea-level rise and storm surge with adaptation (abandonment or property protection using various strategies) and without adaptation, using a risk-based cost–benefit framework to estimate optimal responses based on the costs of protection versus property and asset values. The roads analysis estimates the costs of climate change impacts in the form of reactive adaptation (repairs) to maintain current levels of service and evaluates the ability of proactive adaptation measures (planned rehabilitation) to improve resiliency and reduce overall costs. The rail analysis quantifies the costs associated with delays from train speed reductions to reduce the risk of track buckling during high-temperature periods (reactive adaptation), and the costs of proactive adaptation that include both investments in track monitoring equipment and the implications of unavoidable residual delays.

Table 2 summarizes the effects of global-scale GHG mitigation and local-scale adaptation in reducing impacts in these three

Table 2 | Modelled effects of adaptation and mitigation in reducing infrastructure damages

		Annual average costs in 2090 (billions of undiscounted 2015 US$)		
Sector[a]	**Scenarios**	**RCP8.5**	**RCP4.5**	**Damages avoided by mitigation (RCP8.5 – RCP4.5)**
Coastal property	Without adaptation	120	92	26 (22%)
	With adaptation	7.3	5.7	1.6 (22%)
	Damages avoided by adaptation	110 (94%)	87 (94%)	**110 (95%)**
Roads[b,c]	Reactive adaptation	20	8.2	12 (59%)
	Proactive adaptation	−7.3	−3.1	−4.2 (58%)
	Damages avoided by proactive adaptation	27 (140%)	11 (140%)	**23 (120%)**
Rail[b]	Reactive adaptation	5.5	3.5	2 (36%)
	Proactive adaptation	1.6	0.40	1.2 (75%)
	Damages avoided by proactive adaptation	3.9 (71%)	3.1 (89%)	**5.1 (93%)**

[a]Roads and rail include estimates for Alaska. [b]Damages due to delays or loss of infrastructure use (that is, indirect effects) are not included in these results and are the focus of future analysis. [c]Supplementary Section 3.2 contains additional information regarding proactive adaptation results for road infrastructure. The results represent averages across the five GCMs by sector. Values shown in bold represent the combined effects of reduced climate change (mitigation) and adaptation (difference in damage reductions between RCP8.5 without adaptation and RCP4.5 with adaptation). The values may not sum due to rounding.

infrastructure sectors. As shown, proactive adaptation measures can substantially reduce the estimated damages from climate change, with projected reductions from adaptation being potentially larger than the effect of mitigation in these specific sectors. All values shown with adaptation include both the costs of implementing those adaptations, and any residual damages not prevented by the protection (but excluding indirect effects). However, implementation of well-timed adaptation measures to maintain service levels is probably an overly optimistic assumption given that infrastructure investments are often delayed and underfunded, and because decision-makers and the public are typically not fully aware of potential risks[21]. In addition, prolonged deferral of maintenance can affect the service level of infrastructure and possibly result in failure, leading to larger public costs than those reported here. The specific adaptation scenarios used in these analyses are designed to bound potential outcomes via no-adaptation (worst case) and well-timed (and for some sectors, economically optimal) actions. In reality, adaptation responses in the aggregate are likely to lie in between these scenarios and be heavily influenced by local-level decision-making that is difficult to capture in national-scale modelling. While the modelled responses for the three exemplary sectors show large potential benefits of adaptation, these findings are not necessarily generalizable to other sectors, many of which are unlikely to show such benefits.

Discussion

Here, the findings from multi-sector economic modelling projects were used to inform the United States Government's Fourth National Climate Assessment[22]. These findings, derived from internally consistent modelling frameworks, provided new opportunities for assessment authors to characterize physical and economic impacts of climate change across sectors, and describe how those risks may be avoided or reduced through global mitigation and adaptation actions. However, there is a continuing need to expand the science and economics involved in this modelling to include additional sectors and to improve characterization of impacts within existing sectors. Given the magnitude and diversity of climate risks that Americans face, decision-makers will increasingly need access to improved projections of how, when and where these risks will change in the future under a range of potential GHG pathways.

This suggests the need for a sustained, and continuously improving, multi-sector modelling process whose periodic findings can be used to inform climate assessments of the USGCRP by further quantifying and assessing the diversity of risks posed by climate change. Similar efforts involving large numbers of modelling groups have successfully been implemented for other climate research topics, including the evaluation of mitigation technologies[23] and strategies for mitigation through energy efficiency[24].

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of data availability and associated accession codes are available at https://doi.org/10.1038/s41558-019-0444-6.

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Author contributions

J.M. and A.C. developed and coordinated the study, compiled data for this paper, designed figures and tables, and wrote the manuscript.

Competing interests

The authors declare no competing interests.

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Methods

Technical documentation for the analytic framework of the second modelling phase of the CIRA project was developed as an input to NCA4[51]. Individual sectoral impact models have been separately documented (see the citations in Table 1 and Supplementary Table 3), including several special issues[52,53].

Climate projections. Selection of scenarios and projections was made consistent, to the greatest extent possible, with inputs being used in the Fourth National Climate Assessment of the USGCRP[22]. Due to the reliance on detailed process-based models for most sectors, computational and resource constraints required the use of a subset of GCMs available in the locally constructed analogues statistically downscaled dataset for the CONUS[54] and the SNAP dataset for Alaska[55]. The locally constructed analogue method was developed to address a variety of shortcomings of earlier approaches, including: increased ability to preserve the daily sequence of weather events simulated in the underlying GCMs, which is important for accurately representing changes in extremes; the construction of a more realistic depiction of the spatial coherence of the downscaled field; and improved ability to more realistically represent the timing and magnitude of regional precipitation[56].

For the CONUS, we chose five GCMs (CCSM4, GISS-E2-R, CanESM2, HadGEM2-ES and MIROC5) with the intent of ensuring that: the subset captured a large range of variability in climate outcomes for the CONUS observed across the entire CMIP5 ensemble; and the models were sufficiently independent and broadly used by the scientific community. The Alaska analyses used only CCSM4 and GISS-E2-R due to the availability of these GCMs in the SNAP database. For each GCM, RCP8.5 and RCP4.5 were chosen to provide a range of plausible emission scenarios. By late century, RCP8.5 is projected to result in mean temperature increases over the CONUS of about 4.8 °C (3.2–6.6 °C) relative to 1976–2005[1], with a global-scale warming of approximately 4.2 °C (2.6–4.7 °C) relative to 1986–2005[57]. Under RCP4.5, mean temperatures are projected to rise by 2.8 °C (1.6–4.1 °C) domestically relative to 1976–2005, and 1.8 °C (1.1–2.7 °C) globally relative to 1986–2005. See Supplementary Sections 2.1 and 2.2 for additional information regarding the selection and characteristics of the climate projections.

We use the United States Government's most recent projections for eustatic sea-level rise[58], which are based on recent empirical research[59]. These projections of location-specific differences in relative sea-level change account for land uplift or subsidence, oceanographic effects, and responses of the geoid and the lithosphere to shrinking land ice. Mean values for tide gauge locations are used, along with a distance weighting procedure for interpolating between tide gauge locations. We apply location-specific storm surge modelling for the Atlantic, Gulf and West coasts of the CONUS[60]. See Supplementary Section 2.3 for additional information regarding these scenarios.

Socioeconomic projections. To account for the effects of increasing population and income on impact estimates, the sectoral analyses use a single trajectory of socioeconomic change under both RCPs. Using a single projection isolates the differences in climate change impacts between the two RCPs, and therefore the effects of GHG mitigation, such that the results will not be influenced by differing pathways of socioeconomic change. The median variant projection of the United Nation's 2015 World Population Prospects dataset is used to represent changes in population for 2015–2100[61]. This scenario represents a reasonable, mid-range population projection: ~450 million residents of the United States by 2100, thus similar to Shared Socioeconomic Pathway 2 (SSP2). We use Census data for historical population changes for the period 1986–2014[62].

As the median variant population projection is available only at a national scale, disaggregated population projections are produced at the county level using the Environmental Protection Agency's Integrated Climate and Land Use Scenarios version 2 (ICLUSv2) model[63]. Supplementary Fig. 7 shows absolute and percentage change in county-scale population in 2050 and 2090. The spatial pattern of population change in ICLUSv2 is dependent on underlying assumptions regarding fertility, migration rate and international immigration. These assumptions are parameterized using the storyline of SSP2, which suggests medium levels of fertility, mortality and international immigration. While global emissions large enough to reach a radiative forcing of $8.5\,\mathrm{W\,m^{-2}}$ are not possible under the SSP2 storyline, the intention of the broader impacts modelling framework was to capture the effects of changing socioeconomics on impact projections, while still allowing for the isolation of damages due to climate change. Therefore, a mid-range storyline was chosen, with the acknowledgement that selection of alternative scenarios would influence impact estimates across sectors[64,65]. Finally, the ICLUSv2 model is also used to develop county-scale demography projections (that is, age, gender and race) and a developed-lands (municipal and industrial development) map layer.

Using the median variant population projection for the United States, the Emissions Predictions and Policy Analysis version 6 (EPPA-6) model[66] is run to generate a projection of economic growth (that is, gross domestic product (GDP)). The projection of GDP growth through 2040 was taken from the 2016 Annual Energy Outlook reference case[67], with post-2040 assumptions for labour productivity growth taken from the EPPA-6 baseline. EPPA-6 baseline assumptions were used for all other world regions across all time periods (see Supplementary Fig. 8 for a depiction of the domestic GDP pathway). The impacts of climate change on economic activity (for example, losses to labour supply or increased capital expenditures for adaptation) are not accounted for in the macroeconomic input projections. As such, the economic growth projection may be overestimated when considering multi-sector damages, and the use of a single national-scale economic growth projection that omits region-specific socioeconomic changes may lead to different localized results from those reported.

Sectoral impact models. The CIRA2.0 modelling framework contains a large number of partial-equilibrium, process-based sectoral impact models, each of which develops a unique set of physical and economic endpoints (Table 1). Each sectoral model was developed to simulate endpoints at temporal and spatial scales most appropriate to that particular impact, while also considering constraints imposed by data availability and computational efficiency. Modelling results can be reported at the native resolution of each sectoral impact model, varying from different administrative scales (for example, cities and counties) to watershed-based boundaries (for example, four-digit HUCs), and then spatially aggregated to NCA4 regions and the national level. To account for climate variability, impact modelling results presented in this paper generally represent annual averages across 20-year periods centred on the target years of 2050 and 2090. All economic values represent annual averages for those target years in undiscounted 2015 US dollars. Many of the sectoral models directly simulate how adaptive actions, including region-specific changes in behaviour and technology, may reduce adverse impacts and exposure.

Interpretation of results. In this paper, we do not focus on the sum of economic damages at national scales or discuss the social or economic implications of redistributive effects for two main reasons. First, while this project includes extensive coverage of sectoral impacts, the full extent of physical and/or economic impacts is not captured in many of the sectoral impact analyses. For example, the wildfire analysis captures only suppression costs, and does not estimate health impacts from degraded air or water quality, property damage or timber loss. Furthermore, our framework would be improved by including other important sector estimates, such as impacts on national security, mass migration, crop yields due to changes in pests/ozone, forest products, other air pollutants (for example, fine and coarse dust) and other infrastructure (for example, ports, telecommunications and electricity distribution). While the magnitude of reported estimates for many sectors is quite large, the omitted impacts lead to an incomplete estimate of total economic risk. Second, aggregating sectoral damages at national scales, which often become the focus of science communication, can conceal important risks and potentially introduce uncertainty. As this paper has shown, the regional patterns of climate change impacts for each sector can show complex patterns of positive or negative individual effects.

Several additional limitations are important to note for proper interpretation of our results. First, the predominant use of computationally intensive process-based models limited the number of scenarios that could reasonably be employed in this project's framework. The set of GCMs used in this framework, along with the broader CMIP5 ensemble, do not collectively represent a complete probability distribution of potential future outcomes because they systematically underestimate tail risks[68]. Evaluation of impacts under a broader set of global climate models and socioeconomic scenarios would provide a more complete characterization of potential impacts in the future. Second, with the exception of several sectors (for example, electricity demand and supply and water quality), the impact estimates presented were developed using a single-sectoral impact model. These models are complex analytical tools, and choices regarding the structure and parameter values of the model affect estimation of impacts. Ongoing studies are finding that the influence of these structural assumptions can be substantial across impact models[17]. Third, while the current work included inter-sectoral connections between the agriculture, water and electric power system models, the project framework generally fails to capture other important interactive effects between sectors, such as compounding health effects of extreme heat and high ozone. Fourth, while our approach generally uses dynamic, internally consistent assumptions about socioeconomic change over time, we do not investigate uncertainties regarding this projection; the importance of which has been highlighted in recent research[7]. Despite these important uncertainties, this project produced estimates of future impacts using best available data and methods, and developed a framework that can be revisited and updated over time as science and modelling capabilities continue to advance.

Data availability

Scenario and projection data used in this project are publicly available at http://loca.ucsd.edu/, https://www.snap.uaf.edu/ and https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf. Metadata, figures and results have been posted to the Global Change Information System (https://data.globalchange.gov/), and technical documentation for the project is available on the Environmental Protection Agency's Science Inventory (https://cfpub.epa.gov/si/si_public_record_Report.cfm?dirEntryId=335095). Sectoral impact data from the CIRA2.0 modelling project have been posted (https://www.indecon.com/projects/benefits-of-global-action-on-climate-change/). Remaining data and results of this paper are available through the corresponding author on request.

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