Labour productivity and economic impacts of carbon mitigation: a modelling study and benefit–cost analysis

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Summary

Background Despite the emerging carbon neutrality pledges from different countries, it is still unclear how much these pledges would cost and how the costs would compare with the economic benefits. Comparisons at the country level are important for tightening country-specific emissions trajectories to keep the temperature limit targets outlined in the Paris Agreement within reach. We aimed to systematically estimate avoided heat-related labour productivity losses against the costs of climate change mitigation at country and regional levels.

Methods In this modelling study, to address the above-mentioned research gaps, we first selected two representative climate change scenarios (Representative Concentration Pathway 6.0 [RCP6.0] scenario, a higher warming scenario representing limited mitigation pledges before the Paris Agreement with around 3°C warming by the end of this century; and RCP2.6 scenario, a lower warming scenario assuming global temperature rise is limited to 2°C) and estimated heat-related labour productivity loss using the exposure–response function at country and regional levels. By representing the direct heat-related labour productivity losses in a multiregional global computable general equilibrium model, we then did a benefit–cost analysis to quantify the economic benefits of avoided heat-related labour productivity losses as well as the estimated reduction in gross domestic product (GDP) related to carbon reduction.

Findings By 2100, the overall economic losses due to heat-related labour productivity loss could range from about 1·5% of global GDP under the RCP6.0 scenario to about 0·1% of global GDP under the RCP2.6 scenario. The productivity losses will be highly concentrated in low-latitude regions, especially in southeast Asia, India, and the Middle East, implying the necessity of additional adaptation measures. By 2100, about 51·8% of global climate change mitigation costs could be offset by economic benefits from reduced labour productivity losses. Cumulatively, about 17·0% of climate change mitigation costs could be offset by the economic benefits between 2020 and 2100, when using a 2% social discounting rate. The costs and benefits of climate change mitigation will be distributed highly unevenly across regions due to their varying climate zones and economic structures. Regions with benefits from reduced productivity losses higher than mitigation costs are mainly low-latitude and tropical regions with lower income and lower emissions, such as southeast Asia, Brazil, and Mexico. More than half the climate change mitigation costs could be offset by the economic benefits by 2100 for the world's largest emitters, including the USA, China, the EU, and India. Low benefit–cost ratios are expected in economies that rely on fossil fuels, such as Canada, Russia, and the Middle East.

Interpretation Although pledging carbon neutrality implies radical changes to most economies, substantial health and economic gains can be achieved by reduced heat-related labour productivity loss, even without accounting for other benefits. The benefit–cost analysis in this study shows the potential for choosing more stringent climate change mitigation pathways in some regions. Regions with low benefit–cost ratios need to restructure their economies to reduce mitigation costs as well as losses from declined fossil fuel exports.

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Introduction

From unprecedented heatwaves to ruinous floods and wildfires globally, worsening climate extremes demonstrate that the current progress in reducing carbon emissions is inadequate. Although more than 80 countries, representing about 70% of global greenhouse gas emissions, have presented a net-zero target in their recent pledges (mostly by 2050 or 2060), it is still unclear how much these pledges would cost and how the costs would compare with the benefits. Besides, more aggressive emissions reductions are still needed to keep the temperature limit in the Paris Agreement within reach.[1] Therefore, it is important to compare the costs and benefits of carbon emissions reductions at country and regional levels, taking into

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Research in context

Evidence before this study

We searched Web of Science for studies published between Jan 1, 1990, and March 15, 2021, relating to economic impacts of heat-related labour productivity losses and benefit–cost analyses on carbon neutrality by Nov 30, 2021. Two inclusion and exclusion criteria were applied: only quantitative studies published in English were included (reviews and qualitative studies were excluded); and book chapters and conference articles that did not undergo a strict peer-review process were excluded. Nearly all previously published studies reported high economic costs due to heat-related labour productivity losses under high warming scenarios. They also suggested that a large proportion of the global mitigation costs of achieving the 2°C or 1·5°C temperature rise limit goals could be offset by avoiding losses in labour productivity. Only one study, by Orlov and colleagues, estimated the global offset ratio, showing that approximately 42% of the mitigation costs could be offset by avoided heat-related labour productivity losses by 2100. However, this study did not consider the impacts of global carbon neutrality pledges made after 2014. To the best of our knowledge, no published study has presented a comprehensive benefit–cost analysis for all major countries and regions while also taking into account the latest pledges.

Added value of this study

To the best of our knowledge, this modelling study is the first to conduct a benefit–cost analysis of climate change mitigation strategies focusing on heat-related labour losses for all major countries and regions while also considering the latest global mitigation pledges. This study further identifies countries with different benefit–cost ratios and provides policy recommendations.

Implications of all the available evidence

We show that a higher warming scenario representing limited mitigation pledges before the Paris Agreement with around 3°C warming (Representative Concentration Pathway 6.0 [RCP6.0] scenario) could lead to a global gross domestic product (GDP) loss that is 1·4 percentage points higher than a lower warming scenario (RCP2.6 scenario) by 2100, which implies that achieving the 1·5–2·0°C temperature rise limit goal can avoid large economic losses globally. Most global labour productivity losses are concentrated in low-income and middle-income regions such as southeast Asia, India, and the Middle East, because of the high heat exposure and high proportion of labour-intensive industries in these regions. Even with climate change mitigation strategies, these regions would still incur substantial economic losses, implying the necessity of adequate adaptation countermeasures. The benefit–cost analysis indicates that about 51·8% of the global costs of reaching the 2°C target could be offset by the economic benefits by 2100. However, mitigation costs and benefits would be distributed unevenly across regions. The benefits in southeast Asia, Brazil, and Mexico will exceed the costs by 2100; more than half the mitigation costs in the countries with the largest carbon emissions could be offset by the benefits in 2100, implying the potential to choose more stringent mitigation pathways. Regions with large fossil fuel exports, such as Canada, Russia, and the Middle East, are projected to face small benefit–cost ratios; thus, these regions would benefit from reducing reliance on fossil fuel exports and exploring new economic growth frontiers.

account these countries' recent pledges. These findings could be useful for developing country-specific carbon mitigation pathways.

Heat-related labour productivity loss is estimated to account for more than 60% of total economic losses associated with climate change.[2–4] In other words, economic benefits from avoided heat-related labour productivity losses would take up a large share in the overall benefits due to reductions in carbon emissions. However, only a few studies to date have quantified how the global economic mitigation costs can be offset by the avoided reduction in labour productivity.[5,6] No study, to the best of our knowledge, has conducted a global benefit–cost analysis at the country or regional level. A comparison of country-specific or region-specific mitigation costs with economic benefits from avoided heat-related labour productivity losses would better inform policy making.

In order to bridge the above-mentioned knowledge gap, we used the China-in-Global Energy Model (C-GEM)[7] to quantify the scale and the distribution of economic impacts from heat-related labour productivity losses as well as the mitigation costs at country and regional levels under different warming and mitigation scenarios. The C-GEM is a multiregional global computable general equilibrium model developed by the China Energy and Climate Project, which captures production, consumption, and trade among various global regions and economic sectors.

Methods

Study design

This modelling study considered heat-related labour productivity losses under two emissions trajectories consistent with the Representative Concentration Pathway 6.0 (RCP6.0) scenario (a higher warming scenario representing limited mitigation pledges before the Paris Agreement with around 3°C warming by the end of this century) and RCP2.6 scenario (a lower warming scenario assuming global temperature rise is limited to 2°C) provided by the International Institute for Applied Systems Analysis (IIASA).[8] These two emissions trajectories are inputs of the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP), whose outputs are climate projections (eg, daily temperatures and relative humidity). In this study, we used ISI-MIP's climate projections to quantify heat-related labour productivity losses by adopting the exposure–response function developed by Kjellstrom and colleagues.[9] We then used the C-GEM to estimate the economic impacts. Since RCP6.0 can represent limited mitigation pledges before the Paris Agreement, with around 3°C warming, we applied RCP6.0 as our baseline scenario. Compared to RCP8.5, which is an extreme no-action scenario that assumes around 5°C warming by the end of the century, RCP6.0 can reflect more plausible economic and technology trends.[10] We adopted RCP2·6 to represent more aggressive mitigation, under which countries would achieve carbon neutrality (details for carbon neutrality setting are provided in the appendix p 10), and overall emissions in this scenario are compatible with the 1·5–2°C temperature rise limit by 2100.[11]

Scenarios design

The time scope of this study was from 2020 to 2100. Four scenarios were constructed: a high warming scenario (RCP6·0), a low warming scenario (RCP2.6), and two counterfactual scenarios (RCP6.0cf and RCP2.6cf) for comparison purposes. The energy-related CO_2 emissions trajectories of the RCP6.0 scenario and RCP2.6 scenario were consistent with those of IIASA's RCP6.0 scenario and RCP2.6 scenario, and heat-related labour productivity losses represented in the model were consistent with the temperature rise. The RCP6·0cf scenario had an emissions trajectory in line with the RCP6·0 scenario and the RCP2.6cf scenario had an emissions trajectory in line with the RCP2.6 scenario, but heat-related labour productivity losses represented in the model were set to maintain the loss level in 2020.

Gross domestic product (GDP) differences between the RCP6·0cf scenario and RCP2·6cf scenario could reflect the mitigation costs caused by energy-related reductions in CO_2 emissions, as heat-related labour productivity losses are controlled in these two scenarios. Mitigation costs mainly stem from energy transformation costs and changes in international trade. The benefits from avoided heat-related labour productivity losses can be represented by differences in GDP losses under different warming scenarios. For example, under the high warming scenario, GDP losses constitute the reduced GDP in RCP6.0 compared to its corresponding values in the counterfactual scenario (RCP6.0cf), with increased heat-related labour productivity losses not accounted for beyond 2020. Thus, the net benefits are defined as the benefits minus mitigation costs, which correspond to GDP differences between the RCP6.0 scenario and the RCP2.6 scenario. Notably, GDP differences only show the annual economic impacts of different climate change trends. The changes in country wealth (physical capital and investments) accumulated across multiple decades are potentially much larger.

Since the global emissions trajectory from the C-GEM simulation with no carbon pricing beyond 2020 was consistent with the global emissions trajectory of IIASA's RCP6.0 scenario, we adjusted the regional emissions trajectory constraints on the basis of C-GEM's simulation result for the RCP6.0 scenario. For the RCP2.6 scenario, emissions trajectory constraints for countries and regions were based on their pledges; details are provided in the appendix (pp 8–10).

See Online for appendix

Methodology for estimating change in labour productivity

The labour productivity loss rate was calculated by combining the estimated heat stress and the exposure–response function for three work intensity groups (low-intensity work [200W], moderate-intensity work [300W], and high-intensity work [400W]) developed by Kjellstrom and colleagues,[9] which are provided in the appendix (pp 1–2). This exposure–response function has been used in previously published studies.[5,12] Here, the labour productivity loss rate was defined as the percentage of potential working hours lost when exposed to heat stress out of the total hours worked without any heat effect. There are many indices that can be used as a proxy for heat stress on workers, such as wet-bulb globe temperature (WBGT), universal thermal climate index, effective temperature, and heat stress index. Each of these indices has its advantages and disadvantages. Given that the WBGT is the main occupational health guideline heat index[13] and is widely used in occupational heat exposure studies,[6,13–16] we also adopted the WBGT as the heat assessment index for the present study. The WBGT is a composite measure combining temperature, humidity, solar radiation, and wind speed. Given that outdoor workers usually take measures to avoid direct sunlight, we took a conservative approach and only estimated the WBGT for all workers using formulas for working in the shade or an indoor (without air conditioning) environment.[9] As there is little knowledge about how future adaptation would influence labour productivity losses, no additional adaptation measures besides working in shade were considered.

Based on the projection of climate variables under the RCP2.6 and RCP6·0 scenarios as well as the exposure–response function, we first estimated the WBGT values and calculated the labour productivity loss for each work intensity group at the grid level (0·5°×0·5°). We then aggregated the grid-level loss to the sectoral and regional level based on population density and sectoral employment data, under the assumption that sectoral employment shares are identical across grid cells within a region (for details see the appendix pp 1–2). Our analysis based on grid-cell-level information can incorporate substantial variation in climate and population density within each region.

Methodology for estimating economic losses

The C-GEM is a multiregional global recursive-dynamic computable general equilibrium model that simulates economic activities in different sectors and their associated energy flows and CO_2 emissions. It is used to evaluate the economy-wide mitigation costs and corresponding benefits from avoiding heat-related labour productivity loss for countries and regions.

The model has been applied to study various energy and climate policies in China and other countries.[17–19] The input–output and bilateral trade data are constructed on the basis of the Global Trade Analysis Project database version 10,[20] with the base year of 2014. We first calibrated the model to the year 2020 using regional economic and energy data[21,22] and then iterated the model to the year 2100 with a recursive dynamic for the reference calibration. The C-GEM disaggregates the world into 17 geographical regions, with the main high-income and lower-middle-income countries (eg, Brazil, China, India, Japan, Russia, and the USA) as separate regions and other countries represented in composite regions (eg, the European Union, Australia and New Zealand, the Middle East, Africa, and Latin America). Detailed sectoral and regional aggregation schemes, as well as production and consumption functions, have been previously described by Huang and colleagues.[20] In this study, heat-related labour productivity loss was defined as increased demand for labour for a unit of output (differing by sector and by region) in the C-GEM.

Additionally, we did an uncertainty analysis by changing key parameter values in C-GEM, including the labour productivity loss rate of different forms of labour, the elasticity of substitution between capital and labour, the future costs of renewable energy; changing the cutoff ratio in the exposure–response function; and changing the discount rate range and mitigation cost of agriculture, forestry, and other land use sectors in the process of external accounting. Details are given in the appendix (pp 11–18).

Although our modelling results cover the full period from 2020 to 2100, we focused our discussions on 2050 (the timepoint when many major economies have pledged to achieve carbon neutrality) and 2100. We selected a 2% social discounting rate[23] to discount future costs and benefits to the year 2020. We also did a sensitivity analysis on social discounting rates (appendix p 18).

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

Our modelling estimates show that the heat-related labour productivity loss is distributed unevenly among different regions. Most heat-related labour productivity losses occur in low-latitude regions (regions found between 0°N/S and 30°N/S; eg, southeast Asia) under the RCP2.6 and RCP6.0 scenarios. Conversely, labour productivity in countries in high-latitude regions (eg, Canada and Russia) is less affected under both scenarios.

From the work intensity group perspective, high-intensity work (400W) is the most heavily affected group; the labour productivity losses in the high-intensity work (400W) group exceed the sum of those in low-intensity (200W) and moderate-intensity work (300W) groups in all regions (figure 1). By 2085 (between 2071 and 2100), the labour productivity loss of high-intensity work is estimated to reach 15·1% in southeast Asia under the RCP6.0 scenario and 9·0% under the RCP2·6 scenario. Specifically, Cambodia will be the most affected by heat-related labour productivity loss, with a loss in high-intensity work of about 21·6% under the RCP6.0 scenario and about 14·4% under the RCP2.6 scenario. In India, by 2085 (between 2071 and 2100) the labour productivity loss of the high-intensity work group could reach as high as 14·1% under the RCP6.0 scenario and 9·2% under the RCP2.6 scenario. The labour productivity loss of the low-intensity work group is projected to be smaller. However, it could still reach 3·6% in India and 2·0% in southeast Asia by 2085 under the RCP6.0 scenario. Under the RCP2.6 scenario, by 2085 the labour productivity loss of the low-intensity work group would fall to 1·5% in India and 0·6% in southeast Asia.

We found that the heat-related labour productivity loss would lead to large economic damages if no substantial mitigation effort is taken. By 2100, the overall economic losses under the RCP6.0 scenario could reach about 1·5% of global GDP. However, under the RCP2.6 scenario, the economic losses could be reduced to 0·1% of global GDP. Economic losses would be unevenly distributed across different geographical locations because of different economic structures between regions, with the highest losses concentrated in low-latitude regions, especially in the Middle East and southeast Asia, and the lowest losses observed in regions bordering the North Pole (eg, Canada and Russia; figure 2). However, low-latitude regions would still undergo large heat-related economic losses even if the global temperature rise is controlled to within 2°C. Under the RCP2.6 scenario, the economic loss in the Middle East would reach about 0·5% of GDP. We did another scenario analysis with an assumption that all labour (including labour exempted from heat loss) can be affected by heat stress; details of this analysis are provided in the appendix (pp 11–18).

The drastic reduction in carbon emissions under the RCP2.6 scenario will require industries to phase down production technologies based on fossil fuels, while upgrading to low-carbon technologies, and therefore incur economic costs. The low-carbon transition from the RCP6.0 to RCP2.6 scenario is estimated to cost about 4·5% of global GDP in 2050 and 2·7% of global GDP in 2100. At the same time, reduced labour productivity losses from the RCP6.0 to RCP2.6 scenario will also bring economic benefits. Cumulatively, these economic benefits can offset about 17·0% of the mitigation costs when using a social discounting rate of 2% (the offset ratio is about 7·9% if the social discounting rate is 6%).

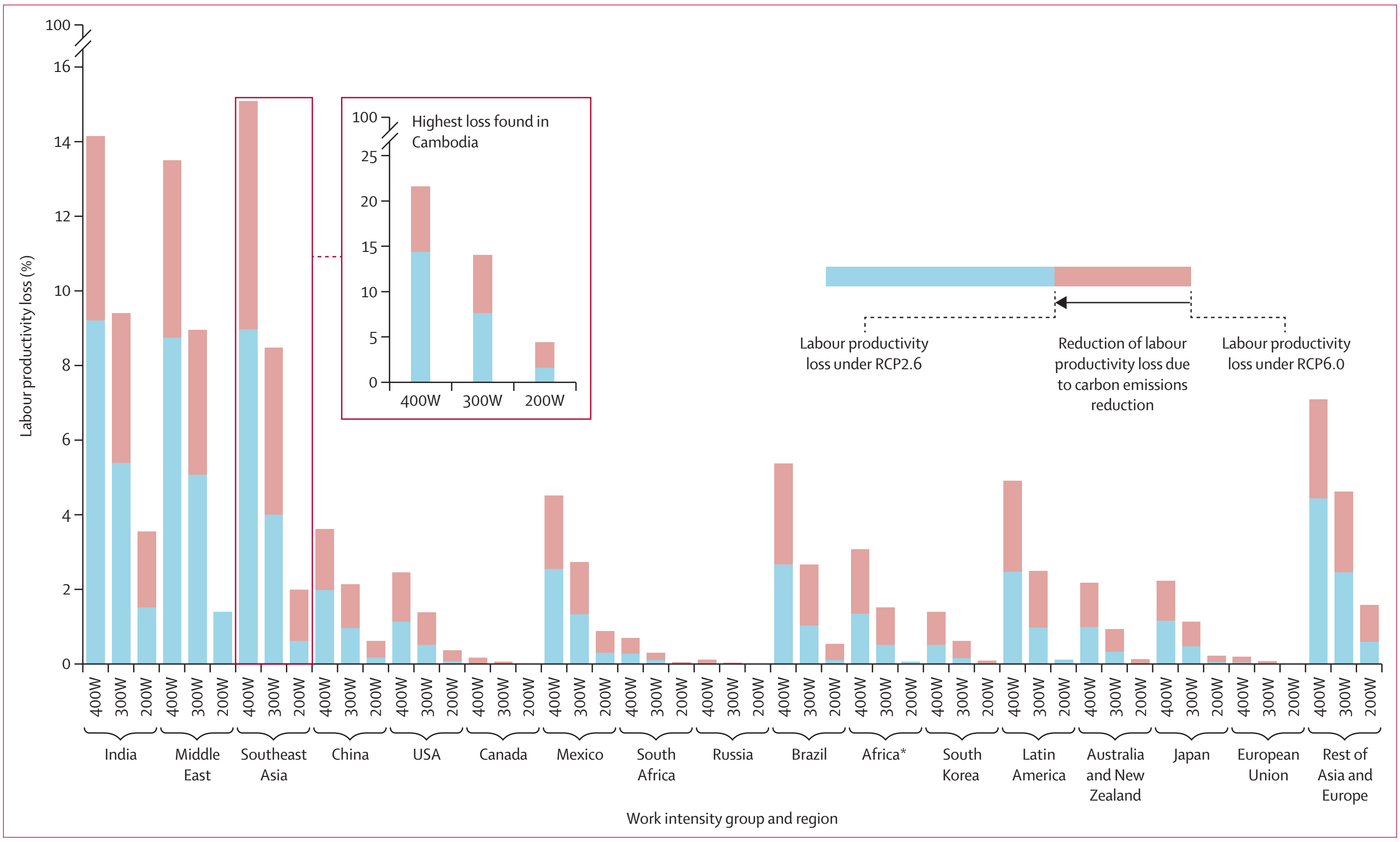

Figure 1: **Average heat-related labour productivity loss for different work intensity groups in 17 countries and regions under RCP2.6 and RCP6.0 scenarios between 2071 and 2100**
Instead of showing the results for the year 2100, an average value for the period between 2071 and 2100 is used because we treated 30 years as the minimum time interval for observing a long-term climate trend and avoiding biases in short-term climate fluctuations. The labour productivity loss by 2100 is extrapolated by assuming labour productivity loss grows linearly between 2071 and 2100, which is applied further in the economic assessment. 200W=low-intensity work group. 300W=moderate-intensity work group. 400W=high-intensity work group. RCP2.6=Representative Concentration Pathway 2.6 (a lower warming scenario assuming global temperature rise is limited to 2°C). RCP6.0=Representative Concentration Pathway 6.0 (a higher warming scenario representing limited mitigation pledges before the Paris Agreement with around 3°C warming by the end of this century). *Excluding South Africa.

Globally, these economic benefits alone can offset about 4·6% of the mitigation costs in 2050, but the economic benefits could increase to about 51·8% of the mitigation costs in 2100; sensitivity analyses demonstrating the robustness of these findings are shown in the appendix (pp 11–18). The increase in economic benefits from 2050 to 2100 is large because the temperature difference (and therefore the difference in heat-related labour productivity loss) between the RCP2.6 and RCP6.0 scenarios does not differ much until 2050. Therefore, the economic benefits of more ambitious decarbonisation manifest more rapidly between 2050 and 2100.

At the regional level, we found a large disparity across regions in the share of mitigation costs that could be offset by the economic benefits from avoiding labour productivity losses. The mitigation costs, economic benefits, and benefit–cost ratios for all regions in 2050 and 2100 are shown in figure 3. In 2050, if only labour productivity losses are considered, no region will have an economic benefit higher than the cost of ambitious decarbonisation. The largest benefit–cost ratio is estimated to be in southeast Asia, with about 70·9% of the cost covered by the economic benefit. As the temperature difference between the RCP6.0 and RCP2.6 scenarios mainly becomes more pronounced after 2050, larger benefits from carbon mitigation will be witnessed after 2100. The economic benefits would exceed the costs in many low-latitude and tropical regions by 2100, including southeast Asia, Brazil, Mexico, and Africa (excluding South Africa). In high-carbon emission regions (including the USA, China, the European Union, and India), which accounted for about 60% of global emissions in 2020,[24] more than 50% of climate change mitigation costs could be offset by the total economic benefits from reduced productivity loss by 2100. Some regions have the smallest benefit–cost ratios (eg, about 3·9% in Russia, 11·7% in Canada, and 26·9% in the Middle East by 2100), mainly because ambitious climate change mitigation targets require a reduction in the demand for fossil fuels at the global level. As these economies rely heavily on fossil fuel exports, they would face considerable costs from both reductions in domestic emissions and substantial declines in fossil fuel exports. We estimate that costs from the decline in fossil fuel

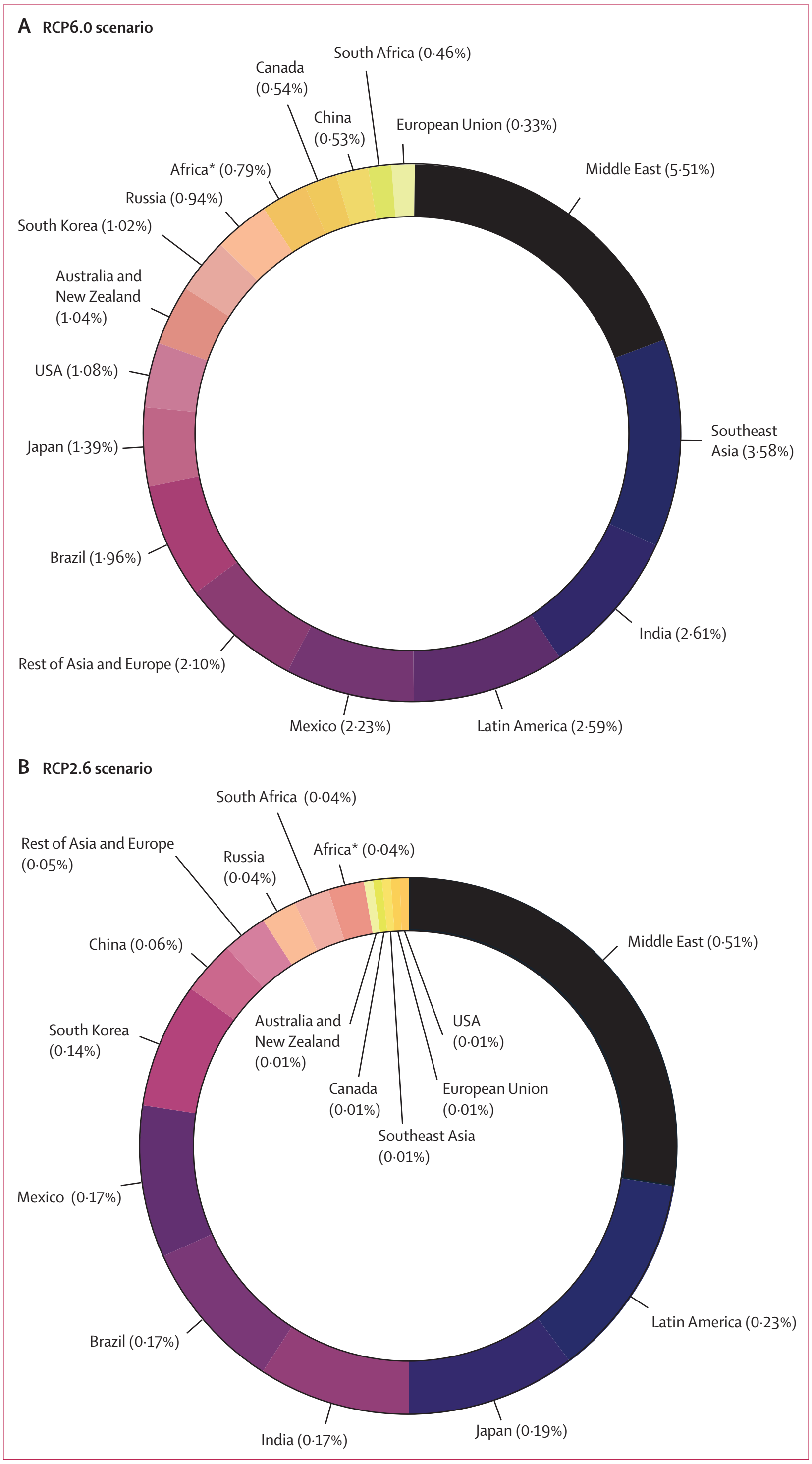

Figure 2: **GDP loss rate caused by heat-related labour productivity losses in different regions by 2100**
(A) GDP loss rate by region by 2100 under RCP 6.0 scenario. (B) GDP loss rate by region by 2100 under RCP 2.6 scenario. RCP2.6=Representative Concentration Pathway 2.6 (a lower warming scenario assuming global temperature rise is limited to 2°C). GDP=gross domestic product. RCP6.0=Representative Concentration Pathway 6.0 (a higher warming scenario representing limited mitigation pledges before the Paris Agreement with around 3°C warming by the end of this century). *Excluding South Africa.

exports would account for GDP losses of 37·8% in Canada, 19·7% in Russia, and 27·1% in the Middle East by 2100.

Discussion

In this modelling study, we estimated the economic costs of carbon emissions mitigation needed from the RCP6.0 to RCP2·6 scenario at country and regional levels, considering the latest mitigation pledges in major countries. We also estimated the corresponding economic benefits from reduced heat-related labour productivity losses and further showed the distribution of benefit–cost ratios across regions.

The benefit–cost ratio by 2100 at the global level (about 51·8%) is similar to the estimate of about 40–70% by Takakura and colleagues[6] and the estimate of 42% by Orlov and colleagues.[5] However, our work made improvements in two areas. First, we estimated costs and benefits using a more reasonable baseline scenario (RCP6.0) rather than the RCP8.5 scenario used in these two studies. Second, our modelling framework provides consistent regional cost and benefit estimations, while the studies by Takakura and colleagues[6] and by Orlov and colleagues[5] relied on numbers directly derived from the results of the Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change, published in 2014.[11]

The regions included in this study can be roughly categorised into three distinct groups. The first group is low-latitude regions (including Latin America and South Africa), where economic benefits would exceed costs by the end of this century, although these regions would still face substantial heat-related labour productivity losses even if the global temperature rise is controlled to within 2°C. Therefore, these regions need to substantially strengthen their adaptation measures against heat-related labour productivity losses while also taking reasonable steps to reduce their emissions. However, some countries in this group (such as African countries) have a relatively low per capita income, meaning potentially lower capacities to reduce emissions and adapt. Additionally, it should be noted that high benefit–cost ratios in these countries can only be achieved through successful global climate change mitigation efforts rather than unilateral actions by these countries. Therefore, the low-income countries in this group might need to seek financial and technological support to increase their adaptability and promote climate change mitigation.

The second group comprises regions with the smallest benefit–cost ratios (including Canada, the Middle East, and Russia). These regions are usually large fossil fuel exporters. The main reason for their small benefit–cost ratios is not their own emissions reductions but rather the impacts of global emissions reductions. The costs from decline in fossil fuel exports would account for more than 19% of GDP loss for these regions by 2100.

With more countries committing to net zero targets, these regions should reduce their reliance on fossil fuel exports and increase investment in low-carbon and zero-carbon technologies to reduce the negative impacts of reductions in global emissions on their economy.

The third group comprises regions with high carbon emissions (including the USA, China, and India). Most of these countries and regions have larger benefit–cost ratios than the global average. Since this study only considered economic benefits from reduced labour loss due to heat exposure, if a more comprehensive scope of costs in the high-warming scenarios (including losses of labour, tourism, and physical assets, and increased health-care costs associated with increased health impacts) and a more comprehensive scope of climate change mitigation co-benefits (including potential gains and savings from cleaner air, healthier diets, more active lifestyles, better urban design, and more exposure to greenness) are considered, the benefit–cost ratios could be even higher. Therefore, these regions are also recommended to advance their carbon emissions reduction goals.

Several limitations of this study should also be noted. First, this study only adopted the WBGT to measure heat stress and used the same heat labour exposure–response function for all regions due to a scarcity of epidemiological data. Finer-grained exposure–response functions based on epidemiological data can improve the credibility of the results.[4] Future work could consider region-specific epidemiological studies and adopt more heat stress indices to reduce the uncertainty in the data. Second, this study selected only one representative growth pathway for future economic, population, and baseline regional emissions trajectories. Economic costs and benefits would differ under different socioeconomic assumptions.[25] For example, a greater population projection will lead to higher benefits of avoiding heat-related labour losses. As for regional emissions trajectories, a greater requirement for reductions in emissions for a region will result in a higher mitigation cost and a lower benefit–cost ratio. Additional sensitivity analyses could be done when more representative regional pathways are available. Third, we did not consider potential international cooperation in future emissions reductions, which could effectively reduce global mitigation costs.[26] Fujimori and colleagues[26] showed that international emissions trading can reduce about 38% of global mitigation costs (reducing GDP loss from approximately 0·29% to 0·17%) by 2030 for major countries to achieve the intended nationally determined contribution. If global mitigation costs in our study reduce by the same percentage, the global mitigation benefit–cost ratio could increase from 0·52 to 0·84 by 2100. Last, this study only focused on mitigation of energy-related CO_2 emissions. We briefly discuss the mitigation costs of the agriculture, forestry, and other land use sectors in the appendix (pp 18) and the results show that the global benefit–cost ratio is relatively robust.

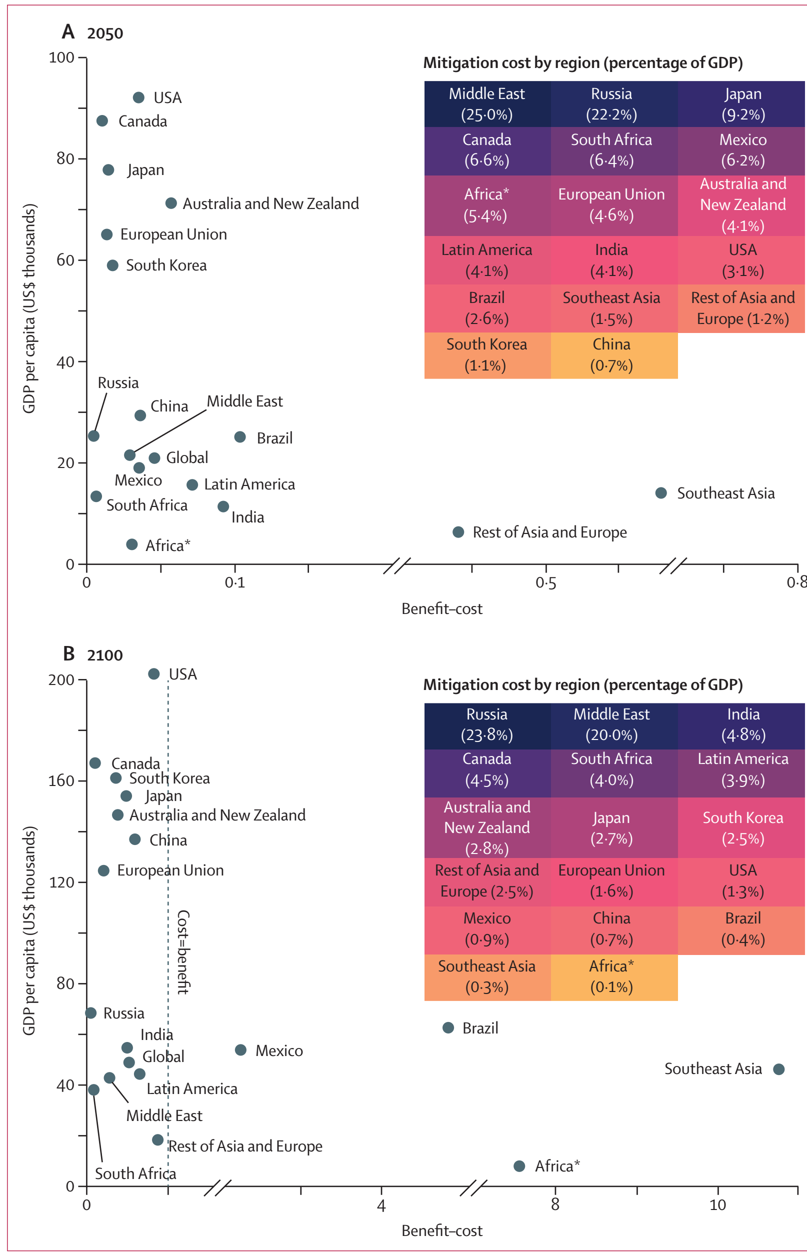

Figure 3: **Benefits and costs of carbon mitigation in 2050 (A) and in 2100 (B)**
Regions to the right of the dashed line in panel B indicate that the benefits exceed the costs, and regions to the left of the dashed line indicate that the benefits are smaller than the costs; the shading in the table corresponds to the mitigation cost (as a percentage of gross domestic product [GDP]), with dark purple corresponding to the highest cost and yellow corresponding to the lowest cost. *Excluding South Africa.

In summary, despite the above uncertainties, this study provides a representative and relatively conservative estimate for the benefit–cost ratio of carbon mitigation. The absolute magnitude of these ratios across regions could change under different assumptions, as we show in our sensitivity analyses; however, our study still provides useful insights for policy makers to understand the scale and distribution of benefit–cost ratios related to heat-related labour productivity losses.

Contributors

MZ, XH, TK, DZ, and WC designed the study. MZ and XH developed the modelling framework and wrote the original draft, with contributions from TK, DZ, and WC. MR, MO, JKWL, and XZ provided constructive comments to improve the original draft. WC and DZ designed the scenario and conducted the analyses. MZ and XH collected and verified the underlying data in the manuscript. WC and DZ were responsible for the decision to submit the manuscript for publication.

Declaration of interests

MR is the Executive Director of the *Lancet* Countdown, and MR's work was supported by an unrestricted grant from the Wellcome Trust (209734/Z/17/Z). All other authors declare no competing interests.

Data sharing

Data sources are listed in the appendix (p 8). Additional data can be shared upon reasonable request to the corresponding authors.

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