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The Unintended Health Consequences of Carbon Pricing Policies

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Abstract

Climate mitigation policies curb emissions by raising the price of energy, yet energy is also what households rely on to adapt to extreme temperatures. Can these policies generate unintended health harms by constraining adaptation? Using data on carbon pricing and mortality for 346 first-level administrative units in 14 countries from 1991 to 2021, we find that each additional US\$1/tCO₂ is associated with 1.1 additional deaths per 100,000 people on a 35°C day. Carbon pricing lowers residential energy consumption and air-conditioning use, shifts households toward cheaper but more polluting solid fuels, and increases heat-related morbidity beyond mortality. Weighing these mortality costs against climate and air-quality benefits, the global benefit-cost ratio of carbon pricing is approximately 20, but net benefits may be negative for some developing countries. These findings reveal an inherent tension between climate mitigation and adaptation, highlighting the need to integrate health protection into climate policy design.

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1 As climate change increasingly harms human health, carbon pricing policies have become
2 essential tools for climate mitigation. By the end of 2025, 43 carbon taxes and 40 active emissions
3 trading systems (ETs) had been implemented worldwide, collectively overseeing 28% of global
4 greenhouse gas emissions and covering 67% of the global GDP¹. Looking forward, there is
5 notable momentum in this area, with an additional 15 carbon taxes and 24 ETs currently under
6 development or consideration¹.

7 However, these policies may also generate unintended health consequences. By raising en-
8 ergy costs, they weaken households' ability to adapt to climate stress. This places mitigation in
9 tension with adaptation. The 2018 Yellow Vest protests in France exemplify the backlash against
10 the increased costs placed on low- and middle-income households. These economic pressures
11 may restrict access to cooling, heating and other forms of health protection, thereby increasing
12 health risks in a warming climate.

13 Despite the recognition that climate policies must balance environmental sustainability with
14 social and economic equity, most studies either offer conceptual frameworks or *ex ante* predic-
15 tions of green transition pathways. There remains a lack of empirical assessment of how carbon
16 mitigation policies *have* affected health outcomes related to climate adaptation—a gap this article
17 seeks to fill.

18 We first estimate the unintended health impacts of carbon pricing policies at the subna-
19 tional scale, covering 346 first-level administrative (ADM1) units in 14 countries, then examine
20 the mechanisms underlying these impacts. We next conduct a further analysis that examines
21 detailed heat-related health outcomes and adaptation behavior following the implementation of
22 state-level carbon pricing policies in the United States, taking full advantage of rich state-level
23 data on heat-related morbidity, air-conditioning use, electricity prices and consumption, and
24 income. Lastly, we perform a cost-benefit analysis of carbon pricing policies, comparing the
25 benefits of reducing greenhouse gas emissions and air pollution with the estimated mortality
26 costs associated with reduced adaptation.

27 This paper is related to three strands of literature. The first strand studies how access to
28 energy shapes households' ability to protect their health during extreme weather. A large em-
29 pirical literature shows that electricity use, particularly for air conditioning, rises substantially
30 during extreme weather events as households rely on cooling or heating technologies to maintain
31 safe living conditions^{2,3,4}. The diffusion of air conditioning has played a central role in reduc-
32 ing heat-related mortality: over the past 60 years, the mortality impact of extreme heat in the
33 United States has fallen by approximately 75%⁵. However, access to energy for climate adap-
34 tation is uneven. Low-income households often face difficult "heat or eat" trade-offs during
35 extreme weather^{6,7}. In 2020, the U.S. Energy Information Administration reported that 34 mil-

lion American households struggled to pay energy bills needed to maintain comfortable indoor temperatures. These households are also more likely to live in energy-inefficient buildings and rely on outdated appliances^{8,9}, which further increases their health vulnerability to climate risks. This paper contributes to this literature by linking carbon pricing policies to extreme-weather mortality through their effects on energy access.

The second examines the impacts of carbon pricing policies. A large body of research emphasizes their environmental benefits, showing that carbon taxes and ETSs significantly reduce CO₂ emissions, particularly in the power sector^{10,11,12,13,14}. By limiting emissions from regulated firms, these policies also reduce ambient concentrations of air pollutants, including SO₂, PM_{2.5}, PM₁₀, and NO_X, generating important health co-benefits through cleaner air^{15,16,17}. Some studies also consider the economic costs of carbon pricing, generally finding limited effects on economic performance but mixed distributional consequences for households^{13,14,18,19,20,21,22}. This paper contributes to this literature by documenting the unintended health effects of carbon pricing policies and their underlying mechanisms.

The third strand studies climate justice and the concept of a “just transition.” Existing work highlights both the unequal distribution of climate risks and adaptation burdens, and the challenge of sharing mitigation responsibilities fairly across countries and social groups^{9,23,24,25,26,27,28}. More recent work has begun to recognize that the challenges of climate mitigation may be particularly acute in low- and middle-income countries (LMICs)^{29,30,31}. Some even argue that carbon pricing may be ill-suited for the poorest countries³². Empirical evidence, however, remains limited, especially from studies focused directly on LMICs^{33,34}. This paper contributes to this literature by providing global ex post evidence on how carbon pricing policies affect health associated with climate adaptation, and on how these risks are distributed unevenly across countries.

Results

Impacts of Carbon Pricing Policies on Mortality

Mortality by Income and Climate. Figure 1 presents the effects of carbon pricing policies on all-cause mortality rates across daily mean temperatures, estimated using the fourth-order polynomial specification in Equation (1) with data for 346 ADM1 units in 14 countries from 1991 to 2021. This approach identifies the mortality effects of carbon pricing policies from variation in distribution of daily mean temperatures and carbon prices across ADM1 units and years, while allowing these effects to vary with long-run income and climate. To illustrate the heterogeneous carbon pricing effects on the mortality-temperature response function, we divide the sample into nine income-climate cells based on terciles of long-run income and climate. Then, we plot

the estimated policy effects across daily mean temperatures, evaluated at the mean income and climate values of the corresponding cell.

Importantly, all regressions include country-specific precipitation functions and interactions between the temperature polynomial terms and healthcare quality and air pollution to account for other mortality determinants. The air pollution controls deserve particular emphasis: since carbon pricing lowers ambient air pollution, controlling for pollution absorbs the health gains operating through improved air quality, so the estimated coefficients recover the gross adaptation-related health costs of the policies rather than their net health effects. The air quality co-benefits are instead quantified separately in the cost-benefit analysis. ADM1-specific linear time trends are included to absorb gradual changes within each ADM1 unit over time. ADM1 fixed effects are included to control for time-invariant local characteristics. Country-by-year fixed effects absorb everything common to a country in a given year, including the overall stance of national environmental and energy policy, concurrent regulations, macroeconomic conditions and nationwide energy price movements, so that the effects of carbon pricing are identified solely from within-country variation across ADM1 units.

On average, each additional US\$1/tCO₂ raises the mortality impacts of a hot day at 35°C by 1.1 deaths per 100,000 people relative to a 20°C day. This indicates that the implementation of carbon pricing policies, at the sample average price of US\$4.9/tCO₂, will increase the mortality impact of hot weather by 5.4 deaths per 100,000 people. These policy effects vary substantially across income and climate conditions. Within each climate tercile, the mortality effects of carbon pricing on an additional 35°C day decline from low to high income regions. Specifically, in low income regions, an additional hot day under carbon pricing increases mortality by 2.07–2.26 deaths per 100,000 people, far above the 0.02–0.20 increase in high income regions. This indicates that high income largely neutralizes the adverse effects of carbon pricing. Households in high income regions can absorb higher energy costs without cutting protective energy use, so the mortality effects there are close to zero, while the burden falls almost entirely on low income regions. Compared with income, variation in long-term climate plays a limited role in shaping the mortality impacts of carbon pricing policies. For a 35°C day, carbon pricing policies lead to 1.19 extra deaths per 100,000 people in colder regions, 0.19 more than in hotter regions. One plausible explanation is that residents of colder regions are less adapted to high temperatures, so the same 35°C day poses a greater health threat there than in regions long accustomed to heat.

Impacts across Age Groups and Causes. We then examine the mortality effects across different age groups and causes of death. The impacts differ across age groups ([Supplementary Note 2](#)). Both young and elderly populations are negatively affected by the implementation of carbon pricing policies, but the magnitudes are much larger for those aged above 55: at 35°C,

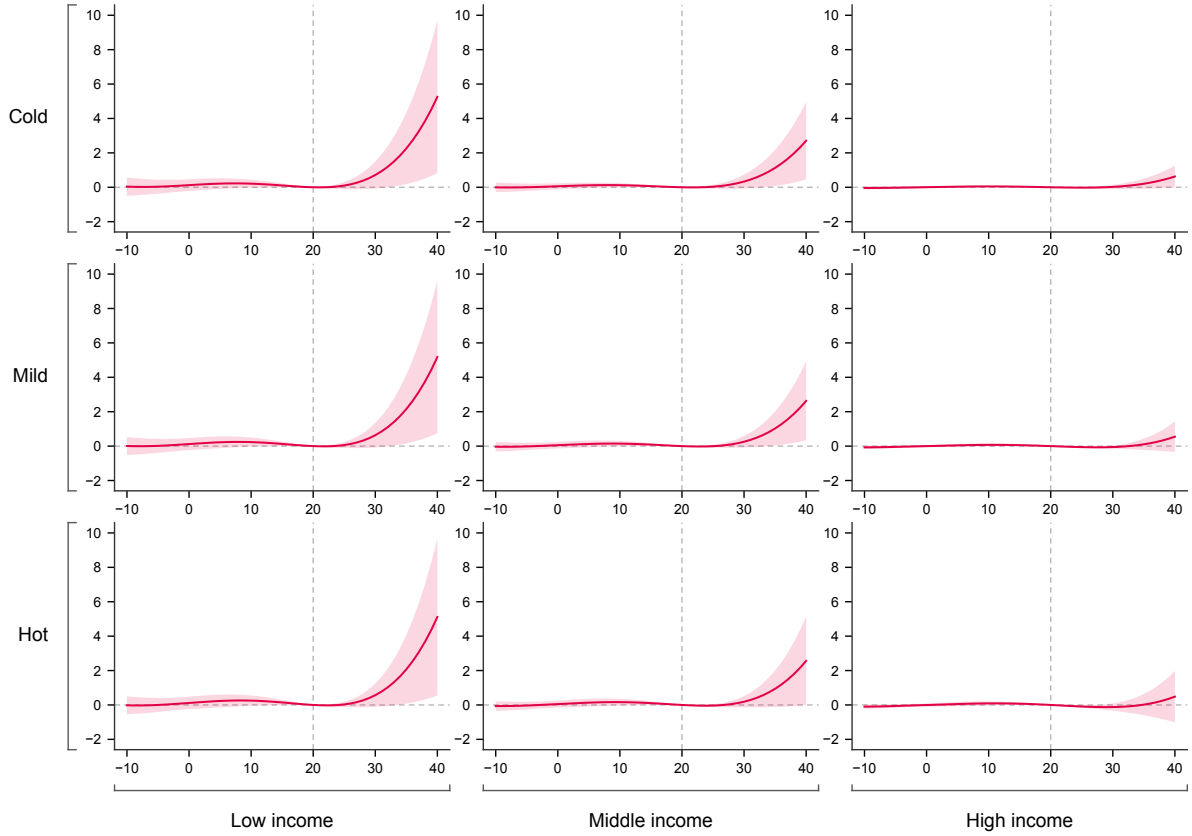


FIGURE 1 | Effects of Carbon Pricing Policies on Mortality by Income and Climate. The figure presents the effects of carbon pricing policies on all-cause mortality rates across daily mean temperatures, estimated using Equation (1) with data for 346 ADM1 units in 14 countries from 1991 to 2021. Each panel corresponds to one cell of the income-climate covariate space, defined by terciles of long-term GDP per capita and long-term mean temperature. Columns show low, middle and high income groups from left to right, and rows show cold, mild and hot climate groups from top to bottom. Estimates in each panel are evaluated at the mean income and climate values of the corresponding tercile cell. The x-axis denotes daily mean temperature, and the y-axis denotes deaths per 100,000 people. The coefficient estimates (lines) and their 90% confidence intervals (shaded areas), calculated using standard errors clustered at the ADM1 level, are presented. The control variables include country-specific precipitation functions, interactions between the temperature polynomial terms and healthcare quality and air pollution, and ADM1-specific linear time trends. All regressions include ADM1 fixed effects and country-by-year fixed effects. The corresponding regression results are reported in [Supplementary Table 1](#).

the mortality increase in the high income and hot regions is 0.2–0.7 larger than that for younger populations, and in low income and cold regions it is even 1.7–2.2 larger. This reveals that carbon pricing policies disproportionately increase mortality among the elderly, whose greater physiological vulnerability to extreme temperatures makes them especially sensitive to the loss of adaptive protection.

These mortality effects are also particularly pronounced for temperature-related causes, including chronic respiratory and cardiovascular diseases ([Supplementary Note 3](#)). Carbon pricing policies significantly increase the mortality responses of these two causes across the temperature distribution relative to 20°C, with larger increases at extreme high temperatures. Specifically, at 35°C, deaths from chronic respiratory and cardiovascular diseases increase by 0.09 and 0.31 per 100,000 people, respectively. This pattern is consistent with the literature^{35,36}. By contrast, a placebo analysis shows no significant effects on temperature-unrelated causes, including infectious diseases, unintentional injuries and other causes ([Supplementary Note 3](#)).

Robustness. We verify the robustness of the estimated mortality effects by considering alternative control variables, model specifications, climate measures and mortality-temperature response function forms, with the results presented in [Supplementary Note 4](#). First, we add educational attainment, institutional quality, labor force informality and income inequality as additional control variables. As with the healthcare and pollution controls in the baseline model, each is interacted with the temperature polynomial terms. Second, we re-estimate the baseline model without population weights to assess the sensitivity of the results to weighting choices. We also exclude controls for air pollution and healthcare quality, allowing these factors to contribute to the estimated mortality effects of carbon pricing. Third, we replace the long-run mean temperature with cooling degree days above 20°C and heating degree days below 20°C, calculated as the sum of temperature differences for all days when the daily mean temperature exceeds and falls below 20°C, respectively. Finally, we use alternative mortality-temperature response function forms, including temperature bin, restricted cubic spline and linear spline specifications to ensure that our results are not driven by the baseline fourth-order polynomial model. All estimates above are comparable to the baseline results, confirming the robustness of our findings.

Mechanisms

In this section, we investigate the mechanisms underlying the health costs. Carbon pricing policies internalize the external costs of emissions by raising energy prices. As a result, households reduce energy consumption to manage expenses, which can limit their ability to cope

effectively with extreme weather events. Our findings indicate that per capita electricity consumption declines by 0.1% following a US\$1/tCO₂ increase in carbon prices (Figure 2a). With the sample average carbon price of US\$4.9/tCO₂, the estimated coefficients imply a reduction of approximately 0.5% in average electricity consumption per capita.

Furthermore, regions with lower income, colder long-term climates, lower urbanization and higher electrification can experience larger reductions in electricity use. First, households in low income regions face tighter budget constraints and are therefore more likely to cut electricity use when electricity prices rise. Second, in cold regions a smaller share of electricity use is tied to essential temperature regulation. Electricity demand in cold regions is therefore more responsive to price increases, resulting in larger reductions in electricity use. Third, rural households often have access to alternative energy sources for heating, cooking or lighting. When electricity prices rise, they can shift toward solid fuels such as coal and firewood, resulting in larger reductions in electricity consumption. Finally, electrification determines how strongly households are exposed to the policy-induced price shock. In highly electrified regions, electricity accounts for a dominant share of household energy use, so carbon pricing, which mainly targets the power sector, raises the cost of most of the energy these households consume, and their electricity consumption falls more sharply.

This reduction in electricity use has significant health consequences, particularly for lower-income households. First, electricity is essential for operating cooling and heating devices that protect against temperature-related illnesses. Studies in Canada, Japan, Mexico, and the U.S. have shown that increased air conditioning use has lowered heat-related mortality over the past decades^{5,37,38}. Moreover, access to electricity allows households to store perishable food through refrigeration³⁹. Improved food quality reduces the incidence of gastrointestinal diseases and food poisoning during heatwaves. Electricity also facilitates the operation of water pumps, ensuring a reliable and clean supply of household tap water, which helps mitigate dehydration risks associated with extreme temperatures. Finally, electricity powers information devices such as televisions, radios, and mobile phones, enabling timely access to extreme weather warnings and enhancing households' capacity to protect their health.

Second, higher electricity costs also lead low-income households, especially in rural areas, to revert to using solid fuels such as coal and firewood for heating and cooking. In 2020, 83% of the global rural population had access to electricity, whereas only 48% used clean cooking fuels, indicating substantial scope for fuel switching among vulnerable households⁴⁰. Burning solid fuels indoors generates high levels of indoor air pollution. We estimate that each additional US\$1/tCO₂ increase in the carbon price raises PM_{2.5} emissions from residential fuel combustion by 0.07% (Figure 2b). The increase is larger in lower income and less urbanized regions, reach-

ing 0.18% and 0.14%, respectively. Residential PM_{2.5} emissions also rise substantially in regions with greater electricity access. In these regions, households are more dependent on electricity, so higher electricity prices create stronger incentives to substitute toward cheaper but more polluting solid fuels.

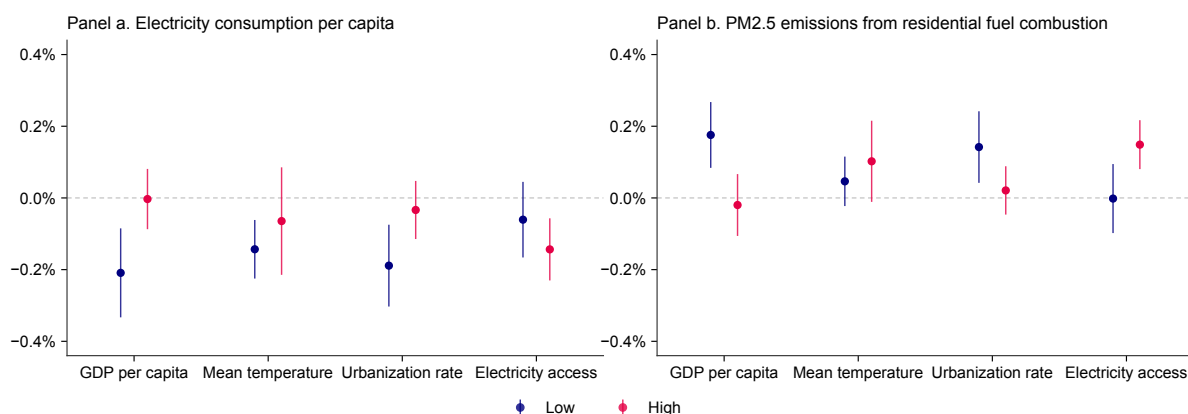


FIGURE 2 | Mechanisms. Panels a and b show the effects of a 1 USD/tCO₂ increase in carbon prices on electricity consumption per capita and on PM_{2.5} emissions from residential fuel combustion, respectively. Both dependent variables are logarithmized. Within each panel, we examine the heterogeneity of these effects across four regional characteristics: GDP per capita, long-term mean temperature, urbanization rate and electricity-accessed population density. For each characteristic, the effect of carbon pricing is allowed to vary with that characteristic. Following the baseline specification, the characteristic is divided into terciles. For clarity and representativeness, we report only estimates evaluated at the mean values of the lower tercile (blue dots) and upper tercile (red dots), comparing the responses of regions with low and high levels of the characteristic. The coefficient estimates (dots) and their 90% confidence intervals (capped lines), calculated using standard errors clustered at the ADM1 level, are presented. All regressions include the same control variables and fixed effects as those used in the baseline analysis. The corresponding regression results are reported in [Supplementary Table 2](#).

Heterogeneity

Our mechanism analysis shows that carbon pricing reduces electricity consumption, thereby constraining electricity-dependent adaptation such as cooling. This suggests that the effects may be stronger in countries where electricity supply is more carbon-intensive. To examine this, we focus on the share of total electricity generation produced from fossil fuels. Countries with higher fossil fuel shares experience significantly larger increases in mortality during hot weather following the introduction of carbon pricing ([Figure 3](#)).

To provide a more comprehensive measurement of climate adaptation capacity, we use the ND-GAIN Country Index from Notre Dame Global Adaptation Initiative, which captures both a country's vulnerability to climate impacts across sectors such as health, food, water, ecosystems and infrastructure, and its readiness to attract and deploy adaptation investment across economic, social and governance dimensions. The index ranges from 0 to 1, with higher val-

ues indicating lower vulnerability and greater readiness to adapt to climate change. The implementation of carbon pricing policies substantially steepens the mortality-temperature response function at high temperatures among countries in the lower tercile of the index.

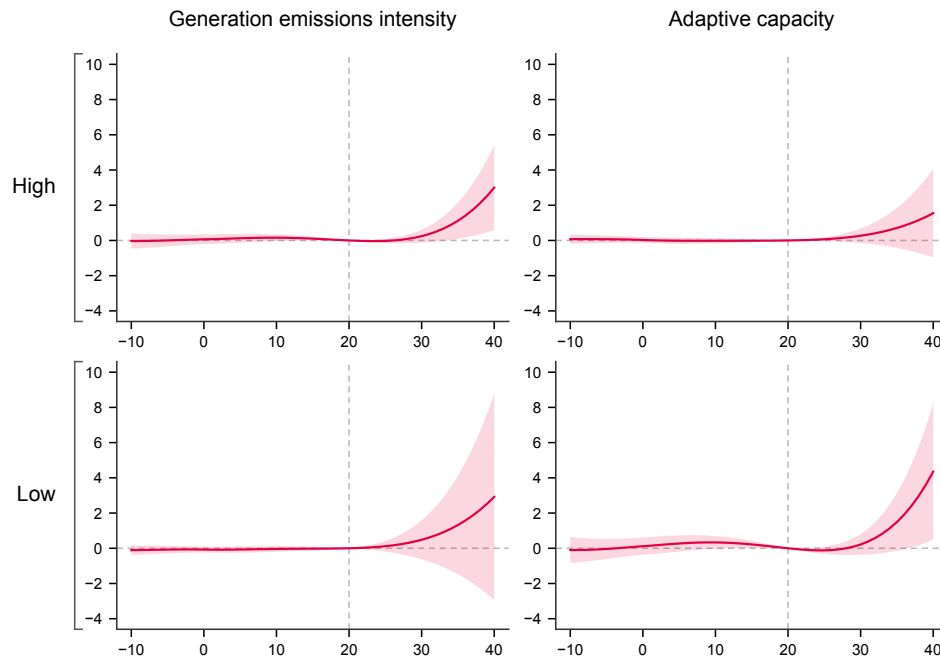


FIGURE 3 | Heterogeneous Effects across Countries. This figure provides evidence on the heterogeneous effects of carbon pricing policies across countries with varying characteristics, estimated by extending Equation (1) to interact the carbon pricing terms with each characteristic. The dependent variable is the all-cause mortality rate. The lines and shaded areas represent the coefficient estimates and 90% confidence intervals, respectively. The first column examines electricity supply, measured by the fossil-fuel share of power generation, where a larger share indicates more carbon-intensive electricity generation. The second column examines adaptive capacity, measured by the ND-GAIN Country Index from Notre-Dame Global Adaptation Initiative, with higher values indicating greater adaptation capacity. Following the baseline specification, the characteristic is divided into terciles. For clarity and representativeness, we report only estimates evaluated at the mean values of the upper tercile (first row) and lower tercile (second row). The control variables and fixed effects are the same as the baseline regressions. The corresponding regression results are reported in [Supplementary Table 3](#).

Beyond Mortality

Mortality captures only the most severe health consequences of carbon pricing policies. However, these policies may also worsen health in ways that increase illness and healthcare use without causing death. To provide a more complete picture of their health effects, we extend the analysis to heat-related morbidity, including emergency department visits and hospitalizations alongside mortality. In addition, we examine more direct and higher-frequency measures of adaptation behavior and capacity that are unavailable in the cross-country subnational analysis, including air conditioning use and state-month data on electricity prices, electricity consumption, and income.

We focus on two major subnational carbon pricing policies in the U.S., including the Regional Greenhouse Gas Initiative (RGGI) launched in 2009 and California’s cap-and-trade (CaT) program launched in 2013. Their staggered subnational adoption provides a useful within-country setting for identifying the health impacts of carbon pricing. We first examine how these policies affect heat-related health outcomes across temperature ranges and age groups.

The implementation of carbon pricing policies drives up the emergency department visit rate for heat-related illnesses on days with daily mean temperature above 25°C across all age groups (Figure 4a-c). The adverse effect is largest among working-age adults (aged 15–64), reaching 0.6 additional visits per 100,000 population. One plausible explanation is that, relative to children and the elderly, working-age adults spend more time outdoors for work and other activities, which increases their exposure to extreme heat and the incidence of acute heat-related illness, resulting in more heat-related emergency care use.

By contrast, adults over 65 exhibit the largest hospitalization response (Figure 4d-f). This pattern suggests that extreme heat affects age groups through different clinical pathways: among children and working-age adults, it more often causes acute illness managed in the emergency department, whereas among the elderly it is more likely to exacerbate chronic underlying conditions and lead to hospitalization. Since age-specific heat-related mortality data are unavailable, we report overall mortality impacts (Figure 4g). We estimate that, following the implementation of carbon pricing policies in the U.S., an additional hot day with daily mean temperature above 30°C increases the annual number of deaths attributable to heat stress by 1.2, corresponding to a 16% increase relative to the no-policy counterfactual.

We also investigate potential mechanisms utilizing more direct and higher-frequency data on adaptation behavior and capacity. First, we analyze state-level air-conditioning use, which is unavailable in the global analysis but provides direct evidence on the adaptation-constraint mechanism. A US\$1/tCO₂ increase in carbon price lowers air-conditioning penetration by 1 percentage point, which indicates that stricter carbon policy can limit access to cooling during extreme heat, thereby increasing heat-related health risks. In addition, using higher-frequency state-month data, we also find that the electricity price rises and electricity consumption falls following the implementation of carbon pricing in the United States (Figure 4h).

Furthermore, the within-country analysis also allows us to document wage changes across industries after carbon policies are introduced. We classify industries by CO₂ emission intensity into carbon-intensive and non-carbon-intensive sectors. Carbon-intensive sectors include manufacturing, construction, and utilities, whereas non-carbon-intensive sectors are predominantly services. As shown in Figure 4i, carbon pricing reduces hourly wages strongly in high-emitting and more polluted sectors, with no comparable effect in relatively cleaner sectors. As “brown”

jobs are disproportionately held by less-educated and lower-earnings individuals^{41,42}, our results imply that the unintended health costs of carbon pricing may fall more heavily on socioeconomically disadvantaged groups, weakening their capacity to cope with climate change.

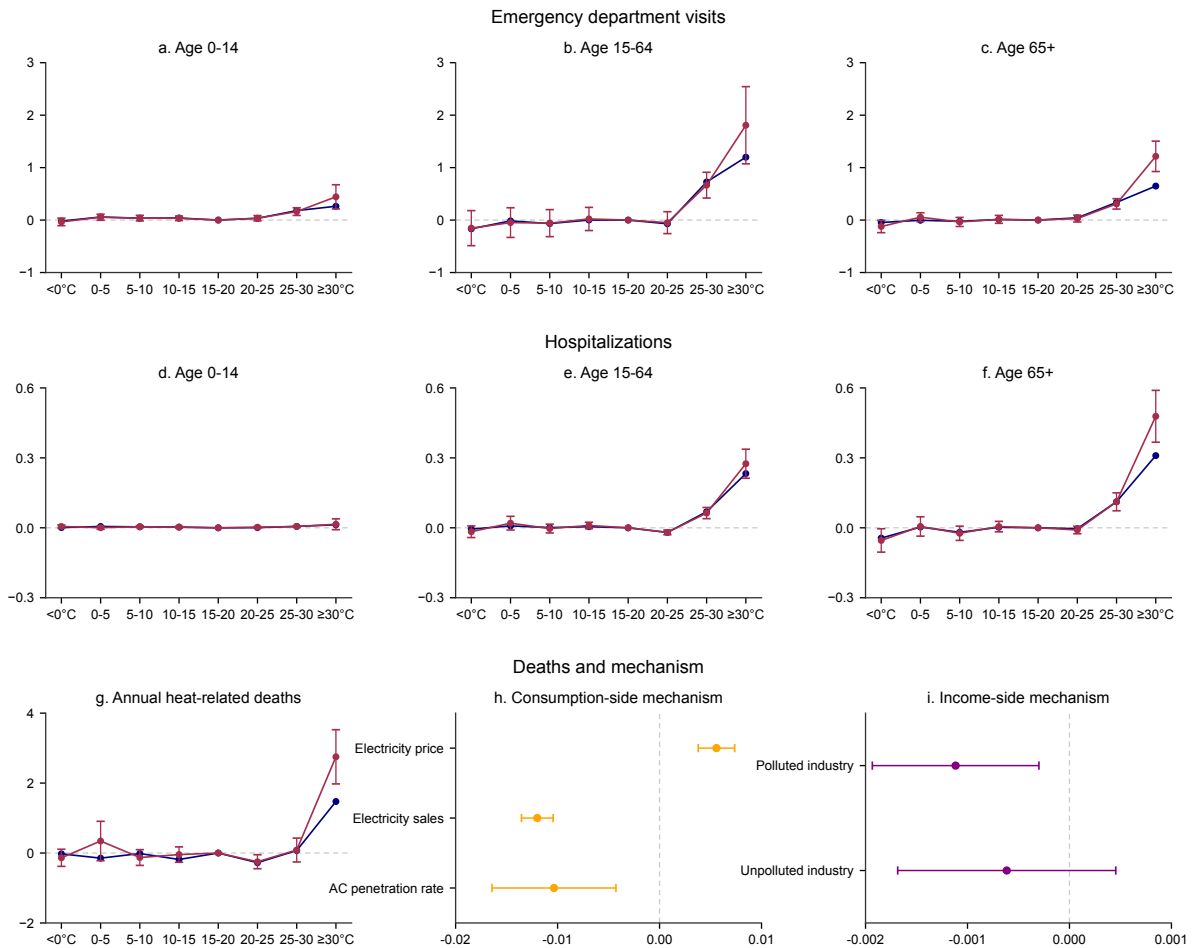


FIGURE 4 | Effects of RGGI and California's CaT program. Blue: no policy (US\$0/tCO₂); Red: policy (US\$1.1/tCO₂). Subfigures a–c: emergency department visit rate for heat-related diseases; Subfigures d–f: hospitalization rate for heat-related diseases; Subfigure g: annual heat-related deaths; Subfigure h: consumption-side outcomes, including electricity price, electricity consumption and air-conditioning penetration rate from residential sector; Subfigure i: income-side outcomes, including hourly wage from carbon-intensive and non-carbon-intensive sectors. The dependent variables in subfigures h–i are logarithmized. The control group consists of states that did not implement carbon pricing policies during the sample period. All regressions include the control variables and fixed effects specified in Equation (2). The coefficient estimates (dots) and their 90% confidence intervals (capped lines), calculated using standard errors clustered at the state level, are presented. The corresponding regression results are reported in [Supplementary Table 4](#).

Cost-benefit Analysis

Our final analysis weighs the adaptation-related health costs of carbon pricing documented above against the benefits generated by the same policies. The benefits comprise two compo-

nents: direct climate benefits from reduced CO₂ emissions and co-benefits from improved air quality.

We first measure the adaptation-related health costs by estimating Equation (3), in which the dependent variable is the ADM1-level all-cause mortality rate and the carbon price is interacted with the number of hot days with daily mean temperature above 30°C. As in the baseline specification, the regression controls for air pollution, so the estimated coefficient captures the gross adaptation-related mortality cost rather than being offset by the air quality improvements of carbon pricing; these improvements enter the benefit side separately, avoiding double counting. As reported in Column (1) of [Supplementary Table 6](#), this interaction yields a positive and statistically significant coefficient, indicating that each additional US\$1/tCO₂ raises the mortality impact of an additional hot day by 0.268 extra all-cause deaths per 100,000 population. We combine this coefficient with ADM1 level hot day exposure and carbon prices, and then aggregate the associated changes in deaths to the country level.

For the direct climate benefits, Column (2) of [Supplementary Table 6](#), estimated using Equation (5), shows that each additional US\$1/tCO₂ reduces CO₂ emissions by 2.7%. For the air quality co-benefits, we focus on PM_{2.5}, which remains the most harmful ambient pollutant today and a major contributor to premature mortality from air pollution^{43,44}. Column (3) shows that each additional US\$1/tCO₂ lowers ambient PM_{2.5} concentrations by 0.6%. With the global population-weighted mean carbon price of about US\$3.8/tCO₂, these coefficients imply reductions of 10.3% in CO₂ emissions and 2.3% in ambient PM_{2.5} concentrations, consistent with earlier studies^{11,12,13,14}.

We then translate these changes into monetary terms. First, we value the excess deaths attributable to reduced adaptation capacity by multiplying the estimated rise in mortality by a value of a statistical life (VSL) of US\$8.0 million (90% CI: US\$2.4-14.0 million) drawn from the meta analysis of Banzhaf⁴⁵. Second, the observed decline in CO₂ emissions delivers annual global climate benefits per capita of US\$178.2-364.0, using country-specific social cost of carbon estimates from Ricke et al.⁴⁶. Third, we calculate health benefits from improved air quality by using a mortality elasticity of 7.3 percent per 10 µg/m³ decline in PM_{2.5}⁴⁷ together with the same VSL, which yields approximately US\$46.1 in annual benefits per capita.

The top row of [Figure 5](#) shows global net benefits per capita ranging from US\$210.8 to US\$396.5 per year. On average, the benefit-cost ratio of carbon pricing policies is approximately 20 ([Supplementary Note 5](#)). We further examine how net benefits vary across socioeconomic and emissions scenarios. For a given Representative Concentration Pathway (RCP), net benefits are largest under Shared Socioeconomic Pathways 3 (SSP3). Compared with SSP1 (sustainability) and SSP2 (middle of the road), SSP3 describes a more fragmented and unequal world with

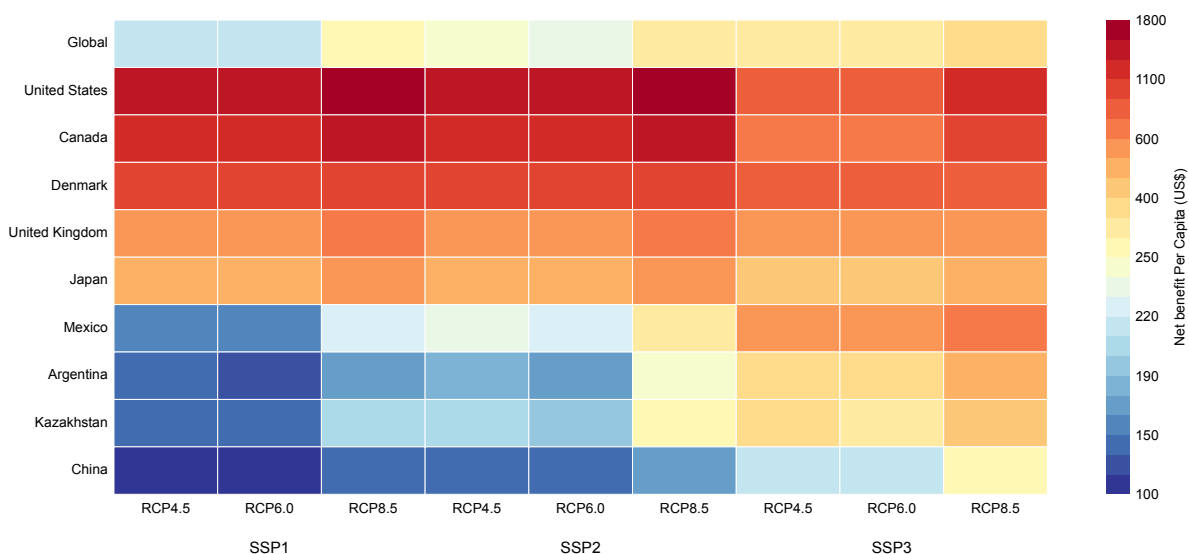


FIGURE 5 | Annual Net Benefits. This figure presents the estimated annual net benefits per capita associated with the implementation of carbon pricing policies (ETs and carbon taxes). The top row reports global aggregate estimates, calculated by summing the estimates for all countries, while the remaining rows provide estimates for selected representative countries. The estimates rely on the selected socioeconomic scenario (Shared Socioeconomic Pathways, SSP) and emissions scenario (Representative Concentration Pathways, RCP). [Supplementary Table 7](#) shows the confidence intervals of the estimates. [Supplementary Tables 8–16](#) present detailed results on climate benefits, air-quality benefits and adaptation costs for each scenario.

slower economic growth, which raises the present value of future climate damages, particularly in developing economies, and thereby raises the benefits of carbon pricing. For a given SSP, net benefits are largest under RCP8.5 (high emissions), relative to RCP4.5 (low emissions) and RCP6.0 (moderate emissions). Under RCP8.5, which has a more severe warming scenario, carbon pricing policies yields higher marginal benefits from avoided CO₂ emissions.

The remaining rows provide regional estimates for several key countries to illustrate the unequal distribution of net benefits. Developed countries, including the United States, Canada, Denmark, the United Kingdom, and Japan, reap substantial benefits from carbon pricing policies, because they have higher income to mitigate the adaptation costs. In contrast, developing countries like Mexico, Kazakhstan, Argentina, and China, which have lower adaptive capacities and are more vulnerable to climate change, may experience much smaller benefits. For Mexico, Kazakhstan, and Argentina, the lower bounds of the confidence intervals fall below zero under most scenarios, so net losses cannot be ruled out.

Discussion

Climate change presents a dual challenge for public health: the need to mitigate greenhouse gas emissions to limit long-term climate-related health harms and the need to protect populations from the immediate and ongoing health risks of a changing climate. While mitigation is often prioritized as the cornerstone of global climate action, its implementation can unintentionally hamper adaptation to climate change, particularly for vulnerable populations. Neglecting the adaptation-related health costs can erode public support for climate policies.

This paper quantitatively assesses the health costs associated with weakened adaptive capacities caused by carbon pricing policies. We find that the implementation of these policies significantly increases mortality rates during extreme weather events, with particularly pronounced effects for temperature-related causes and elderly populations. Beyond mortality, carbon pricing also worsens other health outcomes, increasing heat-related morbidity such as emergency department visits and hospitalizations. Furthermore, the impacts are highly uneven, with disproportionately greater negative effects observed in countries with lower income, more carbon-intensive electricity generation, and weaker adaptive capacity.

Several mechanisms underpin these findings, operating on both the consumption side and the income side of households. On the consumption side, carbon pricing raises electricity prices, prompting households to cut electricity consumption and air-conditioning use and thereby limiting their ability to cope with extreme weather. Some households also revert to cheaper but more polluting solid fuels such as coal and firewood, increasing indoor air pollution and related health risks. On the income side, carbon pricing lowers wages in carbon-intensive sectors. Because these jobs are disproportionately held by less-educated and lower-earning workers, the income losses further weaken the adaptive capacity of socioeconomically disadvantaged groups.

Despite these health costs, our cost-benefit analysis reveals that the global benefit-cost ratio of carbon pricing policies is approximately 20. However, these impacts are distributed unevenly across countries. In some developing countries with lower adaptive capacities, the health costs associated with reduced adaptation may offset a substantial share of the climate benefits and air quality co-benefits, or even outweigh them entirely.

This study underscores the need for climate policies to incorporate health considerations into their design and balance mitigation with equity, ensuring that adaptation-related health costs are not disproportionately borne by vulnerable populations, including by ensuring affordable clean energy. Recycling carbon tax or ETS revenues through targeted lump-sum transfers, labor income tax cuts, or clean energy subsidies is a critical yet often overlooked component in the design of carbon pricing policies in most countries, with only 3 ETSs and 4 carbon taxes explicitly

recycling revenues to vulnerable households and communities, accounting for just 10% of global carbon revenue redistribution⁴⁸. It is not only a distributional tool, but also a public health intervention that can reduce the health costs of carbon pricing while making decarbonization more equitable and politically durable.

Methods

Data

Mortality

We utilize two data sources for mortality rates. The first source is the Global Burden of Disease Mortality Database, which provides annual subnational cause-specific mortality rates for 346 first-level administrative (ADM1) units in 14 countries, including Brazil, Ethiopia, India, Indonesia, Iran, Italy, Japan, Kenya, Mexico, Norway, Pakistan, South Africa, the United Kingdom and the United States, from 1991 to 2021. Together, these countries account for approximately 40.2% of the global population. The dataset includes detailed classifications of mortality causes based on its own cause list, with breakdowns by age group. The major causes of death in this dataset include (1) respiratory diseases, (2) cardiovascular diseases, (3) infectious diseases, (4) unintentional injuries, and (5) others. The first two causes—respiratory diseases and cardiovascular diseases—are classified as temperature-related diseases due to their established links with extreme temperatures^{35,36,49,50}. Following Barreca et al.⁵, we categorize infectious diseases and unintentional injuries as temperature-unrelated causes, and group all remaining causes as other causes. This dataset is used to estimate the subnational mortality effects of carbon pricing policies across countries.

The second source is the Environmental Health Tracking Branch of the U.S. Centers for Disease Control and Prevention, which reports annual summer emergency department visits, hospitalizations, and deaths from heat-related diseases for each state from 2000 to 2020. This dataset provides a direct measure of heat-related morbidity and mortality, coded in the International Classification of Diseases (ICD-10) as effects of heat and light, exposure to excessive natural heat, and exposure to sunlight. We use these data to estimate how heat-related illnesses respond across temperature ranges following the implementation of U.S. Regional Greenhouse Gas Initiative and California’s cap-and-trade program.

Carbon pricing

Carbon pricing includes carbon taxes and emissions trading systems (ETs), which impose costs directly on emissions or the carbon content of products. We obtain information on carbon tax rates and ETS prices from the World Bank Carbon Pricing Dashboard. As of 2025, 58 national-level carbon pricing policies had been implemented globally, alongside 42 subnational policies operating in parallel. In our subnational sample, 7 of the 14 countries—Italy, Japan, Mexico, Norway, South Africa, the United Kingdom and the United States—had implemented carbon pricing policies, providing substantial policy variation for identification.

Environmental variables

Environmental variables, including weather and pollution, are control variables in our main analysis. Daily climate data are drawn from the ERA5-Land reanalysis product, which provides globally gridded land-surface climate variables at approximately 9 km resolution since 1950. We aggregate gridded daily temperature and precipitation data to the annual measures at ADM1 level using area-weighted method, as adopted in Wenz et al.⁵¹. The ND-GAIN Country Index is from the Notre-Dame Global Adaptation Initiative, which captures both a country's vulnerability to climate impacts across sectors such as health, food, water, ecosystems and infrastructure, and its readiness to attract and deploy adaptation investment across economic, social and governance dimensions. The index ranges from 0 to 1, with higher value indicating lower vulnerability and greater readiness to adapt to climate change.

Pollution data come from two sources. We gather the PM_{2.5} concentration data from the Organization for Economic Co-operation and Development. Then we collect annual gridded data on PM_{2.5} emissions from fuel combustion in residential and other building-related activities from the Emissions Database for Global Atmospheric Research, and aggregate them to ADM1 level.

Economic variables

We collect GDP per capita from a downscaled gridded global dataset⁵². To account for a broader set of mortality determinants, we source country-level data on physicians per 1,000 people, the share of the population with at least lower secondary education, the political stability score, the share of self employed workers and the Gini index from the World Bank. Electricity data are drawn from both national and gridded sources. For the 14 countries in our subnational sample, we obtain data on total electricity generation and fossil fuel-based electricity generation from the U.S. Energy Information Administration. Gridded electricity consumption data

are drawn from a global 1 km $\times$ 1 km gridded electricity consumption dataset covering 1992 to 2019⁵³. For electricity access, we use a spatially scalable global dataset derived from satellite nighttime lights⁵⁴, which provides electricity-accessed population density at 30-arc-second resolution. We aggregate these gridded data to the ADM1 level using the same spatial aggregation procedure.

Method

Effects of carbon pricing across countries

We estimate the mortality effects of carbon pricing policies by extending the mortality-temperature response framework of Carleton et al.⁵⁵. Their model identifies the mortality effects of temperature from year-to-year variation in daily temperature exposure within the same sub-national units, while allowing the response to vary with long-term income and climate. Building on this framework, we interact carbon prices with the mortality-temperature response function to test whether carbon pricing policies reshape the mortality response to daily temperature exposure, and whether this reshaping differs by income and climate. Specifically, we run the following regression:

$$Y_{i,c,t} = g(T_{i,t}, TMEAN_i, \log(GDPpc)_i) \times CP_{i,c,t} + g(T_{i,t}, TMEAN_i, \log(GDPpc)_i) + CP_{i,c,t} + g(T_{i,t}, Health_c, Pollution_c) + q_c(R_{i,t}) + \beta_i f_t + \alpha_i + \delta_{c,t} + \epsilon_{i,c,t} \quad (1)$$

where $Y_{i,c,t}$ denotes the mortality rate in first-level administrative unit i in country c and year t . $T_{i,t}$ represents the fourth-order polynomial terms of daily average temperatures, summed across the year. This specification flexibly captures nonlinearities in the temperature-mortality relationship while limiting instability and overfitting. In robustness checks, we follow Carleton et al.⁵⁵ and examine alternative functional forms for temperature. $R_{i,t}$ denotes second-order polynomial terms of daily precipitation, also summed over the year. We allow these precipitation effects to vary by country through a country-specific linear function, $q_c(\cdot)$, to control for other contemporaneous weather conditions.

Existing studies have emphasized long-run climate and income as central determinants of climate adaptation^{56,57,3,58,55}. First, population in warmer regions often develop adaptive strategies and tools to cope with extreme weather^{58,59}, leading to a flatter mortality response at high temperatures. Second, higher income may further relax household budget constraints and enable costly adaptive investments, thereby mitigating the adverse mortality effects of extreme temperatures^{60,4}. Therefore, we define the interaction function $g(\cdot)$ by interacting each term of the temperature polynomial with sample-period average temperature, $TMEAN_i$, and sample-

period average GDP per capita, $\log(GDPpc)_i$, which allows adaptation to differ across climate and income conditions. By interacting this function with carbon prices $CP_{i,c,t}$, the coefficients capture how carbon pricing policies reshape the temperature-mortality response curve under different local climate conditions and economic resources. To illustrate this heterogeneity, we generate the nine panels of [Figure 1](#) in three steps. First, we estimate Equation (1) once on the full sample; the estimated coefficients on $CP_{i,c,t}$ and its interactions describe how the policy effect varies continuously with $TMEAN_i$ and $\log(GDPpc)_i$. Second, we divide ADM1 units into nine cells defined by terciles of long-run income and climate, and compute the mean values of $\log(GDPpc)_i$ and $TMEAN_i$ within each cell. Third, for each cell we plug these two mean values into the estimated coefficients and trace out the implied policy effect across daily temperatures, which yields the response curve shown in the corresponding panel. The panels therefore differ only in the income and climate values at which the same underlying estimates are evaluated, not in the sample used for estimation. The standalone terms $g(T_{i,t}, TMEAN_i, \log(GDPpc)_i)$ and $CP_{i,c,t}$ are also included, controlling for the baseline temperature-mortality response in the absence of carbon pricing and for the level effect of the policy on mortality that is common across temperatures, so that the interaction coefficients isolate the policy-induced shifts in the response curve.

The temperature-mortality response also depends on determinants other than household adaptation. Two are particularly important: air pollution, which itself declines under carbon pricing and improves health, and healthcare quality, which shapes the mortality burden of extreme temperatures. We therefore include air pollution, $Pollution_c$, measured by $PM_{2.5}$ exposure, and healthcare quality, $Health_c$, measured by physicians per 1,000 people, and interact each of them with every term of the temperature polynomial. Controlling for air pollution absorbs the air quality co-benefits of carbon pricing, so the interaction coefficients recover the gross adaptation-related health costs of the policies. In robustness checks, we further consider four additional country-level covariates that may affect mortality: educational attainment, political stability, labor force informality and income inequality⁵⁵.

We add ADM1-specific linear time trends to control for confounders that evolve linearly within ADM1 over time. We also include ADM1 fixed effects α_i to absorb time-invariant characteristics of each ADM1 unit, and country-by-year fixed effects $\delta_{c,t}$. The country-by-year fixed effects play a central role in identification: they absorb everything common to a country in a given year, including the overall stance of national environmental and energy policy, concurrent regulations, macroeconomic conditions and nationwide energy price movements. The effects of carbon pricing are therefore identified from variation across ADM1 units within the same country and year, rather than from cross-country or over-time comparisons that could be con-

founded by national policy environments. The $\epsilon_{i,c,t}$ denotes the residual term. Standard errors are clustered at the ADM1 level. The regression is weighted by population, so that estimates reflect effects for the average person rather than the average ADM1 unit. In robustness checks, we also report the estimated results from specifications that use no population weights, or exclude healthcare and pollution controls.

Effects of Regional Greenhouse Gas Initiative and California's Cap-and-Trade Program

To examine whether the U.S. Regional Greenhouse Gas Initiative and California's cap-and-trade program have adverse effects on heat-related health outcomes during extreme heat, we estimate the effects of these policies across temperature bins. Because this section focuses on carbon pricing policies within a single country, the fourth-order polynomial specification in Equation (1) may generate collinearity and unstable estimates. We therefore adopt a temperature bin specification, which is also commonly used in the literature^{4,5}:

$$Y_{s,t} = \sum_k \gamma_{1k} \times Tbin_{s,t,k} \times CP_{s,t} + \sum_k \gamma_{2k} \times Tbin_{s,t,k} + \gamma_3 CP_{s,t} + \sigma X_{s,t} + \delta_s + \eta_t + \epsilon_{s,t} \quad (2)$$

where $Y_{s,t}$ represents heat-related health outcomes in state s and year t , including emergency department visit rates, hospitalization rates, and annual heat-related deaths. $Tbin_{s,t,k}$ is the number of days in state s in year t with daily mean temperatures falling within the k^{th} temperature bins. We define eight temperature bins: $<0^\circ\text{C}$, $0-5^\circ\text{C}$, $5-10^\circ\text{C}$, $10-15^\circ\text{C}$, $15-20^\circ\text{C}$, $20-25^\circ\text{C}$, $25-30^\circ\text{C}$ and $\geq 30^\circ\text{C}$. The $15-20^\circ\text{C}$ bin serves as the reference bin and is omitted in the regression model, so the coefficients of the other temperature bins should be interpreted as the impacts relative to the $15-20^\circ\text{C}$ bin. $CP_{s,t}$ denotes the carbon price in state s in year t . The model includes the temperature bins and the carbon price on their own. The standalone bins (γ_{2k}) capture the baseline health effects of temperature in the absence of carbon pricing. The standalone carbon price (γ_3) captures the effect of the policy that does not vary with temperature. By interacting the temperature bins $Tbin_{s,t,k}$ with $CP_{s,t}$, the coefficients γ_{1k} then capture how carbon policies affect heat-related illness risk under different temperatures, relative to the no-policy case. The control variables $X_{s,t}$ include state-level economic variables such as GDP per capita and health expense per capita, climate variables such as precipitation, wind speed, snow depth that are classified into ten quantile groups, and pollution variables such as $\text{PM}_{2.5}$ concentration. We also include state fixed effects δ_s and year fixed effects η_t .

Cost-benefit analysis

To quantify the welfare effects of carbon pricing policies, we first estimate the adaptation-related mortality response to carbon pricing under extreme heat exposure. The specification is as follows:

$$Y_{i,c,t} = \theta_1 \times Tbin30_{i,c,t} \times CP_{i,c,t} + \theta_2 \times Tbin30_{i,c,t} + \theta_3 \times CP_{i,c,t} + X_{i,c,t} + \beta_i f_t + \alpha_i + \delta_{c,t} + \epsilon_{i,c,t} \quad (3)$$

where $Y_{i,c,t}$ denotes the mortality rate in ADM1 unit i in country c and year t . $Tbin30_{i,c,t}$ denotes the number of days with daily mean temperatures above 30°C in ADM1 unit i , country c and year t . We use 30°C as the threshold because the estimated policy-related mortality response becomes statistically significant above this temperature (Figure 1). The control vector $X_{i,c,t}$ includes country-specific second-order polynomial functions of precipitation, summed over the year, as well as country-specific linear controls for healthcare capacity and air pollution. As before, controlling for air pollution absorbs the air quality co-benefits of carbon pricing, so the coefficient recovers the gross adaptation-related mortality cost. The remaining terms are defined as in Equation (1).

The interaction coefficient θ_1 captures how carbon pricing changes the marginal mortality effect of an additional hot day above 30°C. Therefore, the adaptation-related health cost in country c and year t is defined as:

$$\text{Adaptation-Related Health Cost}_{c,t} = VSL \times \sum_{i \in c} \frac{\theta_1 \times CP_{i,c,t} \times Tbin30_{i,c,t}}{100,000} \times Population_{i,c,t} \quad (4)$$

where VSL is the value of a statistical life, taken from the meta analysis of Banzhaf⁴⁵. $Population_{i,c,t}$ is the total population of ADM1 unit i in country c and year t . For each ADM1 unit, we combine local hot day exposure with the carbon price to estimate policy-induced changes in deaths. These ADM1-level death changes are then aggregated to the country level and monetized using the value of a statistical life. This subnational aggregation exploits spatial variation in both heat exposure and carbon pricing policy implementation, while avoids treating each country as a single unit that averages over regional differences.

Then, we estimate the mitigation benefits of policies, including both climate-related direct benefits and air quality co-benefits. Because comparable subnational emissions and pollution data are not available globally, we conduct this analysis at the country level, which expands the sample to 185 countries and enables a more comprehensive assessment of policy benefits. Denoting by $Y_{c,t}$ the log level of CO₂ emissions or PM_{2.5} concentrations for country c in year t , we

run the following model at the country level:

$$Y_{c,t} = \zeta \times CP_{c,t} + X_{c,t} + \alpha_c + \delta_t + \epsilon_{c,t} \quad (5)$$

where $CP_{c,t}$ denotes the carbon price in country c and year t . $X_{c,t}$ includes GDP per capita, health expense per capita, annual mean temperature and precipitation. Country fixed effects α_c and year fixed effects δ_t are also included. The coefficient ζ estimates the average change in log CO₂ emissions or log PM_{2.5} concentrations associated with a dollar per ton increase in carbon price. Since CO₂ is a global gas, its reduction benefits are distributed worldwide. To capture the heterogeneous effects, we calculate the global CO₂ reduction and then apply country-specific social cost of carbon estimates from Ricke et al.⁴⁶, which provide median and 66.7% confidence interval estimates under various shared socioeconomic pathways and carbon emissions scenarios. The direct climate-related benefits for each country c in year t are then:

$$\text{Direct Benefit}_{c,t} = SCC_c \times \Delta CO_{2t} = SCC_c \times \zeta_{CO_2} \times GCP_t \times CO_{2t} \quad (6)$$

where SCC_c represents the country-specific social cost of carbon. ζ_{CO_2} is the estimated carbon price coefficient when the dependent variable is log CO₂ emissions in Equation (5). GCP_t and CO_{2t} denotes global average carbon price and total CO₂ emissions, respectively.

In addition to direct benefits associated with CO₂ emissions reductions, reductions in PM_{2.5} concentrations improve air quality and lower mortality risks. The associated co-benefit is:

$$\begin{aligned} \text{Co-Benefit}_{c,t} &= VSL \times \frac{\xi \times \text{Mortality}_{c,t} \times \Delta PM_{c,t}}{100,000} \times \text{Population}_{c,t} \\ &= VSL \times \frac{\xi \times \text{Mortality}_{c,t} \times \zeta_{PM} \times CP_{c,t} \times PM_{c,t}}{100,000} \times \text{Population}_{c,t} \end{aligned} \quad (7)$$

where ξ represents the proportional increase in mortality rate per 100,000 people associated with 1 $\mu\text{g}/\text{m}^3$ increase in PM_{2.5} concentrations, based on estimates from Di et al.⁴⁷. $\Delta PM_{c,t}$ denotes the reduction in PM_{2.5} levels following the policy introduction, calculated using the estimated coefficient ζ_{PM} , carbon price $CP_{c,t}$ and PM_{2.5} levels $PM_{c,t}$.

Finally, annual net benefits for country c in year t are:

$$\text{Net Benefit}_{c,t} = \text{Direct Benefit}_{c,t} + \text{Co-Benefit}_{c,t} - \text{Adaptation-Related Health Cost}_{c,t} \quad (8)$$

Aggregating across countries yields the global figure:

$$\text{Global Net Benefit}_t = \sum_c \text{Net Benefit}_{c,t} \quad (9)$$

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Supplementary Information

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Supplementary Note 1 Tabulated Results for Main Figures

Supplementary Table 1 | Effects of Carbon Pricing on Mortality by Income and Climate

	Low GDPpc			Middle GDPpc			High GDPpc		
	Cold (1)	Mild (2)	Hot (3)	Cold (4)	Mild (5)	Hot (6)	Cold (7)	Mild (8)	Hot (9)
40°C	5.253* (2.695)	5.176* (2.694)	5.111* (2.770)	2.705** (1.369)	2.628* (1.395)	2.563 (1.559)	0.626 (0.391)	0.548 (0.538)	0.483 (0.910)
35°C	2.256* (1.260)	2.154* (1.214)	2.069* (1.213)	1.127* (0.640)	1.025* (0.601)	0.940 (0.646)	0.205 (0.179)	0.104 (0.199)	0.018 (0.376)
30°C	0.712 (0.478)	0.633 (0.433)	0.567 (0.411)	0.332 (0.245)	0.253 (0.201)	0.188 (0.199)	0.022 (0.072)	-0.056 (0.054)	-0.122 (0.128)
25°C	0.099 (0.123)	0.061 (0.105)	0.030 (0.095)	0.032 (0.066)	-0.005 (0.049)	-0.037 (0.048)	-0.022 (0.024)	-0.059** (0.023)	-0.091** (0.044)
20°C	/	/	/	/	/	/	/	/	/
10°C	0.209 (0.140)	0.232 (0.162)	0.252 (0.182)	0.120* (0.072)	0.144 (0.096)	0.163 (0.118)	0.048** (0.023)	0.071 (0.048)	0.091 (0.072)
5°C	0.213 (0.190)	0.223 (0.209)	0.232 (0.227)	0.114 (0.097)	0.125 (0.117)	0.133 (0.138)	0.034 (0.026)	0.044 (0.050)	0.053 (0.075)
0°C	0.123 (0.207)	0.119 (0.213)	0.116 (0.220)	0.057 (0.107)	0.053 (0.114)	0.050 (0.123)	0.003 (0.031)	-0.001 (0.039)	-0.004 (0.055)
-5°C	0.033 (0.248)	0.015 (0.246)	-0.001 (0.247)	0.000 (0.131)	-0.018 (0.131)	-0.034 (0.134)	-0.027 (0.044)	-0.045 (0.048)	-0.061 (0.061)
Control	Y	Y	Y	Y	Y	Y	Y	Y	Y
ADM1 linear trends	Y	Y	Y	Y	Y	Y	Y	Y	Y
ADM1 FE	Y	Y	Y	Y	Y	Y	Y	Y	Y
Country-by-year FE	Y	Y	Y	Y	Y	Y	Y	Y	Y
Observations	10,726	10,726	10,726	10,726	10,726	10,726	10,726	10,726	10,726

Note: This table presents the effects of carbon pricing policies on all-cause mortality rates across daily mean temperatures, estimated using Equation (1) with data for 346 ADM1 units in 14 countries from 1991 to 2021. The dependent variable is deaths per 100,000 people. Estimates are evaluated at the temperatures shown in the first column and at the mean income and climate values of the corresponding tercile cells shown in the first two rows. The control variables include country-specific precipitation functions, interactions between the temperature polynomial terms and healthcare quality and air pollution, and ADM1-specific linear time trends. All regressions include ADM1 fixed effects and country-by-year fixed effects. Standard errors, shown in parentheses, are clustered at the ADM1 level. Significance levels are *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$.

Supplementary Table 2 | Mechanisms

	Log of electricity consumption p.c. (1)	Log of residential PM _{2.5} emissions (2)
$CP \times \log(GDPpc)$	0.0008*** (0.0003)	-0.0008*** (0.0002)
$CP \times TMEAN$	0.0001 (0.0001)	0.0000 (0.0001)
$CP \times \log(urban)$	0.0025*** (0.0008)	-0.0019** (0.0008)
$CP \times \log(elec_density)$	-0.0002* (0.0001)	0.0004*** (0.0001)
CP	-0.0077** (0.0032)	0.0050* (0.0026)
Control	Y	Y
ADM1 linear trends	Y	Y
ADM1 FE	Y	Y
Country-by-year FE	Y	Y
Observations	9688	10726

Note: This table reports the effects of carbon pricing policies on per capita electricity consumption and PM_{2.5} emissions from residential fuel combustion in Columns (1) and (2), respectively. Both dependent variables are logarithmized. CP denotes the carbon price and is interacted with log GDP per capita, $\log(GDPpc)$, long-term mean temperature, $TMEAN$, log urbanization rate, $\log(urban)$, and log electricity-accessed population density, $\log(elec_density)$, to capture the heterogeneous policy effects across regional characteristics. All regressions include the same control variables and fixed effects as those used in the baseline analysis. Standard errors, shown in parentheses, are clustered at the ADM1 level. Significance levels are *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$.

Supplementary Table 3 | Heterogeneous Effects across Countries

	Generation emissions intensity		Adaptive capacity	
	Low (1)	High (2)	Low (3)	High (4)
40°C	2.919 (3.557)	3.000** (1.468)	4.349* (2.351)	1.545 (1.527)
35°C	1.321 (1.702)	1.119* (0.625)	1.492 (0.996)	0.709 (0.692)
30°C	0.483 (0.673)	0.244 (0.222)	0.215 (0.358)	0.267 (0.252)
25°C	0.116 (0.184)	-0.026 (0.070)	-0.118 (0.126)	0.068 (0.065)
20°C	/	/	/	/
10°C	-0.038 (0.099)	0.156 (0.116)	0.331 (0.223)	-0.019 (0.089)
5°C	-0.070 (0.110)	0.124 (0.151)	0.271 (0.280)	-0.015 (0.106)
0°C	-0.072 (0.105)	0.063 (0.169)	0.116 (0.300)	0.028 (0.103)
-5°C	-0.075 (0.135)	0.002 (0.205)	-0.038 (0.348)	0.071 (0.128)
Control	Y	Y	Y	Y
ADM1 linear trends	Y	Y	Y	Y
ADM1 FE	Y	Y	Y	Y
Country-by-year FE	Y	Y	Y	Y
Observations	10,726	10,726	10,726	10,726

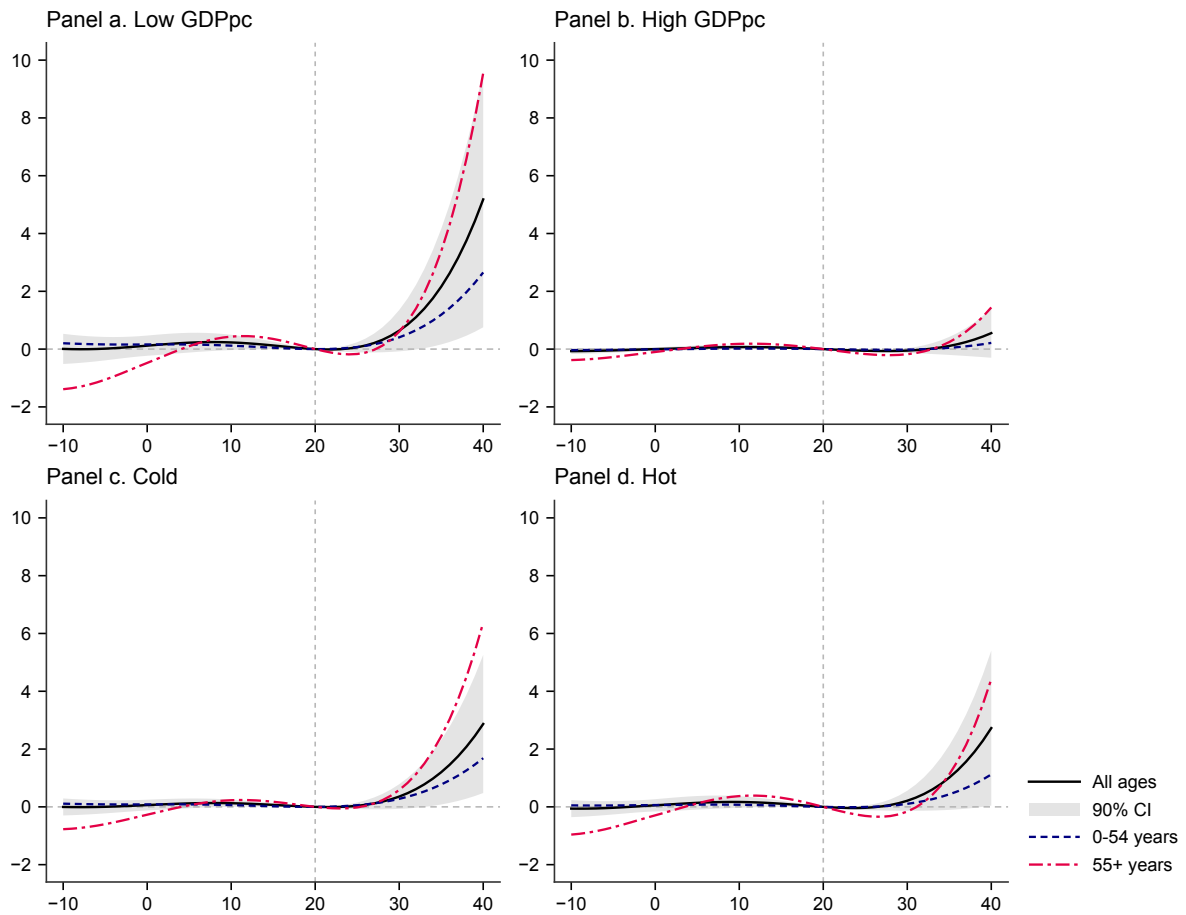
Note: This table provides evidence on the heterogeneous effects of carbon pricing policies across countries with varying characteristics, estimated by extending Equation (1) to interact the carbon pricing terms with each characteristic. The dependent variable is the all-cause mortality rate. Estimates are evaluated at the temperatures shown in the first column and at the mean values of the corresponding characteristic tercile cells shown in the first two rows. All regressions include the same control variables and fixed effects as those used in the baseline analysis. Standard errors, shown in parentheses, are clustered at the ADM1 level. Significance levels are *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$.

Supplementary Table 4 | Effects of RGGI and California's CaT on Heat-related Morbidity

	Emergency department visits per 100,000 population			Hospitalization per 100,000 population			Annual number of deaths
	Age 0-14 (1)	Age 15-64 (2)	Age 65+ (3)	Age 0-14 (4)	Age 15-64 (5)	Age 65+ (6)	
# of days above 30°C × <i>CP</i>	0.1638*** (0.0550)	0.5538*** (0.1585)	0.5153*** (0.0854)	0.0019 (0.0049)	0.0386** (0.0169)	0.1534*** (0.0294)	1.1622*** (0.3241)
# of days 25-30°C × <i>CP</i>	-0.0173 (0.0177)	-0.0556 (0.0364)	-0.0256 (0.0195)	-0.0003 (0.0008)	-0.0051 (0.0047)	-0.0003 (0.0096)	0.0129 (0.0849)
# of days 20-25°C × <i>CP</i>	0.0015 (0.0082)	0.0195 (0.0191)	-0.0132 (0.0092)	0.0015*** (0.0004)	0.0000 (0.0014)	-0.0051* (0.0028)	0.0245 (0.0277)
# of days 15-20°C × <i>CP</i>	/	/	/	/	/	/	/
# of days 10-15°C × <i>CP</i>	-0.0057 (0.0041)	0.0187 (0.0166)	0.0024 (0.0065)	-0.0005 (0.0004)	0.0048*** (0.0015)	0.0026 (0.0022)	0.1267*** (0.0343)
# of days 5-10°C × <i>CP</i>	0.0017 (0.0086)	0.0075 (0.0206)	-0.0107 (0.0111)	0.0007 (0.0007)	-0.0039 (0.0030)	-0.0038 (0.0043)	-0.1033*** (0.0336)
# of days 0-5°C × <i>CP</i>	-0.0040 (0.0252)	-0.0297 (0.0907)	0.0536* (0.0272)	-0.0046** (0.0019)	0.0106 (0.0097)	0.0023 (0.0153)	0.4451* (0.2581)
# of days below 0°C × <i>CP</i>	-0.0142 (0.0244)	0.0118 (0.0768)	-0.0700** (0.0296)	0.0042* (0.0022)	-0.0103 (0.0067)	-0.0092 (0.0116)	-0.1026 (0.1607)
# of days above 30°C	0.2629** (0.1054)	1.1987*** (0.4333)	0.6484*** (0.1758)	0.0130 (0.0112)	0.2325*** (0.0443)	0.3096*** (0.0473)	1.4731*** (0.1729)
# of days 25-30°C	0.1804*** (0.0396)	0.7265*** (0.1191)	0.3368*** (0.0497)	0.0060*** (0.0014)	0.0688*** (0.0097)	0.1118*** (0.0167)	0.0712 (0.1169)
# of days 20-25°C	0.0336 (0.0306)	-0.0707 (0.1158)	0.0430 (0.0390)	0.0008 (0.0015)	-0.0197*** (0.0056)	-0.0037 (0.0091)	-0.2759** (0.1256)
# of days 15-20°C	/	/	/	/	/	/	/
# of days 10-15°C	0.0397 (0.0253)	0.0006 (0.1255)	0.0108 (0.0432)	0.0032 (0.0022)	0.0047 (0.0070)	0.0023 (0.0127)	-0.1837 (0.1404)
# of days 5-10°C	0.0352 (0.0274)	-0.0669 (0.1301)	-0.0240 (0.0442)	0.0041 (0.0025)	0.0010 (0.0099)	-0.0193 (0.0132)	-0.0150 (0.1145)
# of days 0-5°C	0.0584** (0.0226)	-0.0155 (0.1322)	-0.0040 (0.0447)	0.0057* (0.0031)	0.0082 (0.0102)	0.0033 (0.0150)	-0.1464 (0.0925)
# of days below 0°C	-0.0191 (0.0330)	-0.1668 (0.1331)	-0.0459 (0.0452)	0.0011 (0.0027)	-0.0055 (0.0100)	-0.0441** (0.0204)	-0.0237 (0.1957)
<i>CP</i>	0.8991 (1.3557)	-2.7719 (3.0340)	2.0131 (1.5059)	-0.1245* (0.0637)	-0.2249 (0.4016)	0.4203 (0.6730)	-12.0587 (7.3756)
Control	Y	Y	Y	Y	Y	Y	Y
State FE	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y
Observations	440	440	440	620	620	620	1071

Note: This table presents the effects of carbon pricing policies on heat-related morbidity, including emergency department visit rate, hospitalization rate, and annual heat-related deaths, estimated using Equation (2) with data for 51 U.S. states from 2000 to 2020. *CP* denotes the state-year carbon price and is interacted with eight temperature bins: <0°C, 0-5°C, 5-10°C, 10-15°C, 15-20°C, 20-25°C, 25-30°C and ≥30°C. The 15-20°C bin and its interaction with carbon price are omitted as the reference category. The control group consists of states that did not implement carbon pricing policies during the sample period. All regressions include the control variables and fixed effects specified in Equation (2). Standard errors, shown in parentheses, are clustered at the state level. Significance levels are *** p<0.01, ** p<0.05, and * p<0.1.

Supplementary Note 2 Mortality by Age Groups



Supplementary Figure 1 | Effects of Carbon Pricing Policies on Mortality by Age Group.

Black: all ages; Blue: age 0-54; Red: age above 55. The figure presents the age-specific effects of carbon pricing policies on all-cause mortality across the temperature distribution, estimated using the fourth-order polynomial specification in Equation (1) with data for 346 ADM1 units in 14 countries from 1991 to 2021. Panels a and b show policy effects for low and high income terciles, and panels c and d for cold and hot climate terciles. Estimates are evaluated at the mean values of the corresponding terciles. The x-axis denotes daily mean temperature, and the y-axis denotes deaths per 100,000 people. The control variables include country-specific precipitation functions, interactions between the temperature polynomial terms and healthcare quality and air pollution, and ADM1-specific linear time trends. All regressions include ADM1 fixed effects and country-by-year fixed effects.

Supplementary Note 3 Mortality by Causes

Supplementary Table 5 | Effects of Carbon Pricing Policies on Mortality by Causes

	All causes	Respiratory diseases	Cardiovascular diseases	Infectious diseases	Unintentional injuries	Others
	(1)	(2)	(3)	(4)	(5)	(6)
40°C	2.787* (1.465)	0.204*** (0.062)	0.737*** (0.275)	1.287 (0.975)	0.086 (0.059)	0.478 (0.366)
35°C	1.100* (0.638)	0.091*** (0.027)	0.318*** (0.118)	0.505 (0.427)	0.037 (0.027)	0.151 (0.158)
30°C	0.281 (0.217)	0.031*** (0.009)	0.099** (0.039)	0.127 (0.147)	0.012 (0.011)	0.013 (0.053)
25°C	0.001 (0.053)	0.006** (0.002)	0.012 (0.009)	-0.000 (0.037)	0.002 (0.003)	-0.017 (0.013)
20°C	/	/	/	/	/	/
10°C	0.148 (0.098)	0.008*** (0.003)	0.050*** (0.016)	0.052 (0.066)	0.003 (0.003)	0.033 (0.021)
5°C	0.130 (0.121)	0.012*** (0.005)	0.069*** (0.020)	0.018 (0.083)	0.003 (0.004)	0.028 (0.027)
0°C	0.057 (0.119)	0.014** (0.006)	0.076*** (0.023)	-0.062 (0.088)	-0.000 (0.005)	0.028 (0.032)
-5°C	-0.015 (0.137)	0.017* (0.009)	0.084** (0.033)	-0.141 (0.108)	-0.003 (0.010)	0.029 (0.044)
Control	Y	Y	Y	Y	Y	Y
ADM1 linear trends	Y	Y	Y	Y	Y	Y
ADM1 FE	Y	Y	Y	Y	Y	Y
Country-by-year FE	Y	Y	Y	Y	Y	Y
Observations	10,726	10,726	10,726	10,726	10,726	10,726
R ²	0.964	0.994	0.994	0.992	0.172	0.996

Note: This table presents the effects of carbon pricing policies on cause-specific mortality rates across the temperature distribution, estimated using the fourth-order polynomial specification in Equation (1) with data for 346 ADM1 units in 14 countries from 1991 to 2021. The dependent variable in each column is deaths per 100,000 people for the cause indicated in the column heading. Estimates are evaluated at the temperatures shown in the first column and at the sample mean values of income and climate across ADM1 units. The control variables include country-specific precipitation functions, interactions between the temperature polynomial terms and healthcare quality and air pollution, and ADM1-specific linear time trends. All regressions include ADM1 fixed effects and country-by-year fixed effects. Standard errors, shown in parentheses, are clustered at the ADM1 level. Significance levels are *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$.

Supplementary Note 4 Robustness

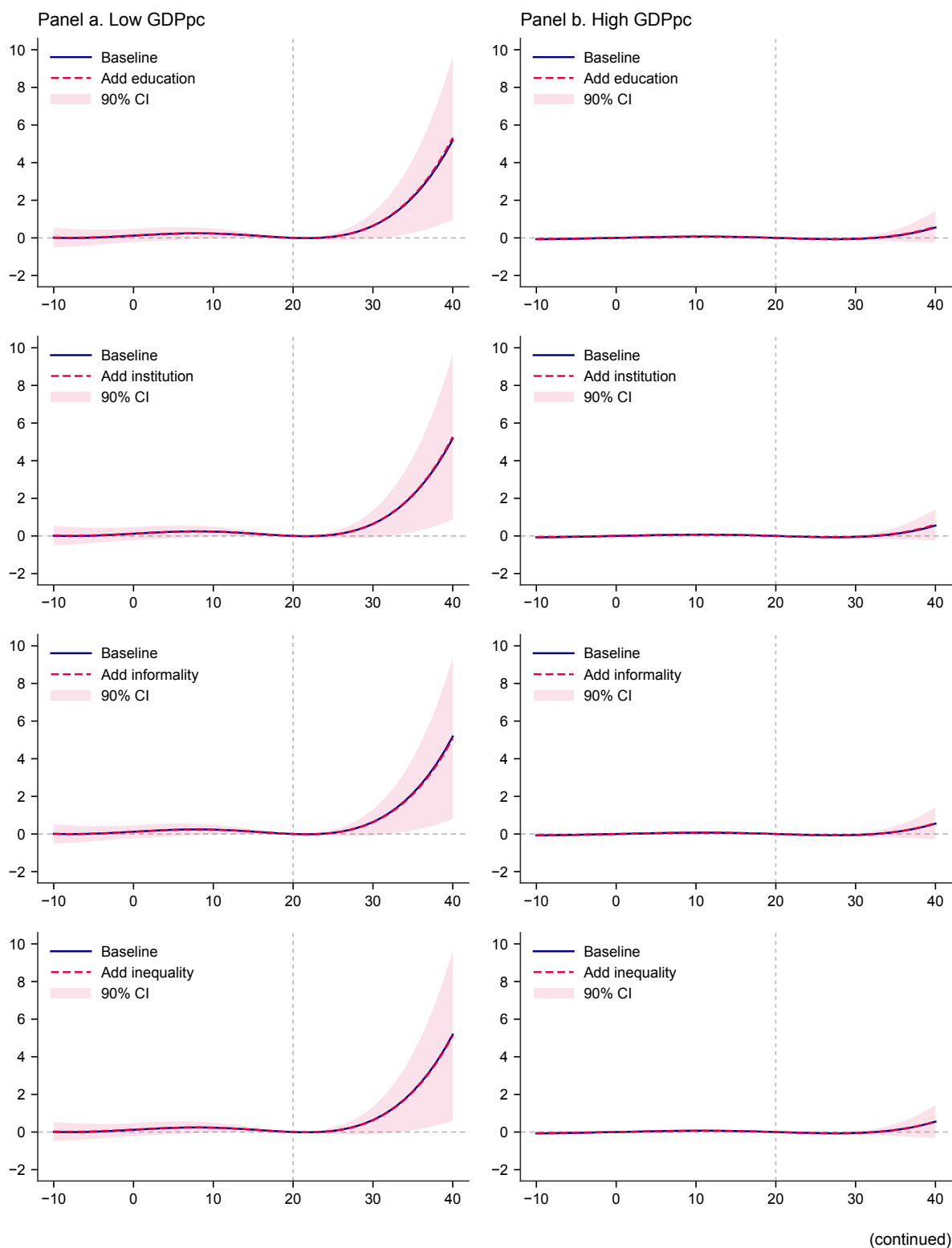
In this supplementary note, we conduct four tests to verify the robustness of the estimated mortality effects of carbon pricing policies, following Carleton et al.¹. The first test incorporates additional country characteristics into Equation (1) to address the concern that factors not considered in the main text may also shape the mortality response. Specifically, we add educational attainment, institutional quality, labor force informality and income inequality, measured by the share of the population with at least lower-secondary education, the political stability score, the share of self-employed workers and the Gini index, respectively. Following the treatment of healthcare quality and air pollution in the baseline model, we interact each of them with every term of the temperature polynomial. We report the estimated mortality response to carbon pricing separately for low and high income regions and for cold and hot regions in [Supplementary Figure 2](#). Compared with the baseline model, adding these controls does not significantly change the shape or position of the response curves.

The second test examines the alternative specifications of baseline model, with results presented in [Supplementary Figure 3](#). Our baseline regressions are weighted by population to estimate effects for the average person rather than the average ADM1 unit. Here, we re-estimate the model without population weights. We then exclude the baseline controls for air pollution and healthcare quality, allowing the air quality co-benefits of carbon pricing and regional capacity to cope with extreme weather to shape the mortality response.

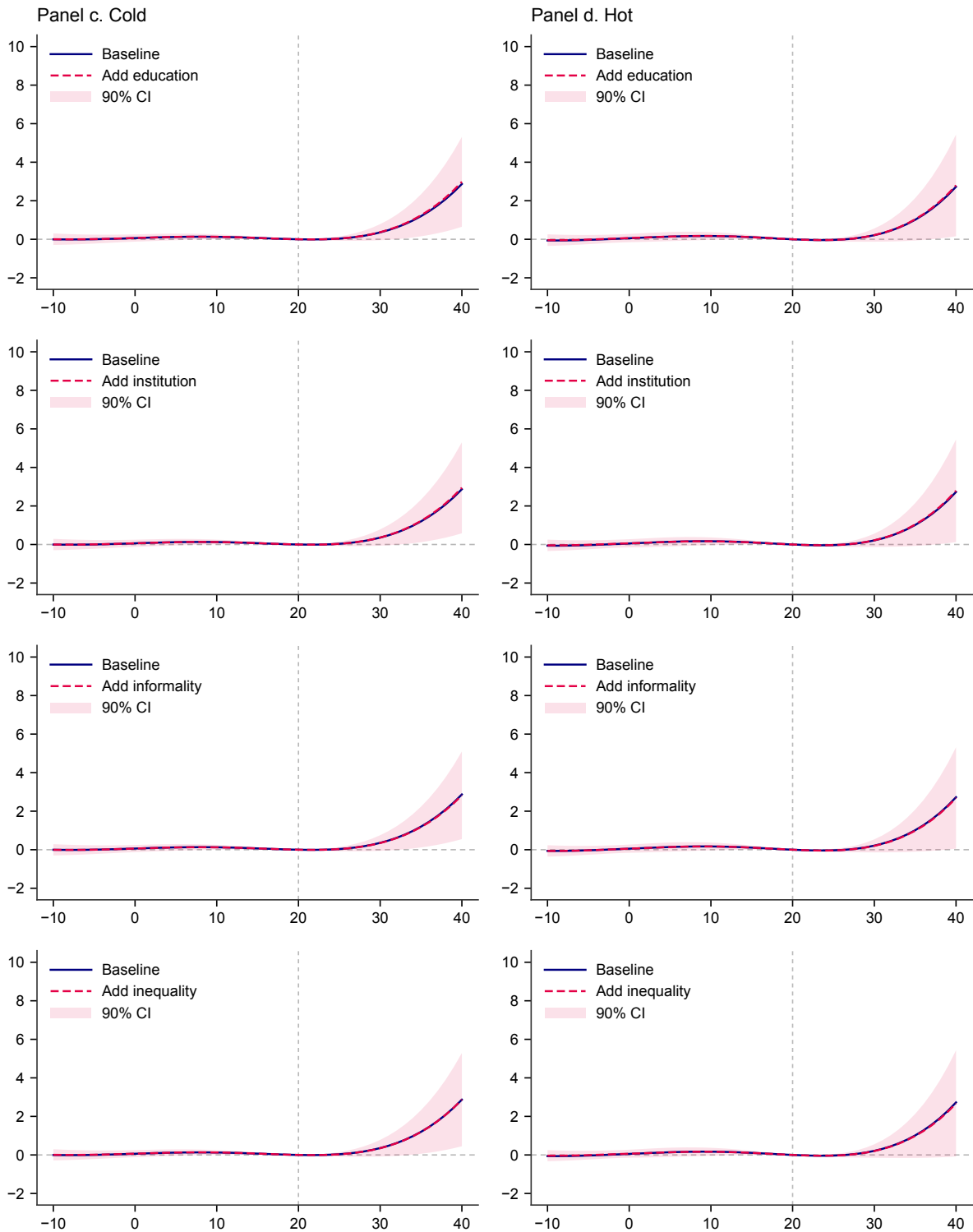
The third test adopts an alternative measure of long-term climate. In the main text, we use sample period average daily mean temperature to characterize long-term climate. Here, we instead use cooling degree days above 20°C and heating degree days below 20°C, calculated as the sum of temperature differences for all days when the daily mean temperature exceeds and falls below 20°C, respectively. Specifically, we replace the interaction term $TMEAN$ in Equation (1) with $CDD20$ and $HDD20$. To compare these two climate measures more directly, we present the marginal mortality effects of carbon pricing under hot weather from two models for each ADM1 unit, measured by the slope of the mortality response function induced by carbon pricing policies at 35°C. As shown in [Supplementary Figure 4](#), the points are evenly distributed around the 45-degree line and mostly lie above and to the right of zero, indicating that our baseline results are not sensitive to the choice of climate measure.

The final test conducts sensitivity analyses for alternative mortality-temperature response function forms. In the baseline analysis, we use a fourth-order polynomial specification to capture the nonlinear temperature effects. To ensure that our results are not driven by this functional form, we complement the main analysis with temperature bin, restricted cubic spline and piecewise linear spline specification. The temperature bin specification is widely used in the lit-

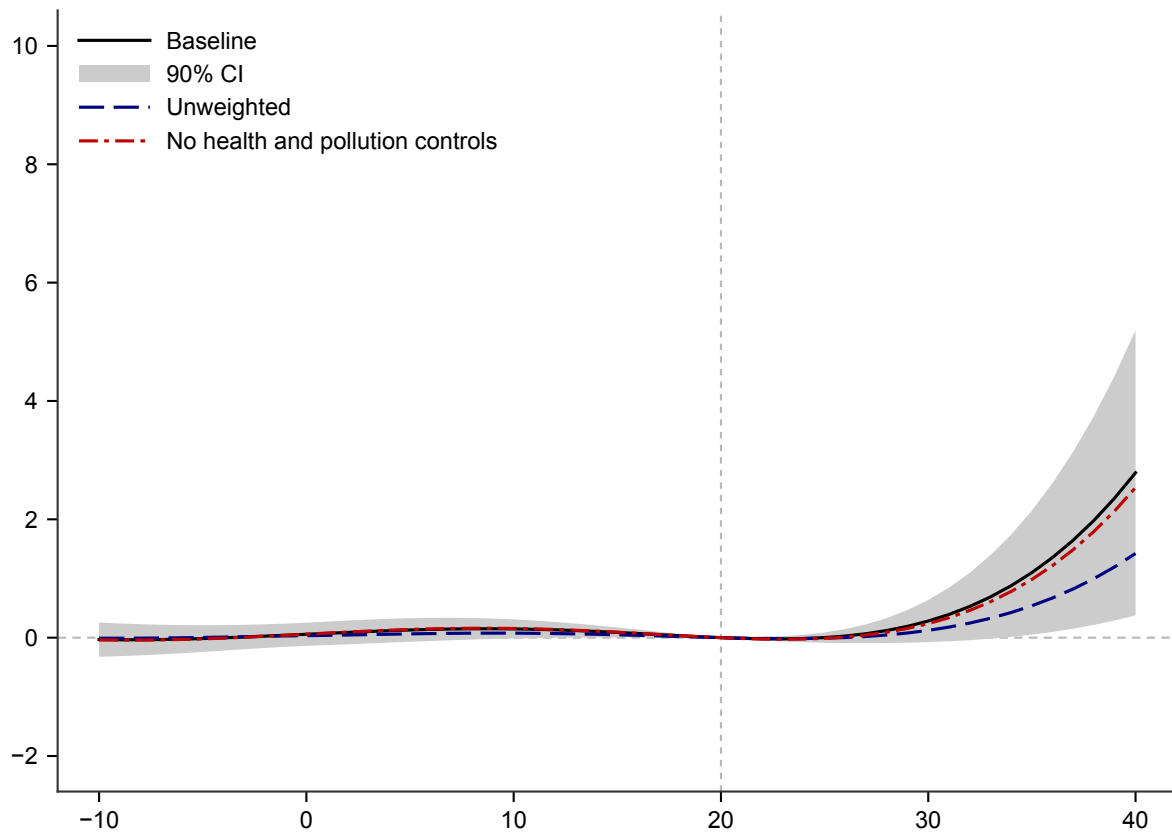
erature^{2,3}. We define ten temperature bins: below -10°C, -10 to -5°C, -5 to 0°C, 0 to 5°C, 5 to 10°C, 10 to 15°C, 15 to 20°C, 20 to 25°C, 25 to 30°C and above 30°C, with 15 to 20°C bin serving as the reference bin. For the restricted cubic spline specification, we sum daily spline terms over the year and place knots at the 5th, 25th, 50th, 75th and 95th percentiles of the pooled daily temperature distribution, corresponding to -1.9, 10.9, 19.3, 24.3 and 28.2°C. For the piecewise linear spline specification, we place knots every 10°C from -5°C to 35°C, ensuring sufficient observations within each temperature segment to identify changes in slope. The results in [Supplementary Figure 5](#) show that, across these three alternative response function forms, carbon pricing policies consistently increase mortality on hot days, especially in low income regions. Together, these estimates are comparable to the baseline results, confirming the robustness of our findings.



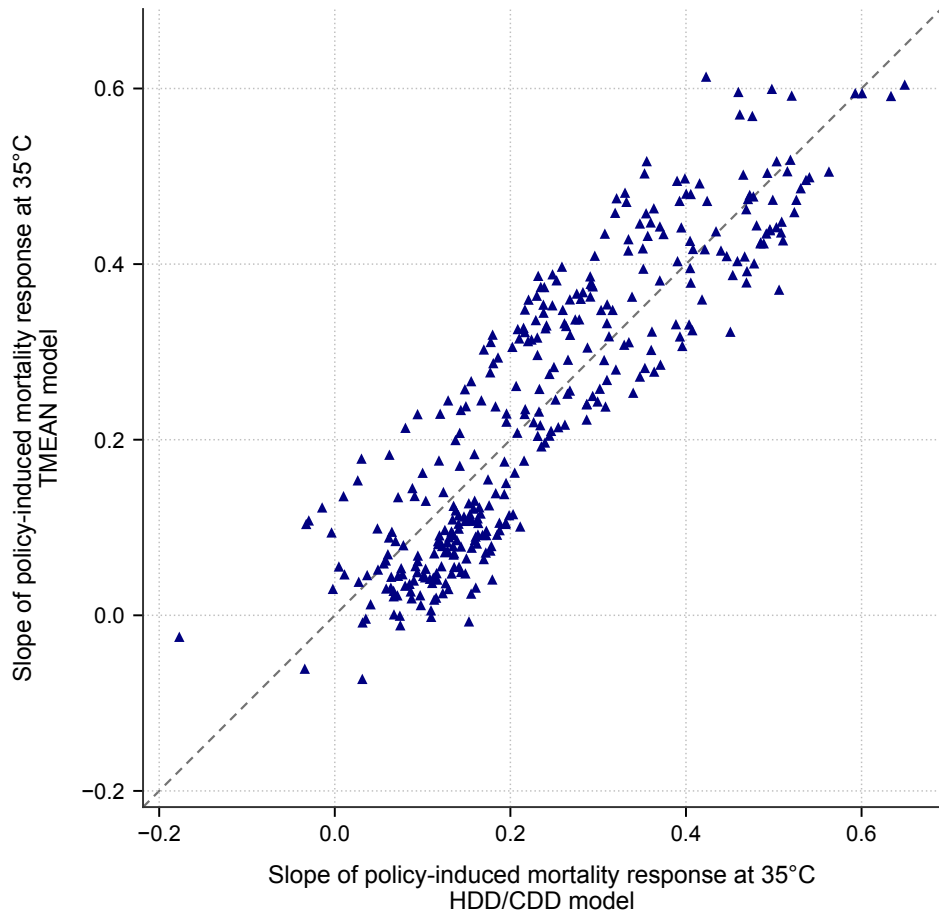
Supplementary Figure 2 | Robustness to Alternative Controls.



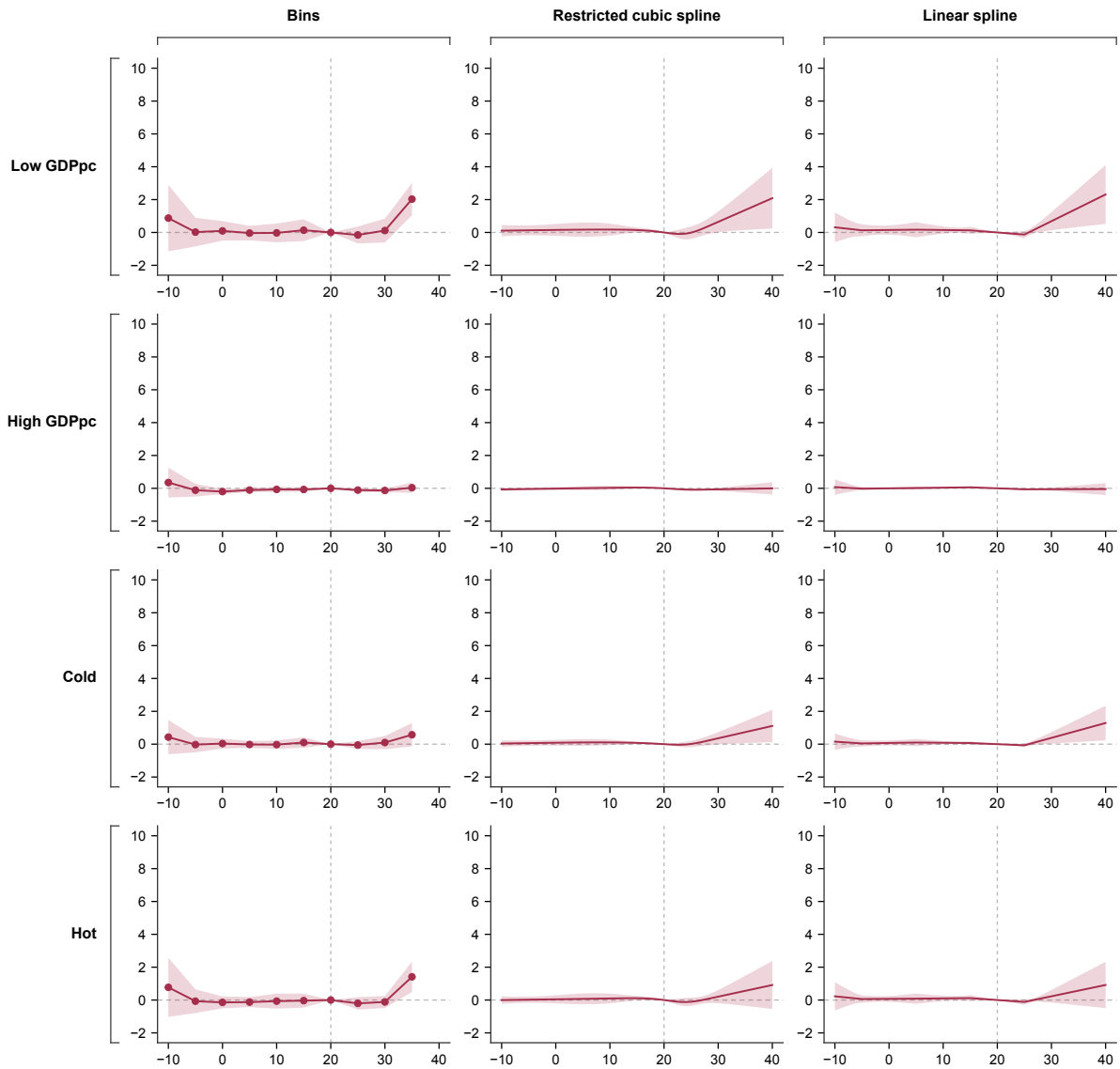
Supplementary Figure 2 | Robustness to Alternative Controls (Continued). Black: baseline estimates; Red: estimates that incorporate additional controls. This figure examines the robustness of the baseline estimates by allowing the mortality response to vary with educational attainment, institutional quality, labor force informality and income inequality, measured by the share of the population with at least lower-secondary education, the political stability score, the share of self-employed workers and the Gini index, respectively. Panels a and b show mortality response to carbon pricing for low and high income terciles, and panels c and d for cold and hot climate terciles. Estimates are evaluated at the mean values of the corresponding terciles. The x-axis denotes daily mean temperature, and the y-axis denotes deaths per 100,000 people. All other specifications remain consistent with the baseline regression.



Supplementary Figure 3 | Robustness to Alternative Specifications. Black: baseline estimates; Blue: unweighted estimates; Red: excluding healthcare quality and air pollution controls. This figure examines the robustness of the baseline estimates to alternative specifications, including changes in population weights and control variables. Estimates are evaluated at the sample mean values of income and climate across ADM1 units. The x-axis denotes daily mean temperature, and the y-axis denotes deaths per 100,000 people. All other specifications remain consistent with the baseline regression.



Supplementary Figure 4 | Robustness to Alternative Climate Measures. This figure examines the robustness of the baseline estimates by comparing coefficients estimated using two alternative measures of long-run climate. Each point represents an ADM1 unit and shows the slope of the mortality response function induced by carbon pricing policies at 35°C. The dashed line denotes the 45-degree line. The y-axis shows estimates from the baseline specification, where climate is measured by long-run annual average temperature *TMEAN* in Equation (1). The x-axis shows estimates from an alternative specification that replaces *TMEAN* with long-run annual cooling degree days above 20°C *CDD20* and heating degree days below 20°C *HDD20*. All other specifications remain consistent with the baseline regression.



Supplementary Figure 5 | Robustness to Alternative Response Function Forms. This figure examines the robustness of the baseline estimates to alternative response functional forms. Columns report estimates from temperature bin, restricted cubic spline and piecewise linear spline specifications from left to right. In the temperature bin specification, temperature bins are defined as $<-10^{\circ}\text{C}$, -10 to -5°C , -5 to 0°C , 0 to 5°C , 5 to 10°C , 10 to 15°C , 15 to 20°C , 20 to 25°C , 25 to 30°C and $\geq 30^{\circ}\text{C}$, with 15 to 20°C as the reference bin. In the restricted cubic spline specification, daily spline terms are summed across the year, with knots placed at the 5th, 25th, 50th, 75th and 95th percentiles of daily temperature distribution, corresponding to -1.9 , 10.9 , 19.3 , 24.3 and 28.2°C . In the linear spline specification, knots are placed at -5 , 5 , 15 , 25 and 35°C . The top two rows show mortality response to carbon pricing for low and high income terciles, and the bottom two rows for cold and hot climate terciles. Estimates are evaluated at the mean values of the corresponding terciles. The x-axis denotes daily mean temperature, and the y-axis denotes deaths per 100,000 people. All other specifications remain consistent with the baseline regression.

Supplementary Note 5 Cost-benefit Analysis

Supplementary Table 6 | Cost-benefit Analysis of Carbon Pricing Policies

	ADM1-level	Country-level	
	Mortality (1)	CO ₂ emissions (2)	PM _{2.5} concentration (3)
$Tbin30 \times CP$	0.268*** (0.079)		
$Tbin30$	0.090 (0.072)		
CP	-0.615*** (0.202)	-0.027*** (0.003)	-0.006*** (0.002)
Control	Y	Y	Y
ADM1 linear trends	Y	N	N
ADM1 FE	Y	N	N
Country-by-year FE	Y	N	N
Country FE	N	Y	Y
Year FE	N	Y	Y
Observations	10726	5720	5766
R ²	0.966	0.993	0.965

Note: This table presents the effects of carbon pricing policies on both the cost and benefit sides, estimated using the ordinary least squares specifications in Equations (3) and (5). The dependent variable is all-cause mortality in Column (1), log CO₂ emissions in Column (2), and log PM_{2.5} concentrations in Column (3). $Tbin30$ denotes the number of days with daily mean temperatures above 30°C, and CP is the carbon price. Column (1) is estimated at the ADM1 level and covers 15 countries. Columns (2) and (3) are estimated at the country level and extend the analysis to 185 countries. The control variables are the same as the baseline regression. Significance levels are *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$.

Supplementary Table 7 | Annual Net Benefits Per Capita

	SSP1			SSP2			SSP3		
	RCP4.5 (1)	RCP6.0 (2)	RCP8.5 (3)	RCP4.5 (4)	RCP6.0 (5)	RCP8.5 (6)	RCP4.5 (7)	RCP6.0 (8)	RCP8.5 (9)
Panel A. Global estimates									
Aggregate effects	214.88 [23.53, 526.04]	210.75 [22.41, 517.65]	267.22 [27.78, 766.23]	244.93 [28.49, 608.62]	239.88 [27.54, 596.78]	309.67 [34.12, 907.64]	311.00 [37.37, 770.59]	304.70 [36.53, 756.03]	396.49 [42.78, 1216.09]
Panel B. Regional estimates									
United States	1235.30 [24.09, 3188.77]	1206.28 [5.65, 3102.39]	1625.11 [69.37, 4769.86]	1313.65 [41.19, 3358.96]	1277.92 [33.80, 3272.28]	1732.18 [109.36, 5147.54]	858.57 [-53.10, 2276.80]	820.85 [-61.34, 2207.74]	1117.56 [-12.88, 3358.77]
Canada	1166.43 [7.57, 3371.43]	1156.71 [-0.48, 3357.96]	1422.35 [50.62, 5017.57]	1141.57 [11.60, 3351.76]	1139.71 [3.98, 3329.81]	1394.62 [45.23, 4936.03]	775.64 [28.42, 2114.23]	772.35 [24.75, 2107.24]	920.93 [46.52, 2971.87]
Denmark	930.76 [136.98, 2182.45]	932.29 [137.02, 2216.98]	1033.44 [152.42, 2603.09]	902.69 [137.04, 2100.96]	912.54 [142.63, 2135.80]	1011.11 [155.40, 2509.47]	801.54 [135.32, 1751.55]	802.37 [139.30, 1767.48]	863.45 [145.43, 2027.00]
United Kingdom	580.43 [95.60, 1373.86]	561.44 [91.45, 1362.19]	660.20 [103.30, 1657.43]	595.07 [95.53, 1403.89]	578.93 [94.68, 1382.60]	675.03 [105.08, 1693.34]	516.54 [87.92, 1147.53]	504.88 [85.62, 1131.98]	565.77 [94.21, 1353.57]
Japan	464.65 [116.89, 1001.96]	456.46 [117.35, 991.19]	554.17 [127.40, 1275.77]	490.03 [123.02, 1035.62]	483.00 [121.77, 1026.23]	571.77 [133.59, 1317.97]	431.93 [111.88, 886.51]	424.23 [109.52, 875.37]	490.09 [119.48, 1113.19]
Mexico	161.40 [-35.45, 458.43]	154.89 [-37.08, 444.34]	222.85 [-33.22, 678.87]	236.11 [-18.73, 656.72]	226.84 [-21.70, 626.17]	335.60 [-14.68, 975.62]	570.32 [56.54, 1365.82]	557.87 [53.56, 1327.59]	757.10 [73.11, 2193.88]
Kazakhstan	141.67 [-170.79, 709.71]	134.10 [-170.72, 699.91]	207.33 [-161.56, 1042.57]	207.00 [-173.06, 922.28]	198.90 [-174.44, 912.88]	288.78 [-162.37, 1375.47]	351.30 [-177.38, 1364.23]	334.96 [-175.98, 1352.34]	449.16 [-161.54, 2109.33]
Argentina	135.94 [-53.38, 407.35]	129.56 [-55.28, 400.65]	178.78 [-51.27, 575.11]	182.15 [-42.53, 528.24]	175.01 [-44.40, 519.56]	242.82 [-38.19, 754.04]	390.19 [5.24, 975.08]	374.98 [0.53, 952.29]	498.39 [15.65, 1413.49]
China	109.57 [11.90, 264.23]	107.90 [11.77, 260.87]	139.79 [14.17, 371.99]	132.15 [17.18, 322.53]	130.93 [16.79, 314.44]	172.61 [20.65, 449.56]	215.95 [34.68, 493.79]	212.17 [34.51, 485.01]	271.34 [41.18, 723.76]

Note: This table presents the estimated net benefits per capita associated with the implementation of carbon pricing policies (ETs and carbon taxes). Panel A reports global aggregate estimates, calculated by summing the estimates for all countries. Panel B provides estimates for selected representative countries. The estimates rely on the selected socioeconomic scenario (first row) and emissions scenario (second row) applied in the long-run damage model specification. Brackets indicate the lower and upper bounds of the estimates. [Supplementary Tables 8–16](#) present detailed results on the benefits and costs for each scenario.

Supplementary Table 8 | Cost-benefit Analysis for SSP1 and RCP4.5

	Benefit (US\$ per capita)		Cost (US\$ per capita) (3)	Net benefit (US\$ per capita) (4)
	Direct Benefit (1)	Co-Benefit (2)		
Panel A. Global estimates				
Aggregate effects	182.36 [33.43, 449.48]	46.07 [13.82, 80.63]	13.56 [4.07, 23.73]	214.88 [23.53, 526.04]
Panel B. Regional estimates				
United States	1391.20 [328.18, 3204.29]	21.56 [6.47, 37.72]	177.46 [53.24, 310.55]	1235.30 [24.09, 3188.77]
Canada	950.60 [-57.18, 2993.72]	215.84 [64.75, 377.72]	0.00 [0.00, 0.00]	1166.43 [7.57, 3371.43]
Denmark	487.09 [3.88, 1406.04]	443.67 [133.10, 776.42]	0.00 [0.00, 0.00]	930.76 [136.98, 2182.45]
United Kingdom	409.54 [45.22, 1073.90]	171.51 [51.45, 300.15]	0.62 [0.19, 1.08]	580.43 [95.60, 1373.86]
Japan	371.14 [93.20, 833.95]	96.52 [28.96, 168.92]	3.00 [0.90, 5.26]	464.65 [116.89, 1001.96]
Mexico	186.96 [47.46, 427.91]	26.34 [7.90, 46.09]	51.89 [15.57, 90.81]	161.40 [-35.45, 458.43]
Kazakhstan	209.86 [-9.59, 688.30]	28.87 [8.66, 50.53]	97.06 [29.12, 169.85]	141.67 [-170.79, 709.71]
Argentina	151.93 [41.41, 345.34]	46.08 [13.82, 80.63]	62.06 [18.62, 108.61]	135.94 [-53.38, 407.35]
China	104.87 [27.91, 238.59]	16.71 [5.01, 29.24]	12.01 [3.60, 21.02]	109.57 [11.90, 264.23]

Supplementary Table 9 | Cost-benefit Analysis for SSP1 and RCP6.0

	Benefit (US\$ per capita)		Cost (US\$ per capita) (3)	Net benefit (US\$ per capita) (4)
	Direct Benefit	Co-Benefit		
	(1)	(2)		
Panel A. Global estimates				
Aggregate effects	178.24 [32.31, 441.09]	46.07 [13.82, 80.63]	13.56 [4.07, 23.73]	210.75 [22.41, 517.65]
Panel B. Regional estimates				
United States	1362.19 [309.73, 3117.90]	21.56 [6.47, 37.72]	177.46 [53.24, 310.55]	1206.28 [5.65, 3102.39]
Canada	940.88 [-65.23, 2980.24]	215.84 [64.75, 377.72]	0.00 [0.00, 0.00]	1156.71 [-0.48, 3357.96]
Denmark	488.63 [3.92, 1440.56]	443.67 [133.10, 776.42]	0.00 [0.00, 0.00]	932.29 [137.02, 2216.98]
United Kingdom	390.55 [41.08, 1062.23]	171.51 [51.45, 300.15]	0.62 [0.19, 1.08]	561.44 [91.45, 1362.19]
Japan	362.94 [93.65, 823.18]	96.52 [28.96, 168.92]	3.00 [0.90, 5.26]	456.46 [117.35, 991.19]
Mexico	180.45 [45.84, 413.82]	26.34 [7.90, 46.09]	51.89 [15.57, 90.81]	154.89 [-37.08, 444.34]
Kazakhstan	202.29 [-9.53, 678.51]	28.87 [8.66, 50.53]	97.06 [29.12, 169.85]	134.10 [-170.72, 699.91]
Argentina	145.54 [39.51, 338.63]	46.08 [13.82, 80.63]	62.06 [18.62, 108.61]	129.56 [-55.28, 400.65]
China	103.20 [27.78, 235.24]	16.71 [5.01, 29.24]	12.01 [3.60, 21.02]	107.90 [11.77, 260.87]

Supplementary Table 10 | Cost-benefit Analysis for SSP1 and RCP8.5

	Benefit (US\$ per capita)		Cost (US\$ per capita) (3)	Net benefit (US\$ per capita) (4)
	Direct Benefit	Co-Benefit		
	(1)	(2)		
Panel A. Global estimates				
Aggregate effects	234.71 [37.68, 689.67]	46.07 [13.82, 80.63]	13.56 [4.07, 23.73]	267.22 [27.78, 766.23]
Panel B. Regional estimates				
United States	1781.01 [373.46, 4785.37]	21.56 [6.47, 37.72]	177.46 [53.24, 310.55]	1625.11 [69.37, 4769.86]
Canada	1206.51 [-14.13, 4639.85]	215.84 [64.75, 377.72]	0.00 [0.00, 0.00]	1422.35 [50.62, 5017.57]
Denmark	589.78 [19.32, 1826.67]	443.67 [133.10, 776.42]	0.00 [0.00, 0.00]	1033.44 [152.42, 2603.09]
United Kingdom	489.30 [52.93, 1357.47]	171.51 [51.45, 300.15]	0.62 [0.19, 1.08]	660.20 [103.30, 1657.43]
Japan	460.65 [103.70, 1107.76]	96.52 [28.96, 168.92]	3.00 [0.90, 5.26]	554.17 [127.40, 1275.77]
Mexico	248.41 [49.70, 648.35]	26.34 [7.90, 46.09]	51.89 [15.57, 90.81]	222.85 [-33.22, 678.87]
Kazakhstan	275.52 [-0.37, 1021.16]	28.87 [8.66, 50.53]	97.06 [29.12, 169.85]	207.33 [-161.56, 1042.57]
Argentina	194.76 [43.52, 513.09]	46.08 [13.82, 80.63]	62.06 [18.62, 108.61]	178.78 [-51.27, 575.11]
China	135.09 [30.18, 346.35]	16.71 [5.01, 29.24]	12.01 [3.60, 21.02]	139.79 [14.17, 371.99]

Supplementary Table 11 | Cost-benefit Analysis for SSP2 and RCP4.5

	Benefit (US\$ per capita)		Cost (US\$ per capita) (3)	Net benefit (US\$ per capita) (4)
	Direct Benefit	Co-Benefit		
	(1)	(2)		
Panel A. Global estimates				
Aggregate effects	212.41 [38.40, 532.06]	46.07 [13.82, 80.63]	13.56 [4.07, 23.73]	244.93 [28.49, 608.62]
Panel B. Regional estimates				
United States	1469.55 [345.28, 3374.47]	21.56 [6.47, 37.72]	177.46 [53.24, 310.55]	1313.65 [41.19, 3358.96]
Canada	925.73 [-53.16, 2974.05]	215.84 [64.75, 377.72]	0.00 [0.00, 0.00]	1141.57 [11.60, 3351.76]
Denmark	459.03 [3.94, 1324.55]	443.67 [133.10, 776.42]	0.00 [0.00, 0.00]	902.69 [137.04, 2100.96]
United Kingdom	424.18 [45.16, 1103.93]	171.51 [51.45, 300.15]	0.62 [0.19, 1.08]	595.07 [95.53, 1403.89]
Japan	396.51 [99.32, 867.61]	96.52 [28.96, 168.92]	3.00 [0.90, 5.26]	490.03 [123.02, 1035.62]
Mexico	261.67 [64.18, 626.19]	26.34 [7.90, 46.09]	51.89 [15.57, 90.81]	236.11 [-18.73, 656.72]
Kazakhstan	275.19 [-11.87, 900.88]	28.87 [8.66, 50.53]	97.06 [29.12, 169.85]	207.00 [-173.06, 922.28]
Argentina	198.14 [52.26, 466.22]	46.08 [13.82, 80.63]	62.06 [18.62, 108.61]	182.15 [-42.53, 528.24]
China	127.45 [33.19, 296.89]	16.71 [5.01, 29.24]	12.01 [3.60, 21.02]	132.15 [17.18, 322.53]

Supplementary Table 12 | Cost-benefit Analysis for SSP2 and RCP6.0

	Benefit (US\$ per capita)		Cost (US\$ per capita) (3)	Net benefit (US\$ per capita) (4)
	Direct Benefit	Co-Benefit		
	(1)	(2)		
Panel A. Global estimates				
Aggregate effects	207.37 [37.44, 520.21]	46.07 [13.82, 80.63]	13.56 [4.07, 23.73]	239.88 [27.54, 596.78]
Panel B. Regional estimates				
United States	1433.82 [337.88, 3287.80]	21.56 [6.47, 37.72]	177.46 [53.24, 310.55]	1277.92 [33.80, 3272.28]
Canada	923.88 [-60.77, 2952.10]	215.84 [64.75, 377.72]	0.00 [0.00, 0.00]	1139.71 [3.98, 3329.81]
Denmark	468.88 [9.53, 1359.39]	443.67 [133.10, 776.42]	0.00 [0.00, 0.00]	912.54 [142.63, 2135.80]
United Kingdom	408.03 [44.31, 1082.64]	171.51 [51.45, 300.15]	0.62 [0.19, 1.08]	578.93 [94.68, 1382.60]
Japan	389.48 [98.07, 858.21]	96.52 [28.96, 168.92]	3.00 [0.90, 5.26]	483.00 [121.77, 1026.23]
Mexico	252.39 [61.21, 595.65]	26.34 [7.90, 46.09]	51.89 [15.57, 90.81]	226.84 [-21.70, 626.17]
Kazakhstan	267.09 [-13.25, 891.48]	28.87 [8.66, 50.53]	97.06 [29.12, 169.85]	198.90 [-174.44, 912.88]
Argentina	190.99 [50.39, 457.54]	46.08 [13.82, 80.63]	62.06 [18.62, 108.61]	175.01 [-44.40, 519.56]
China	126.23 [32.80, 288.80]	16.71 [5.01, 29.24]	12.01 [3.60, 21.02]	130.93 [16.79, 314.44]

Supplementary Table 13 | Cost-benefit Analysis for SSP2 and RCP8.5

	Benefit (US\$ per capita)		Cost (US\$ per capita) (3)	Net benefit (US\$ per capita) (4)
	Direct Benefit	Co-Benefit		
	(1)	(2)		
Panel A. Global estimates				
Aggregate effects	277.15 [44.02, 831.08]	46.07 [13.82, 80.63]	13.56 [4.07, 23.73]	309.67 [34.12, 907.64]
Panel B. Regional estimates				
United States	1888.08 [413.44, 5163.05]	21.56 [6.47, 37.72]	177.46 [53.24, 310.55]	1732.18 [109.36, 5147.54]
Canada	1178.78 [-19.52, 4558.32]	215.84 [64.75, 377.72]	0.00 [0.00, 0.00]	1394.62 [45.23, 4936.03]
Denmark	567.44 [22.30, 1733.06]	443.67 [133.10, 776.42]	0.00 [0.00, 0.00]	1011.11 [155.40, 2509.47]
United Kingdom	504.13 [54.71, 1393.38]	171.51 [51.45, 300.15]	0.62 [0.19, 1.08]	675.03 [105.08, 1693.34]
Japan	478.25 [109.89, 1149.95]	96.52 [28.96, 168.92]	3.00 [0.90, 5.26]	571.77 [133.59, 1317.97]
Mexico	361.16 [68.23, 945.09]	26.34 [7.90, 46.09]	51.89 [15.57, 90.81]	335.60 [-14.68, 975.62]
Kazakhstan	356.97 [-1.18, 1354.07]	28.87 [8.66, 50.53]	97.06 [29.12, 169.85]	288.78 [-162.37, 1375.47]
Argentina	258.81 [56.60, 692.03]	46.08 [13.82, 80.63]	62.06 [18.62, 108.61]	242.82 [-38.19, 754.04]
China	167.92 [36.66, 423.92]	16.71 [5.01, 29.24]	12.01 [3.60, 21.02]	172.61 [20.65, 449.56]

Supplementary Table 14 | Cost-benefit Analysis for SSP3 and RCP4.5

	Benefit (US\$ per capita)		Cost (US\$ per capita) (3)	Net benefit (US\$ per capita) (4)
	Direct Benefit	Co-Benefit		
	(1)	(2)		
Panel A. Global estimates				
Aggregate effects	278.49 [47.28, 694.03]	46.07 [13.82, 80.63]	13.56 [4.07, 23.73]	311.00 [37.37, 770.59]
Panel B. Regional estimates				
United States	1014.48 [250.98, 2292.31]	21.56 [6.47, 37.72]	177.46 [53.24, 310.55]	858.57 [-53.10, 2276.80]
Canada	559.80 [-36.33, 1736.52]	215.84 [64.75, 377.72]	0.00 [0.00, 0.00]	775.64 [28.42, 2114.23]
Denmark	357.87 [2.22, 975.13]	443.67 [133.10, 776.42]	0.00 [0.00, 0.00]	801.54 [135.32, 1751.55]
United Kingdom	345.65 [37.54, 847.57]	171.51 [51.45, 300.15]	0.62 [0.19, 1.08]	516.54 [87.92, 1147.53]
Japan	338.41 [88.18, 718.49]	96.52 [28.96, 168.92]	3.00 [0.90, 5.26]	431.93 [111.88, 886.51]
Mexico	595.88 [139.45, 1335.29]	26.34 [7.90, 46.09]	51.89 [15.57, 90.81]	570.32 [56.54, 1365.82]
Kazakhstan	419.48 [-16.19, 1342.83]	28.87 [8.66, 50.53]	97.06 [29.12, 169.85]	351.30 [-177.38, 1364.23]
Argentina	406.18 [100.02, 913.07]	46.08 [13.82, 80.63]	62.06 [18.62, 108.61]	390.19 [5.24, 975.08]
China	211.26 [50.68, 468.15]	16.71 [5.01, 29.24]	12.01 [3.60, 21.02]	215.95 [34.68, 493.79]

Supplementary Table 15 | Cost-benefit Analysis for SSP3 and RCP6.0

	Benefit (US\$ per capita)		Cost (US\$ per capita) (3)	Net benefit (US\$ per capita) (4)
	Direct Benefit	Co-Benefit		
	(1)	(2)		
Panel A. Global estimates				
Aggregate effects	272.18 [46.44, 679.47]	46.07 [13.82, 80.63]	13.56 [4.07, 23.73]	304.70 [36.53, 756.03]
Panel B. Regional estimates				
United States	976.76 [242.74, 2223.25]	21.56 [6.47, 37.72]	177.46 [53.24, 310.55]	820.85 [-61.34, 2207.74]
Canada	556.52 [-40.00, 1729.52]	215.84 [64.75, 377.72]	0.00 [0.00, 0.00]	772.35 [24.75, 2107.24]
Denmark	358.70 [6.20, 991.06]	443.67 [133.10, 776.42]	0.00 [0.00, 0.00]	802.37 [139.30, 1767.48]
United Kingdom	333.98 [35.24, 832.02]	171.51 [51.45, 300.15]	0.62 [0.19, 1.08]	504.88 [85.62, 1131.98]
Japan	330.71 [85.82, 707.36]	96.52 [28.96, 168.92]	3.00 [0.90, 5.26]	424.23 [109.52, 875.37]
Mexico	583.43 [136.47, 1297.06]	26.34 [7.90, 46.09]	51.89 [15.57, 90.81]	557.87 [53.56, 1327.59]
Kazakhstan	403.15 [-14.79, 1330.93]	28.87 [8.66, 50.53]	97.06 [29.12, 169.85]	334.96 [-175.98, 1352.34]
Argentina	390.96 [95.31, 890.28]	46.08 [13.82, 80.63]	62.06 [18.62, 108.61]	374.98 [0.53, 952.29]
China	207.47 [50.52, 459.38]	16.71 [5.01, 29.24]	12.01 [3.60, 21.02]	212.17 [34.51, 485.01]

Supplementary Table 16 | Cost-benefit Analysis for SSP3 and RCP8.5

	Benefit (US\$ per capita)		Cost (US\$ per capita) (3)	Net benefit (US\$ per capita) (4)
	Direct Benefit	Co-Benefit		
	(1)	(2)		
Panel A. Global estimates				
Aggregate effects	363.97 [52.69, 1139.53]	46.07 [13.82, 80.63]	13.56 [4.07, 23.73]	396.49 [42.78, 1216.09]
Panel B. Regional estimates				
United States	1273.46 [291.21, 3374.28]	21.56 [6.47, 37.72]	177.46 [53.24, 310.55]	1117.56 [-12.88, 3358.77]
Canada	705.10 [-18.23, 2594.15]	215.84 [64.75, 377.72]	0.00 [0.00, 0.00]	920.93 [46.52, 2971.87]
Denmark	419.79 [12.33, 1250.59]	443.67 [133.10, 776.42]	0.00 [0.00, 0.00]	863.45 [145.43, 2027.00]
United Kingdom	394.88 [43.84, 1053.61]	171.51 [51.45, 300.15]	0.62 [0.19, 1.08]	565.77 [94.21, 1353.57]
Japan	396.57 [95.78, 945.18]	96.52 [28.96, 168.92]	3.00 [0.90, 5.26]	490.09 [119.48, 1113.19]
Mexico	782.66 [156.02, 2163.35]	26.34 [7.90, 46.09]	51.89 [15.57, 90.81]	757.10 [73.11, 2193.88]
Kazakhstan	517.35 [-0.34, 2087.92]	28.87 [8.66, 50.53]	97.06 [29.12, 169.85]	449.16 [-161.54, 2109.33]
Argentina	514.38 [110.44, 1351.48]	46.08 [13.82, 80.63]	62.06 [18.62, 108.61]	498.39 [15.65, 1413.49]
China	266.64 [57.18, 698.13]	16.71 [5.01, 29.24]	12.01 [3.60, 21.02]	271.34 [41.18, 723.76]

Appendix References

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