Potential of shifting work hours for reducing heat-related loss and regional disparities in China: a modelling analysis

Mengzhen Zhao, Yuyou Chen, Jing Shang, Shihui Zhang, Bo Lu, Yanqing Miao, Mingyu Lei, Ruiyao Li, Wenjia Cai, Chi Zhang

Summary

Background As climate change intensifies, the economic losses caused by heat-related labour productivity loss are gaining increasing attention. Shifting work hours has become a prevalent practice to reduce outdoor workers' heat exposure. However, both the potential of this adaptation measure for reducing labour productivity and economic loss and how this potential will change in the future remain unclear. Answers to these questions at the subnational level are important for decision makers to promote the implementation of adaptations and the development of comprehensive strategies to tackle the residual consequences of climate change. This study aimed to model the potential of shifting work hours for reducing labour productivity and economic loss at the national and provincial level in China.

Methods We did a modelling study to estimate the potential of shifting work hours for reducing heat-related labour productivity loss in China under different climate change scenarios. We used the China Hybrid Energy and Economic Research model, a dynamic multiregional computable general equilibrium model, to quantify the economic impacts of heat-related labour productivity loss from 2020 to 2100, with an exposure–response function between heat stress and labour productivity loss and bias-corrected climate change projections from the US National Aeronautics and Space Administration Earth Exchange Global Daily Downscaled Projections dataset conducted under the Coupled Model Intercomparison Project Phase 6 (CMIP6). We used nine different scenarios: three climate change scenarios consistent with the shared socioeconomic pathway (SSP)–representative concentration pathway scenarios used in CMIP6 (SSP1–2·6, SSP2–4·5, and SSP5–8·5); three adaptation scenarios (SSP1–2·6_shift, SSP2–4·5_shift, and SSP5–8·5_shift); and three counterfactual scenarios (SSP1–2·6cf, SSP2–4·5cf, and SSP5–8·5cf). SSP1–2·6 is a scenario with less than 2°C warming by 2100 and low carbon emissions. SSP2–4·5 is a middle scenario with a 2·7°C rise in global mean temperature, representing current emission trends. SSP5–8·5 is an extreme scenario, with a 4·4°C rise in global mean temperature and high carbon emissions. The climate change scenarios and adaptation scenarios considered heat-related labour productivity loss caused by climate change in the future, whereas the counterfactual scenarios held loss constant at the 2020 level. The adaptation scenarios considered the impact of shifting work hours earlier when estimating labour productivity loss. We assumed that outdoor work hours could maximally be rescheduled to sunrise time. The economic growth pathways in the SSP1–2·6cf, SSP2–4·5cf, and SSP5–8·5cf scenarios were derived from SSP1, SSP2, and SSP5, respectively. We compared results for the different adaptation and climate change scenarios to evaluate the reduction potential of the adaptation measure. By comparing the climate, adaptation, and counterfactual scenarios separately, we also estimated the economic loss caused by heat-related labour productivity loss and economic loss. We did not consider specific mitigation measures but rather reflected the influence of mitigation efforts by comparing results under different climate change scenarios.

Findings Shifting work hours could substantially reduce the impact of heat on labour productivity and economic development in China. The potential of this adaptation strategy for reducing loss was projected to increase with lower levels of temperature rise (ie, under improving mitigation efforts). Compared with the SSP2–4·5 climate change scenario, shifting work hours under the SSP2–4·5_shift scenario was projected to reduce up to 26·2% (uncertainty range 24·8–28·5) of national outdoor labour productivity loss in 2100, leading to a decrease in residual GDP loss from 4·3% to 3·8%. The potential for reducing labour productivity loss was projected to increase to 31·0% (uncertainty range 30·1–34·1) in 2100 under the SSP1–2·6_shift scenario. Considering this synergy between shifting work hours and mitigation measures, our results suggest that only simultaneous implementation of adaptation and mitigation measures could achieve the maximum reduction in residual economic loss. However, even with the implementation of ambitious mitigation measures and the most robust implementation of this adaptation measure, the residual damage resulting from heat-related labour productivity loss could not be completely avoided in our modelling results. Under the most optimistic SSP1–2·6_shift scenario, the residual GDP loss in 2100 was projected to be reduced to 2·0%, equivalent to 54% of the expenditure of China's basic medical insurance fund in 2020 (approximately US$303 billion). Moreover, our results suggested that shifting work hours might reduce development disparities among provinces (this measure cannot change the distribution patterns of economic loss). The largest avoided economic loss was projected in low-income provinces with large agricultural populations, including Guangxi, Guizhou, Hainan, and Jiangxi, whereas high-income regions, including Beijing and Shanghai, were projected to see low proportions of avoided economic loss. In 2100, the reduced economic loss was projected to be 9·4% of GDP loss

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in Beijing and 7·7% of GDP loss in Guangdong, compared with 42·3% of GDP loss in Guizhou and 19·2% of GDP loss in Sichuan under the SSP2–4·5_shift scenario.

Interpretation This modelling study suggests that shifting work hours could substantially reduce heat-related labour productivity and economic loss and further reduce development disparities among regions in China. This study contributes to the broader discussion in the literature around the synergistic relationships and trade-offs that exist between climate change adaptation and mitigation measures. Our results show that there are important synergies between shifting work hours (ie, an adaptation measure) and mitigation measures. The effectiveness of this adaptation measure increases with escalating mitigation efforts. However, this single adaptation measure cannot eliminate economic losses entirely. To minimise residual economic loss, local governments will need to implement targeted policies that promote flexible work hours for different regions and develop an integrated adaptation strategy. Moreover, more aggressive mitigation efforts should be pursued together with adaptation measures to minimise residual economic loss.

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Introduction

The negative impact of heat on labour productivity has intensified due to climate change, especially for people who work outdoors.[1,2] In 2023, the global mean temperature approached 1·45°C above pre-industrial levels (ie, 1850–1900), and many countries witnessed record-breaking high temperatures.[3] The maximum temperature in Xinjiang in China reached 52·2°C, setting a new record as the highest temperature ever recorded in Chinese history. As reversing this trend of increasingly extreme hot weather is impossible in the short term,[4] there is an urgent need to speed up our implementation of adaptation measures. However, the resources available to decision makers are scarce, indicating a crucial need for a better understanding of adaptation measures' potential for reducing productivity and economic losses and the residual losses due to climate change. Shifting to early work hours has been endorsed by a number of national guidelines as a prevalent practice for outdoor workers (eg, builders and agricultural workers) to avoid heat exposure, including in Australia, China, Europe, and the USA.[5–8] However, at the subnational level, questions around the scale and regional distribution of this adaption measure's potential for reducing loss and whether this potential will change with temperature rise (ie, whether there are synergies or trade-offs between this adaptation measure and mitigation measures) are still unanswered. Conducting effect analyses to address these questions can provide policy makers with a deeper understanding of the potential for reducing productivity and economic loss, the magnitude of residual losses due to climate change, and the importance of simultaneously implementing mitigation and adaptation measures for tackling climate change. Addressing these questions at the subnational level is essential for designing and implementing policies that are tailored to regional realities.

See Online for appendix

Several studies have reported substantial economic losses resulting from labour productivity loss caused by heat and have further attempted to quantify these losses.[9–13] However, only a few estimates have considered the impact of shifting work hours on reducing heat exposure at global and national levels.[11,14,15] The maximum potential of shifting work hours for reducing labour productivity and economic loss and how this potential might change in the future at a subnational level remain unknown. The subnational level is the most crucial unit for adaptation policy making and implementation and this information scarcity could hinder efforts to promote the implementation of adaptations and development of comprehensive actions to tackle climate change.

This study aimed to model the potential of shifting work hours for reducing labour productivity and economic loss at the national and provincial level in China.

Methods

Study design and scenario design

We did a modelling study to estimate the potential of shifting work hours for reducing heat-related labour productivity loss in China under three different climate change scenarios. The time scope was from 2020 to 2100. We used the China Hybrid Energy and Economic Research (CHEER) model,[16–18] a multiregional computable general equilibrium (CGE) model, to quantify the economic impacts of heat-related labour productivity loss, with an exposure–response function between heat stress and labour productivity loss[19] and bias-corrected climate change projections from the US National Aeronautics and Space Administration (NASA) Earth Exchange Global Daily Downscaled Projections dataset conducted under the Coupled Model Intercomparison Project Phase 6 (CMIP6).[20] The study framework is detailed in the appendix (p 1).

Research in context

Evidence before this study

We conducted a comprehensive literature search of articles published between Jan 1, 1990, and Feb 29, 2024. Our search included the databases Web of Science, PubMed, Google Scholar, and China National Knowledge Infrastructure. We excluded qualitative studies to focus on quantitative research. Of the 57 studies that estimated heat-related labour productivity loss, only three took into consideration the potential impact of shifting work hours at the global level. These three studies all indicated a substantial reduction in labour productivity loss from shifting work hours. However, these studies adopted the same adjustment strategy for all regions, with mostly a 3-h adjustment period, and assumed a 12-h period of work. These assumptions could potentially overestimate the potential for reducing labour productivity loss by shifting work hours. Moreover, the reduction potential at national and subnational levels remains unclear. Therefore, designs of regional adaptation policies are missing a sufficient theoretical basis.

Added value of this study

This study is the first detailed assessment of the maximum potential of shifting work hours for reducing labour productivity and economic loss and the residual negative consequences of implementing this measure at the provincial level in China. This study also plots the distribution patterns of this potential loss reduction across regions of China alongside the resulting impacts on regional development inequity. Moreover, this study estimates changes in loss reduction potential across different mitigation ambition levels, thereby identifying the synergies between this adaptation measure and mitigation measures. The results underscore the collaborative benefits of integrating adaptation and mitigation strategies into climate policy.

Implications of all the available evidence

As in previous studies, this study underscores the fact that shifting work hours can substantially reduce outdoor labour productivity loss. The results further reveal the potential of this adaptation measure in reducing productivity loss and residual economic loss at the provincial level in China. Under a middle warming scenario representing the current policy with approximately 3°C global warming (the SSP2–4·5_shift scenario), shifting work hours is projected to reduce national outdoor labour productivity loss by up to 26·2% (uncertainty range 24·8–28·5) in 2100, leading to a decrease in residual GDP loss from 4·3% to 3·8%. This study also identifies the synergies between this adaptation measure and mitigation measures. In 2100, the potential for reducing labour productivity loss in China would increase to 31·0% (uncertainty range 30·1–34·1) under a scenario with less than 2°C warming and low carbon emissions. Moreover, this study reveals that this adaptation measure could reduce development disparities among Chinese provinces. The largest avoided economic loss was found in low-income provinces with large agricultural populations, including Guangxi, Guizhou, Hainan, and Jiangxi. In 2100, the reduced economic loss would reach 42·3% of GDP loss in Guizhou and 19·2% of GDP loss in Sichuan, but only 9·4% of GDP loss in Beijing and 7·7% of GDP loss in Guangdong under the SSP2–4·5_shift scenario.

SSP=shared socioeconomic pathway.

Nine scenarios were constructed in this study (table): three climate change scenarios consistent with the shared socioeconomic pathway (SSP)–representative concentration pathway scenarios used in CMIP6 (SSP1–2·6, SSP2–4·5, and SSP5–8·5); three adaptation scenarios (SSP1–2·6_shift, SSP2–4·5_shift, and SSP5–8·5_shift); and three counterfactual scenarios (SSP1–2·6cf, SSP2–4·5cf, and SSP5–8·5cf). SSP1–2·6 is a scenario with less than 2°C warming by 2100 and low carbon emissions. SSP2–4·5 is a middle scenario with a 2·7°C rise in global mean temperature, representing current emission trends. SSP5–8·5 is an extreme scenario, with a 4·4°C rise in global mean temperature and high carbon emissions. The climate change scenarios and adaptation scenarios considered heat-related labour productivity loss caused by climate change in the future, whereas the counterfactual scenarios held loss constant at the 2020 level. The adaptation scenarios also considered the impact of shifting work hours earlier when estimating labour productivity loss. The economic growth pathways in the SSP1–2·6cf, SSP2–4·5cf, and SSP5–8·5cf scenarios were derived from SSP1, SSP2, and SSP5, respectively. By comparing the climate, adaptation, and counterfactual scenarios separately, we estimated the economic loss caused by heat-related labour productivity loss and economic loss. Furthermore,

	Global temperature rise	Adaptation
Climate change scenarios		
SSP1–2·6	Less than 2°C	None
SSP2–4·5	Approximately 2·7°C	None
SSP5–8·5	Approximately 4·4°C	None
Adaptation scenarios		
SSP1–2·6_shift	Less than 2°C	Shifting work hours
SSP2–4·5_shift	Approximately 2·7°C	Shifting work hours
SSP5–8·5_shift	Approximately 4·4°C	Shifting work hours
Counterfactual scenarios		
SSP1–2·6cf	Kept constant at the 2020 level	None
SSP2–4·5cf	Kept constant at the 2020 level	None
SSP5–8·5cf	Kept constant at the 2020 level	None

SSP=shared socioeconomic pathway.

***Table:* Scenario designs**

the comparison of adaptation and climate scenarios enabled the evaluation of the reduction potential of adaptation measure. This study did not consider specific mitigation measures but rather reflected the influence of mitigation efforts by comparing results under different climate change scenarios.

Estimating heat-related labour productivity loss

We adopted a widely used exposure–response function developed by Kjellstrom and colleagues,[19] to quantify the relationship between wet-bulb globe temperature (WBGT) and labour productivity loss. The WBGT is the only index used by the International Organization for Standardization to measure heat stress experienced by workers,[21] capturing the combined effects of air temperature, humidity, solar radiation, and other factors. The WBGT value exhibits huge disparity between outdoor and indoor environments due to variations in solar radiation. Recognising that the practice of shifting work hours is more commonly done for outdoor workers, we differentiated between outdoor and indoor environments. Physical work intensity also exhibits a large correlation with the impacts of heat on labourers, with higher-intensity tasks resulting in greater labour productivity loss under identical heat stress conditions. Hence, we further classified work into three intensity levels: low-intensity work, middle-intensity work, and high-intensity work.

First, we estimated daily indoor WBGT values with Bernard's method,[22] and daily outdoor WBGT values with Liljegren's method.[23] Unlike Bernard's method, the latter takes into account the effects of solar radiation and near-surface wind speed. The inputs of climatic parameters, including maximum and average temperature, relative humidity, near-surface wind speed, and solar radiation, on a daily scale were obtained from four models in CMIP6 (appendix p 2). These climatic data were bias-corrected by NASA with a daily variant of the bias-corrected spatial disaggregation method on the basis of historical observations from 1960 to 2014, with a spatial resolution of $0 \cdot 25° \times 0 \cdot 25°$.[20] Due to computation and data storage constraints, we further estimated WBGT at an hourly level by adopting the WBGT 4+4+4 method, which is the weighted sum of the natural wet-bulb temperature, globe temperature, and ambient or dry-bulb temperature. This method is effective because WBGT consists largely of the dew point (ie, the temperature at which air at a given pressure becomes saturated with water vapour), which remains fairly constant throughout the day.[19] Second, we estimated heat-related labour productivity loss for three intensity levels of work in two environments (ie, indoors and outdoors) at the grid level (ie, $0 \cdot 25° \times 0 \cdot 25°$). Third, assuming 2080 h per worker per year (52 weeks × 5 days per week × 8 h per day) and incorporating grid-level population data from Chen and colleagues,[24] we calculated the work hours lost for each grid and aggregated them to the provincial level. Provincial labour productivity loss was estimated as the ratio of lost work hours to total work hours. The future labour productivity loss reported in this study excludes the loss estimated under 2020 climate conditions and represents the heat-related loss caused by future climate change.

Estimating potential shifting work hours

Considering that shifting work hours has already become a practice for outdoor workers in many regions and that indoor workers typically have other adaptation strategies available to them, this study focuses on the potential of this adaptation for outdoor workers. Therefore, we assumed that only outdoor workers could adjust their work schedules. Recognising the importance of natural light for outdoor work activities, sunrise served as a practical threshold for outdoor workers to begin their tasks,[11] particularly in sectors with inadequate lighting conditions. In such contexts, we assumed that work hours could be maximally adjusted to start at the relevant sunrise time. Given that heat-related labour productivity loss almost exclusively occurs during the summer months in China, we conducted the analysis with the average summer sunrise times for each province. We estimated the heat-related labour productivity loss after shifting work hours under three different adaptation scenarios.

First, we calculated the average sunrise time observed in each region during the summer of 2023 and the maximum adjustment hours (ie, the duration between sunrise time and the starting work time) for each province by assuming that starting work times remain consistent across regions in 2023. We adopted the 8-h workday legally mandated in China, assuming a starting work time of 0800 h for all regions except Xinjiang, where the starting work time is 1000 h. The regional maximum shifted hours are reported in the appendix (p 4). Then, we recalculated WBGT values and labour productivity loss for outdoor workers by combining the exposure–response function and climatic projection data after shifting work hours. The ranges for productivity loss reported in this study are the result of the uncertainty of the climatic projection data. Details are given in the appendix (pp 2–4).

Estimating economic impacts

We used the CHEER model to conduct our economic analysis. CHEER is a Chinese provincial dynamic CGE model that has been widely applied in assessing the economic impacts of climate change-related issues in the country.[16,25–27] This model describes the flow of goods and services among different sectors and regions in China. CHEER was built following the 2017 multiregional input–output table of China, which covers 30 provinces in mainland China; Xizang, Hong Kong, Macao, and Taiwan are not included due to data availability. The model was then calibrated to the year 2020 with regional economic data.[28] We extended the model to the year 2100 with projections of population data from Chen and colleagues[24] and economic data from Zhang and colleagues[16] and a recursive dynamic method with 5-year time steps. A detailed description of the dataset can be found in the appendix (pp 6–7).

To describe the different effects of heat on various labour groups, the CHEER model distinguished between two types of labour within each sector: skilled labour (including technically skilled professionals, officers, and managerial professionals) and unskilled labour (including clerks, service and shop floor workers, and other low-skilled workers). Given the challenges of substituting between these labour types, the model conservatively sets the constant elasticity of substitution between them at 0·1. The detailed matching of skilled and unskilled workers with different work intensities in different economic sectors can be found in the appendix (p 6). Only outdoor unskilled labourers in the agricultural and construction sectors can reduce their heat exposure by shifting their work hours. To avoid overestimating the economic benefits of shifting work hours, we also considered the heat-related labour productivity loss of indoor workers in our modelling, despite their inability to shift their work hours. For indoor workers, we did not take into account any adaptation measures, including the use of air-conditioning. The heat-related labour productivity loss was translated into economic impacts in the model by increasing the demand of labour input per unit of output.

We selected a 2% social discounting rate[29] to discount future economic losses to 2020, allowing for the analysis of cumulative losses in monetary terms from 2020 to 2100. The residual losses in the results are measured by the labour productivity and economic losses in different scenarios, highlighting the remaining impacts of climate change even after the application of adaptation and mitigation measures. The potential of shifting work hours for reducing loss was measured by the proportion of the projected labour productivity and economic losses due to heat relative to the total projected losses.

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 results indicate that shifting work hours can substantially reduce heat-related labour productivity loss. Shifting work hours is projected to reduce the labour productivity loss of outdoor unskilled workers from 3·4% (uncertainty range 2·6–4·3) under the extreme SSP5–8·5 climate change scenario in 2050 to 2·4% (1·8–3·2) under the SSP5–8·5_shift scenario in 2050. Furthermore, labour productivity loss was expected to decline to 11·3% (uncertainty range 7·6–14·9) in 2100 under SSP5–8·5_shift scenario compared with 13.8% (9·7–17·5) under SSP5–8·5, representing a potential reduction in labour productivity loss of 17·5% due to shifting work hours (figure 1A). This reduction potential is expected to increase with greater climate change mitigation, mainly because of increasing heat stress in the cooler hours of the day under climate change. Under the SSP5–8·5 scenario, the national outdoor minimum WBGT value averaged over the cooler periods of each day in the summer of 2100 was 2·8°C higher than the outdoor WBGT under the SSP2–4·5 scenario, and 4·3°C higher than the outdoor WBGT under the SSP1–2·6 scenario (figure 1H–J). Under the SSP2–4·5_shift scenario in 2100, the reduction potential was projected to increase compared with the SSP5–8·5_shift scenario to 26·2% (uncertainty range 24·8–28·5), resulting in a residual labour productivity loss of 3·8% (2·8–4·6) for outdoor unskilled workers. If global warming was limited to less than 2°C, this reduction potential would reach 31·0% (uncertainty range 30·2–34·1) in 2100 (figure 1A). Regionally, the greatest potential for reducing labour productivity loss was found in the northern regions of the country, where diurnal temperature variations are large. In contrast, the reduction potential is limited in southern regions (figure 1E–G). In 2100, under the SSP2–4·5_shift scenario, northern regions could see a reduction potential of 67·4% in Qinghai and 51·8% in Heilongjiang, whereas southern regions could see a reduction potential of only 17·9% in Hainan and 19·2% in Guangdong. Regional reduction potential would further increase if warming was limited to less than 2°C (figure 1E–G): under the SSP1–2·6_shift scenario, the reduction potential would increase to 73·0% in Qinghai and 22·5% in Guangdong. Since substantial labour productivity losses were projected to be concentrated in southern regions (figure 1B–D), shifting work hours would not alter the regional distribution of these losses. Under the SSP1–2·6_shift scenario, the largest residual labour productivity loss of outdoor unskilled workers was projected to be concentrated in Hainan (3·3% [uncertainty range 2·0–3·3]), Guangxi (3·3% [2·3–4·8]), and Guangdong (3·5% [2·5–4·6]) by 2100.

Large economic benefits can be achieved by shifting work hours to reduce outdoor labour productivity losses. Over the simulation period (2020–100), shifting work hours was projected to cumulatively reduce GDP loss by approximately 2020 US$587·6 (uncertainty range 389·1–1891·9) billion, accounting for approximately 12·5% (14·3–27·1) of the total losses under the SSP2–4·5 scenario. The cumulative reduction would reach $511·3 (282·3–2017·0) billion under the SSP1–2·6_shift scenario and $1261·2 (943·0–3964·6) billion under the SSP5–8·5_shift scenario, representing about 13·4% of the total loss projected under the SSP1–2·6 scenario and 9·2% of the total loss projected under the SSP5–8·5 scenarios (figure 1A).

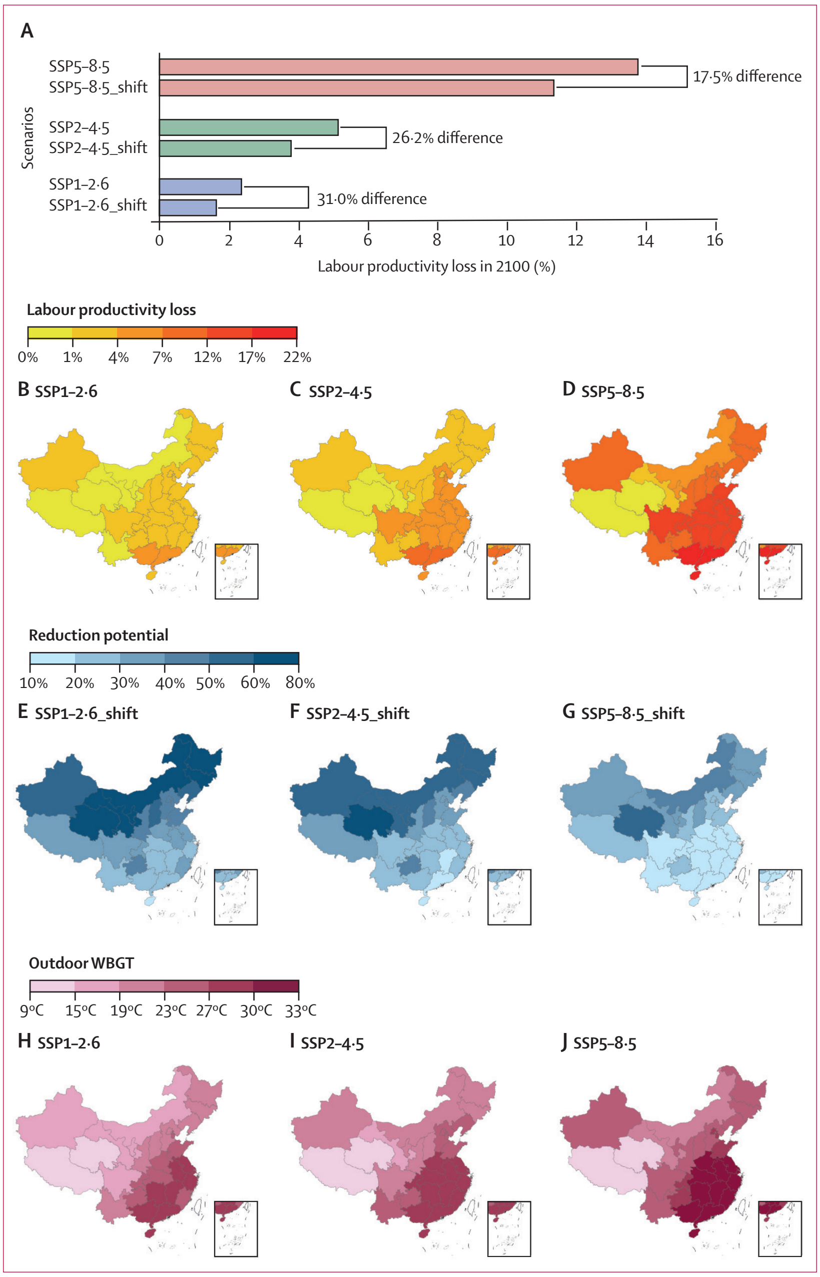

***Figure 1:* Labour productivity loss, loss reduction potential, and outdoor minimum WBGT under different scenarios in China**

(A) National heat-related labour productivity loss (%) of outdoor unskilled workers under different climate change scenarios with and without shifting work hours. (B–D) Provincial labour productivity loss (%) without shifting work hours under different climate change scenarios. (E–G) The potential (% of reduced labour productivity losses relative to total labour productivity loss) of shifting work hours for reducing labour productivity loss. (H–J) Outdoor wet-bulb globe temperature values (°C) averaged over the cooler periods of each day in the summer of 2100. SSP=shared socioeconomic pathway. SSP1–2·6=a lower warming scenario with global warming limited to less than 2°C. SSP2–4·5=a middle warming scenario representing the current policy with around 3°C of global warming by the end of 2100. SSP5–8·5=an extreme warming scenario with approximately 4·5°C of global warming by the end of 2100. _shift=with shifting work hours. WBGT=wet-bulb globe temperature.

The capacity of shifting work hours for reducing economic losses would also be enhanced with heightened climate change mitigation efforts. In 2100, this potential for reducing GDP loss was projected to be 7·1% under the SSP5–8·5_shift scenario, 12·6% under the SSP2–4·5_shift scenario, and 15·0% under the SSP1–2·6_shift scenario. In addition to rising temperatures reducing the loss reduction potential, the limited role of shifting work hours on reducing loss can also be attributed to the labour productivity loss of indoor workers who cannot adopt this adaptation measure, resulting in large economic loss through industrial chains. Without considering the labour productivity loss of indoor workers, the potential for reducing GDP loss in 2100 would increase to 28·2% under the SSP2–4·5_shift scenario, but the distribution of this potential and residual economic loss would not change (appendix pp 8–9).

Regionally, low-latitude regions with large agricultural populations and low incomes, such as Guizhou, Sichuan, Guangxi, and Hainan, and northeastern regions, such as Heilongjiang, Liaoning, and Jilin, were projected to show the greatest loss reduction potential. In 2100, the avoided economic loss was projected to reach 42·3% of GDP loss in Guizhou, 35·7% of GDP loss in Heilongjiang, and 19·2% of GDP loss in Sichuan under the SSP2–4·5_shift scenario. In contrast, high-income regions were projected to experience the smallest potential reductions in economic loss. For instance, by 2100, the economic loss avoided by shifting work hours was projected to account for 9·4% of GDP loss in Beijing, 7·3% of GDP loss in Shanghai, and 7·7% of GDP loss in Guangdong under the SSP2–4·5 scenario. Therefore, shifting work hours could further reduce regional development disparities. The coefficient of variation of regional GDP per capita,[30] which can be used to measure regional disparities, would decline from 1·03 under the SSP1–2·6 scenario to 0·86 under the SSP1–2·6_shift scenario, and from 1·01 under the SSP2–4·5 scenario to 1·00 under the SSP2–4·5 scenario in 2100.

However, although shifting work hours could reduce large economic losses, the residual economic loss was projected to remain substantial without the implementation of mitigation measures. Under the SSP5–8·5_shift scenario, the residual GDP loss was projected to reach 13·7% (uncertainty range 9·1–16·2) in 2100 (figure 1B). Only simultaneous implementation of adaptation measures and mitigation measures can achieve the maximum projected reduction in residual economic loss. In 2100, the residual GDP loss was projected to be reduced to 2·0% (0·9–2·6) if both this adaptation measure and mitigation efforts were implemented to limit temperature rise to less than 2°C (ie, under the SSP1–2·6_shift scenario), equivalent to 54% of the expenditure of China's basic medical insurance fund in 2020 (approximately US$303 billion). Even though shifting work hours could reduce development disparities among regions, this measure cannot change the distribution patterns of economic loss (figure 2C–H). The greatest economic losses were projected in low-latitude regions, including Guangxi, Chongqing, Jiangxi, Sichuan, Hainan, and Guangdong (figure 2F–H). In the absence of implemented climate change mitigation measures, substantial GDP losses were projected for these regions because of their low capacity for shifting work hours to reduce loss. Under the SSP5–8·5_shift scenario, the residual economic loss rate in 2100 was estimated to be 23·5% of GDP in Chongqing, 21·7% of GDP in Guangxi, and 19·2% of GDP in Sichuan (figure 2F–H). These substantial losses highlight the vulnerability of these regions to escalating temperatures and the insufficiency of work-hour adjustments alone as a potential adaptation strategy. Even with simultaneous implementation of both adaptation and mitigation measures, economic losses in these low-latitude regions cannot be overlooked. Under the SSP1–2·6_shift scenario, the residual economic loss in 2100 would decrease to 2·7% of GDP in Chongqing, 4·3% of GDP in Guangxi, and 2·4% of GDP in Sichuan (figure 2F). Therefore, additional adaptation strategies need to be implemented for both indoor and outdoor workers in low-latitude regions in China to mitigate the effects of heat exposure for both indoor and outdoor workers.

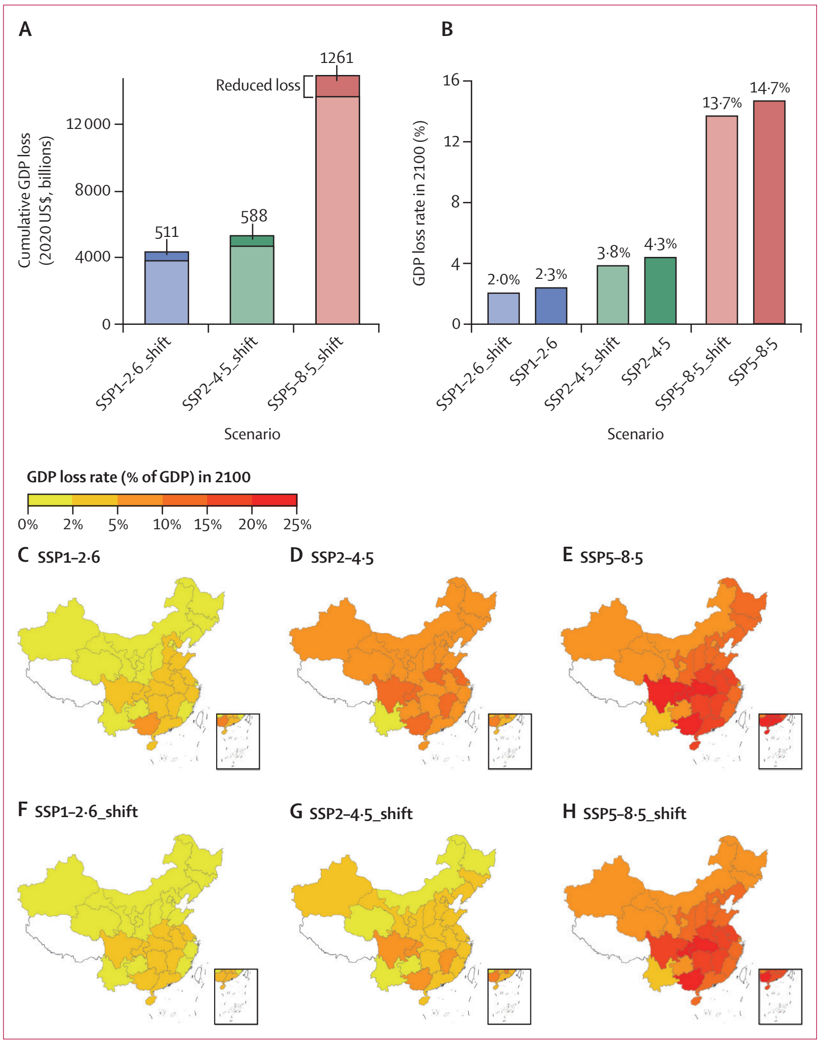

Figure 2: **National and provincial economic loss under different scenarios in China**
(A) Cumulative national GDP loss (2020 US$, billions). (B) National GDP loss rates (% of GDP) in 2100. (C–E) Provincial GDP loss rates in 2100 without shifting work hours. (F–H) Residual GDP loss rates (% of GDP) after shifting work hours. SSP=shared socioeconomic pathway. SSP1–2·6=a lower warming scenario with global warming limited to less than 2°C. SSP2–4·5=a middle warming scenario representing the current policy with around 3°C of global warming by the end of 2100. SSP5–8·5=an extreme warming scenario with approximately 4·5°C of global warming by the end of 2100. _shift=with shifting work hours.

Discussion

This modelling study estimated the potential of shifting work hours earlier in reducing heat-related labour productivity loss for outdoor work and economic loss at the national and provincial level in China and further showed the distribution of this reduction potential across regions. To investigate the relationship between this adaptation measure and mitigation measures, this study also estimated changes in this reduction potential with different temperature rises.

Consistent with existing global studies,[11,15] this study found notable synergies between shifting work hours and mitigation measures. In 2100, shifting work hours was projected to reduce 26·2% (uncertainty range 24·8–28·5) of outdoor heat-related labour productivity loss and 12·6% of GDP loss under a middle warming scenario (ie, the SSP2–4·5_shift scenario). This reduction potential was projected to increase with mitigation of global warming, as global warming might increase heat stress in the cooler hours of the day. The reduction potential of shifting work hours earlier in 2100 would increase to 31·0% (uncertainty range 30·2–34·1) for reducing labour productivity loss and 15·0% for reducing economic loss if global warming was limited to less than 2°C (ie, under the SSP1–2·6_shift scenario). Unlike adaptation measures, mitigation measures require a global collective effort to limit global temperature rise to under 2°C. Therefore, our findings emphasise the need for a global commitment to achieving this crucial temperature target. Furthermore, we recommended that local governments in China actively implement targeted policies on adaptation that promote flexible work hours for different regions, such as designing legal support and guidelines for this adaptation and offering subsidies for companies that protect outdoor workers from heat. The potential for reducing labour productivity loss in China is slightly smaller than the global estimation,[15] which is primarily due to our assumption that workers take a break during the two hottest hours of the day and variability in shifted work hours across different regions.

This study could inform policy makers who need to consider regional differences in adaptive capacity when designing adaptation strategies. We found a large disparity in reduction potential across regions in China. The largest potential for reducing economic loss by shifting work hours earlier was found in the northeast regions of the country (eg, Heilongjiang, Liaoning, and Jilin), and in low-income regions located at low latitudes (eg, Guizhou, Sichuan, Guangxi, and Hainan). This trend is probably due to the northeast regions having large diurnal temperature variations and early sunrise times. The low-income regions, which showed moderate potential for reducing labour productivity loss, have a large number of outdoor workers in agricultural and construction sectors, enhancing their potential for reducing economic loss. In 2100, the potential for reducing economic loss was estimated to be 42·3% of GDP loss in Guizhou and 19·2% of GDP loss in Sichuan under the SSP2–4·5_shift scenario. However, these low-income regions would still experience substantial residual economic loss even with shifting work hours. In 2100, under the SSP2–4·5_shift scenario, the residual economic loss would reach 4·3% of GDP in Guangxi and 2·4% of GDP in Sichuan. For these regions, we recommend combining work hour adjustments with other adaptive measures, such as increasing outdoor shading and enhancing public protection awareness of heat, to more effectively mitigate economic losses.

The study indicates that shifting work hours earlier could further reduce development disparities among regions in China in the context of climate change. The smallest potential for reducing economic loss was concentrated in high-income regions (including Beijing, Shanghai, and Guangdong) probably due to the lower number of outdoor workers in agricultural and construction sectors in these regions. In 2100, the potential for reducing economic loss was projected to be 9·4% of GDP loss in Beijing and 7·7% of GDP loss in Guangdong under the SSP2–4·5 scenario. For high-income regions, especially those located at low latitudes such as Guangdong, local governments should intensify abatement efforts to reduce emissions and develop an integrated adaptation strategy to protect indoor and outdoor workers from heat.

Several limitations in this study should be noted. First, due to data availability and computational capacity constraints, this study used daily data and the WBGT 4+4+4 method to estimate hourly wet bulb globe temperature, which might have introduced uncertainties in the results, but is unlikely to have altered the key findings. This limitation could potentially be addressed in future research through the use of climate projection data with higher spatiotemporal resolution. Second, this study used only sunrise as the threshold for the maximum shifting of work hours, which neglects the potential use of artificial light. However, employing artificial light for outdoor farming is challenging due to practical and economic constraints. Additionally, shifting work hours can be influenced by numerous factors, such as family and social support, personal sleep patterns, and individual work–life balance.[31] Therefore, this study provides a theoretical maximum potential estimation for shifting work hours earlier, rather than a practical one. Third, this study does not consider the negative health impact of shifting work hours. Existing research has shown that shift work can lead to disturbances in circadian systems,[32,33] and health issues including sleep disorders, cardiovascular problems, and psychological conditions.[34] These health problems might, in turn, negatively affect labour productivity, leading to a decrease in overall work efficiency and increased absenteeism. This omission highlights the need for a more holistic approach in future studies that takes workers' health into account. Fourth, due to limitations in epidemiological studies, this study adopted the same exposure–response function between wet bulb globe temperature and labour productivity loss for all regions. However, many factors could influence the effect of heat on labour productivity, such as age, environmental conditions, acclimatization, and socioeconomic factors.[35] Future studies should conduct region-specific epidemiological studies and adopt more finely grained functions to account for these variations and reduce uncertainty. This work would improve the reliability of productivity loss estimates.

In conclusion, despite the limitations mentioned, this study offers a credible and reasonable estimate of the potential of shifting work hours earlier for reducing heat-related labour productivity loss and economic loss across China. Our study contributes to the discussion on the synergistic relationships or trade-offs between adaptation and mitigation measures. In addition, our study provides useful information for policy makers to develop more effective strategies to protect workers in the face of rising temperatures.

For **climatic data from the NASA Center for Climate Simulation** see https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp-cmip6

For the **Global Trade, Assistance, and Production Data Base** see https://www.gtap.agecon.purdue.edu/databases/v10/index

For the **National Bureau of Statistics of China** see https://www.stats.gov.cn/sj/ndsj/2018/indexch.htm

Contributors

MZ, CZ, and WC conceptualised this study. MZ developed the modelling framework; WC and CZ designed the scenarios and conducted the analyses. YC optimised the code to enhance its execution speed. CZ, WC, YC, JS, BL, YM, and RL reviewed and edited the initial manuscript. ML assisted with downloading the climatic data. MZ, YC, and SZ contributed to the manuscript's revision. MZ and YC directly accessed and verified the underlying data in the manuscript. All authors had full access to all the data in the study and accept responsibility for the decision to submit for publication.

Declaration of interests

We declare no competing interests.

Data sharing

Climatic data are publicly available from the US National Aeronautics and Space Administration (NASA) Center for Climate Simulation. The Global Trade, Assistance, and Production Data Base (version 10) can be obtained for a fee from its official website. Population data are publicly available from Chen and colleagues (2020; https://doi.org/10.1038/s41597-020-0421-y). Employment rates for different industries are publicly available from the National Bureau of Statistics of China. All other data will be provided on request to the corresponding authors.

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