



Research article

The uneven impacts of climate change on China's labor productivity and economy

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ARTICLE INFO

Handling Editor: Lixiao Zhang

Keywords:

Climate change

Heat

Labor productivity

Economic loss

ABSTRACT

Climate change is considered to increase economic costs by worsening heat-related labor productivity loss. While extensive global and national research has been conducted on this topic, few studies have analyzed subnational and individual economic impacts, potentially weakening local governments' motivation to tackle climate change. Figuring out the most affected regions and labors could help climate policymakers to identify priority regions and sectors to allocate adaptation resources efficiently, and enhance stakeholder engagement. This study adopted a provincial Computable General Equilibrium model by distinguishing different labors and regions in modelling work to address the aforementioned gap. The study estimated economic costs at different level under three climate change scenarios (lower (SSP126), middle (SSP245), and higher (SSP585) warming scenario). Low-income regions located in southwest part of China (such as Guangxi and Guizhou), would experience the largest economic loss, 3.4–7.1 times higher than high-income in China by 2100 under SSP245 scenario. Additionally, wages for labors highly sensitive to heat in these regions are expected to rise, for example, by an 8.3% rise in Guangxi, driven by the rising demand for these labors. Conversely, others would experience a significant wage decrease, especially those with less sensitivity (e.g., managers). Therefore, we recommended that national financial supports be allocated more to these most affected regions and that government encourage managers provide assistance to workers vulnerable to heat.

1. Introduction

1.1. Background

Climate change poses a growing threat to human health and well-being through a myriad of ways, from increasing the frequency and intensity of extreme weather events to exacerbating the spread of vector-borne diseases (Ebi, 2022; IPCC, 2014). As the most widespread and common health risk of climate change, heat exposure has led to a significant negative impact on labor productivity loss, resulting in the largest economic cost related to climate change (DARA, 2012; Hsiang et al., 2014). In 2021, 470 billion potential work hours were lost globally due to heat, leading to 0.72% of GDP loss (Romanello et al., 2022). A global temperature change of 2.7 °C will double the annual heat impact

on labor in many tropical areas, compared with a temperature change of 1.5 °C (Kjellstrom et al., 2018). Moreover, labor productivity is a crucial economic development indicator. The adverse effect of heat on labor productivity cannot be overlooked, especially as temperatures continue to rise in the future (ILO, 2019). This is true regardless of whether the objective is designing policies to address climate change or planning economic activities.

1.2. Literature review

The economic costs resulting from heat-related labor productivity loss exhibit significant variation across different regions, economic sectors, and labor types. Such disparity in the distribution of the economic costs has raised environmental justice concerns (He et al., 2022).

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This issue requires special attention in designing climate mitigation and adaptation strategies to maintain environmental justice. The majority of studies that estimated heat-related labor productivity loss and its economic impacts adopted a large-scale perspective, focusing on the global (Matsumoto, 2019; Orlov et al., 2020; Takakura et al., 2018), country scale (Chavaillaz et al., 2019; Elshennawy et al., 2016; Orlov et al., 2019; Schleyen et al., 2022), or large regional levels (Liu et al., 2021). These studies have indicated that the disparate economic costs could widen the development gap between countries. The largest economic costs are found in low- and lower-middle-income countries, especially in Sub-Saharan Africa, South and Southeast Asia (Chavaillaz et al., 2019; Parsons et al., 2022), because the developing regions have more labor-intensive sectors and poor adaptive capacity. However, existing studies fall short in exploring the economic impacts among provinces, sectors, and labors. Understanding the magnitude and distribution pattern of provincial economic costs can inform local governments decisions on climate mitigation and adaptation. This significance is particularly pronounced for China, given the substantial regional heterogeneity in terms of geographic location, climate conditions, industrial structure, economic development level, and so on. Only one estimated heat-related labor productivity loss and its economic impacts for seven regions in China (Liu et al., 2021). However, the province serves as the primary unit for policy design, rather than the region in China. If economic impact assessment of the large country is only done as a whole, a significant amount of information may be obscured and the results could lead to incorrect policy implications. Although one study was conducted at the city-level (He et al., 2022), it overlooked the indirect impact from industrial chain, which may account for a large part of the total economic loss. Therefore, this study aims to investigate the scale and distribution patterns of heat-related labor productivity loss and its comprehensive economic costs in China.

The heterogeneous impacts of heat on labor within sectors is another important issue that is often overlooked in previous studies, which assumed labor within sectors has the same vulnerability to heat (He et al., 2022; Knittel et al., 2020; Matsumoto et al., 2021; Xia et al., 2018). Managers in certain sectors typically face lower heat-related risks compared to other labors (Szewczyk et al., 2021). The assumption of homogenous labor within sectors may decrease the credibility of research findings. The existing studies are unable to identify the different mechanisms behind economic impacts on various types of labor and sector due to this assumption. To address this limitation, this study distinguishes two types of labor within a sector to capture the impacts on their wages for analyzing individual economic mechanism. This valuable information can be used to design targeted interventions at both individual and firm-levels. Besides, this study estimates the magnification effect on economic costs from supply chain (the indirect impacts) and analyses the features of sectoral economic impacts. During a single period, a decline in labor productivity within one sector can directly reduce its outputs. This, in turn, can cause a ripple effect of output losses across other sectors, as well as a reduction in future investments (Nam et al., 2010).

1.3. Overview of this study

In this study, by linking a health module and an economic assessment module, we estimated the labor productivity loss and its economic costs at the provincial level in China under three different climate change scenarios along with the corresponding Shared Socio-economic Pathways (SSP126 scenario, a lower warming scenario with global temperature rise limited 2 °C; SSP245 scenario, a middle warming scenario representing current policy with around 3 °C warming by the end of this century; SSP585 scenario, a higher warming scenario with around 5 °C). We chose the widely used exposure-response function (ERF) (ILO, 2019; Zhao et al., 2022a) in the health module to assess labor productivity loss for three intensity work from 2020 to 2100: high intensity work, middle intensity work, and low intensity work. It should be noticed that labor

productivity loss in this study is measured by potential work hours lost attributed to heat as a percentage of total work hours. Subsequently, we used the China Hybrid Energy and Economic Research (CHEER) model (Mu et al., 2018; Weng et al., 2021; Zhang et al., 2019, 2021; Zhao et al., 2022b) in the economic assessment module to estimate the economic costs at both provincial and sectoral level. In contrast to previous studies, which assumed that all labors in one sector belong to the same type of intensity work, this study adopted an approach where single type of labor within a sector is divided into two groups (high heat-sensitive group and low heat-sensitive group) according their occupations and individual heat sensitivity, which allows to capture varying economic impacts on different types of labor.

The information about the most affected regions and labors identified in this study could help climate policy-makers to identify priority regions and labors to allocate adaptation resources efficiently. Based on the results of analysis on effect factors and mechanism, policymakers can design precise and effective adaptations tailored to each region, sector, and labor.

2. Materials and methods

2.1. Scenario setting

For estimating heat-related labor productivity loss and economic costs in the future, this study considered six scenarios: three climate change scenarios and three baseline scenarios. Three climate change scenarios corresponded to three economic development trajectories (Shared Socio-economic Pathways), which is consistent with the scenario design in CMIP6: SSP126 scenario (a lower warming scenario representing an aggressive carbon abatement with achieving of 2 °C target of the Paris Agreement and a lower economic growth), SSP245 scenario (a middle warming scenario representing current policy with around 3 °C warming by the end of this century and a middle economic growth), SSP585 scenario (a highest warming scenario with around 5 °C and a fastest economic growth). Another three baseline scenarios without climate change are consist with the Shared Socio-economic Pathways: SSP1 (a lower economic growth pathway), SSP2 (a middle economic growth pathway), SSP5 (a fastest economic growth pathway). The economic costs under different climate change scenarios can be estimated by comparing the economic indicators under SSP126, SSP245, and SSP585 with that under SSP1, SSP2, and SSP5, respectively.

2.2. Estimation of heat-related labor productivity loss

As many environmental factors, such as humidity, solar radiation, and wind speed, can affect the health impacts of heat on labors, only using temperature data cannot reflect real heat stress on labors (Kjellstrom et al., 2009a). Therefore, this study adopted the Wet Bulb Globe Temperature (WBGT) to measure heat stress. The WBGT is a composite temperature measure combining temperature, humidity, solar radiation, and wind speed, which has been applied in technical manual to keep occupational health in many countries (NIOSH, 2016; Yano et al., 2017). First, we used the projection of climate variables, including temperature and humidity to estimate the WBGT. Here, we distinguished between indoor and outdoor environment. Considering the availability of climate projection data and to simplify the calculation, the calculation of indoor WBGT follows the Kjellstrom et al. (2009b) and ILO (2019) works with assuming no solar radiation, and the calculation of outdoor WBGT follows Liu et al. (2021), which has been widely used to estimate heat-related labor productivity loss (Chavaillaz et al., 2019; Knittel et al., 2020; Zhang and Shindell, 2021; Zhu et al., 2021).

With use of the projection of daily climate data, daily WBGTs can be estimated for each grid. To better characterize changes of heat impacts on labor productivity within a day, we used the '4 + 4+4' method (Kjellstrom et al., 2018) to calculate hourly WBGTs, by assuming WBGT in 2 h a day is closed to daily maximum value of WBGT (WBGTmax)

calculated by daily maximum temperature, WBGT in 2 h is closed to daily mean value of WBGT (WBGTmean) calculated by daily mean temperature, and WBGT in remaining 4 h is closed to the average of WBGTmean and WBGTmax. The '4 + 4 + 4' method has been proven to work effectively (Kjellstrom et al., 2018).

Then, this study estimated labor productivity loss for three intensity work (low-intensity, middle-intensity, and high-intensity) at grid level by combining the estimated WBGT, the grid population data (Chen et al., 2020) and a widely used exposure-response function (Kjellstrom et al., 2018), which describes quantified relationship between WBGT and potential labor productivity loss. The form of the exposure-response function for three intensity works is shown in eq. (1).

$$\text{Productivity losses}_{y=0.5} = 0.5 \left[1 + \operatorname{erf} \left(\frac{\text{WBGT} - \mu}{\sigma\sqrt{2}} \right) \right] \quad (1)$$

Where μ and σ are 35.33 and 3.94 for low-intensity work, 33.49 and 3.94 for moderate-intensity work, 32.47 and 4.16 for high-intensity work.

Assuming theoretical maximum hours for a working person are 2080 h per year (52 weeks times 5 days per week times 8 h per day), we estimated potential working hours lost for each grid cell and each region. The labor productivity loss for each region is calculated by dividing potential working hours lost by regional theoretical maximum working hours. The labor productivity loss showed in this paper is the average results from seven climate models in CMIP6, including IPSL-CM6A-LR, NorESM2-MM, MIROC6, GFDL-ESM4, FGOALS-g3, ACCESS-CM2, and EC-Earth3-Veg-LR.

2.3. Estimation of economic costs

The China Hybrid Energy and Economic Research (CHEER) model is applied to evaluate the economic costs of heat-related labor productivity loss. The flow of factors, goods, and services in the model can be found in supplementary material.

To describe heterogeneous impacts of heat on labor within sectors, we distinguished two types of labor: low-sensitive group (including officials, managers, technicians, and professionals) and high-sensitive group (including clerks, service workers, farmers, and other unskilled labor). We assumed that tasks assigned to the low-sensitive group is the low-intensity work. The classification of work intensity for the high-sensitive group is based on the principle of economic sectors (Kjellstrom et al., 2018; Orlov et al., 2020). The production block in CHEER model is modelled by nested constant elasticity of substitution (CES) production functions which can describe the different substitution possibilities across various intermediate inputs and factor inputs. To distinguish different labor types, the labor in low-sensitive group inputs are combined with labor in high-sensitive group to generate the labor bundle in production block, and the elasticity of substitution between two labor types is assume to be zero. Detailed description of economic sectors and work intensity in the CHEER model can be found in Table S1.

Heat-related labor productivity loss is described as increased demand of heat-loss-affected labor for a unit of output, as shown in Eq. 2.

$$Q(s, r, t) = \frac{Q_0(s, r, t)}{1 - \text{loss}(s, r, t)} \quad (2)$$

where s, r, t represent sectors, regions, and year, respectively, $Q_0(s, r, t)$ is the original unit labour demand without labour productivity loss, $\text{loss}(s, r, t)$ is the labor productivity loss rate, and $Q(s, r, t)$ is the unit labour demand with heat-related labour productivity loss.

We estimated total economic loss (including direct and indirect impacts) by comparing the economic indicator under climate change scenarios with that under the corresponding baseline scenarios. The direct impact was calculated by multiplying labor productivity loss rate by income, and the indirect impact was the difference between total economic loss and direct loss.

2.4. Sensitivity analyses

We conduct several sensitivity analyses in this study, including inputs of climate data, the economic development path, the elasticity of substitution between capital and labor, the elasticity of substitution between labors, and the mobility of labor among sectors. In addition to assess the robustness of the results, the sensitivity analysis allows for figuring out the key factors and mechanisms affecting economic costs.

By estimating labor productivity loss with projections of climate variables from single model mentioned above, we estimated lower and higher bound of labor productivity loss and economic loss (see Fig. 1). We conducted six additional scenarios by recombining the climate change scenario with the economic development path to estimate the uncertainty from economic growth (see Figure S4): S1R85 (climate change scenario SSP585 with economic path SSP1), S1R45 (climate change scenario SSP245 with economic path SSP1), S2R85 (climate change scenario SSP585 with economic path SSP2), S2R26 (climate change scenario SSP126 with economic path SSP2), S5R26 (climate change scenario SSP126 with economic path SSP5), and S5R45 (climate change scenario SSP245 with economic path SSP5).

We conducted three additional scenarios to estimate uncertainty from parameter in the CHEER model, including increasing elasticity of substitution between capital and labor (SSP245_KE scenario), increasing elasticity of substitution between labors (SSP245_KE scenario), and limiting labor mobility among sectors (see Table S4 and Figure S5).

3. Results

The climate data from seven climate models were used to estimated regional heat-related labor productivity loss. Our emphasis in this paper will be placed on the average loss based on these models, while the range of uncertainty can be found in the supplementary materials. Furthermore, to enhance readability, the analysis primarily focuses on evaluating the SSP245 scenario as it is representative of current policy.

3.1. National analysis

3.1.1. National labor productivity loss and economic loss

Our modelling results suggest that without any climate change mitigation (under SSP585 scenario), labor productivity loss and economic costs in China will experience significant increases by the end of this century (Fig. 1). Notably, the discrepancies in labor productivity loss and economic cost under different scenarios become apparent after 2040, mirroring the rising trend in temperature. After 2040, national labor productivity loss and economic costs present a slow growth trend under SSP245 scenario, while under SSP126 scenario, the trend appears relatively flat. In contrast, under SSP585 scenario, the trend is rapid and shows significant increases in both labor productivity loss and economic costs. In 2100, the labor productivity loss is estimated to reach 1.6% (1.3%–1.7%), equivalent to work hours of 9.2 (7.5–9.8) million workers in a year under SSP245 scenario. This loss would decrease by 50% under SSP126 scenario, but increase by 3.1 times under SSP585 scenario. The remarkable contrast in losses among different warming scenarios highlights the importance of ambitious carbon emission reduction.

There are also huge differences among different intensity works. High-intensity work would experience the largest impact, with a 5.9% (5.1%–9.1%) decrease in labor productivity under SSP245 scenario in 2100, 3.6 times higher than middle-intensity work and 13.0 times higher than low-intensity work. Even if global temperature rise is controlled within 2 °C, high-intensity work would still face large labor productivity loss, about 3.0% in 2100 under SSP126 scenario.

As one of main factors of production, the labor productivity loss would result in significant economic costs. If no measures are taken to reduce carbon emissions, national GDP will experience the largest loss. By the end of this century, the national GDP loss rate is estimated to be about 7.2% (5.8%–10.0%) under SSP585 scenario. If we intensify

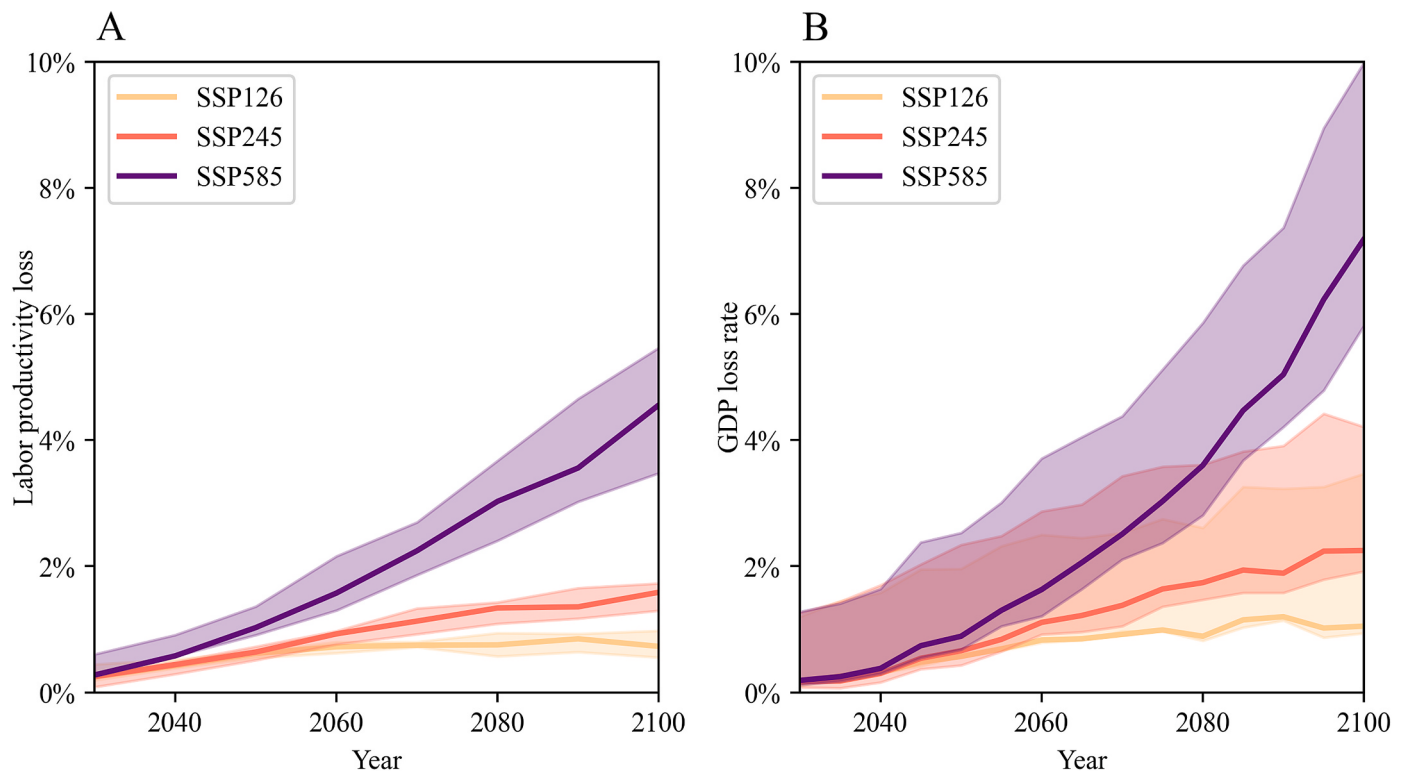


Fig. 1. Temporal trends of national labor productivity loss (A) and GDP loss under different scenarios (B). (Shade area represents the uncertainty range based on different climate models; the solid line represents the average results). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

emission reduction action to limit global warming from 3 °C to 2 °C, the national cumulative economic benefits from 2020 to 2100 would reach \$2386 (1471–3560) billion in China (equivalent to 5 times of national R&D investment in 2022) by using a social discount rate of 2% (Drupp

et al., 2018). The loss would decrease to 1.1% (0.9%–3.5%) if 2 °C temperature target can be achieved. Therefore, carbon abatement can gain large economic benefits by avoiding heat-related labor productivity loss. By adopting a marginal carbon emission reduction cost in China

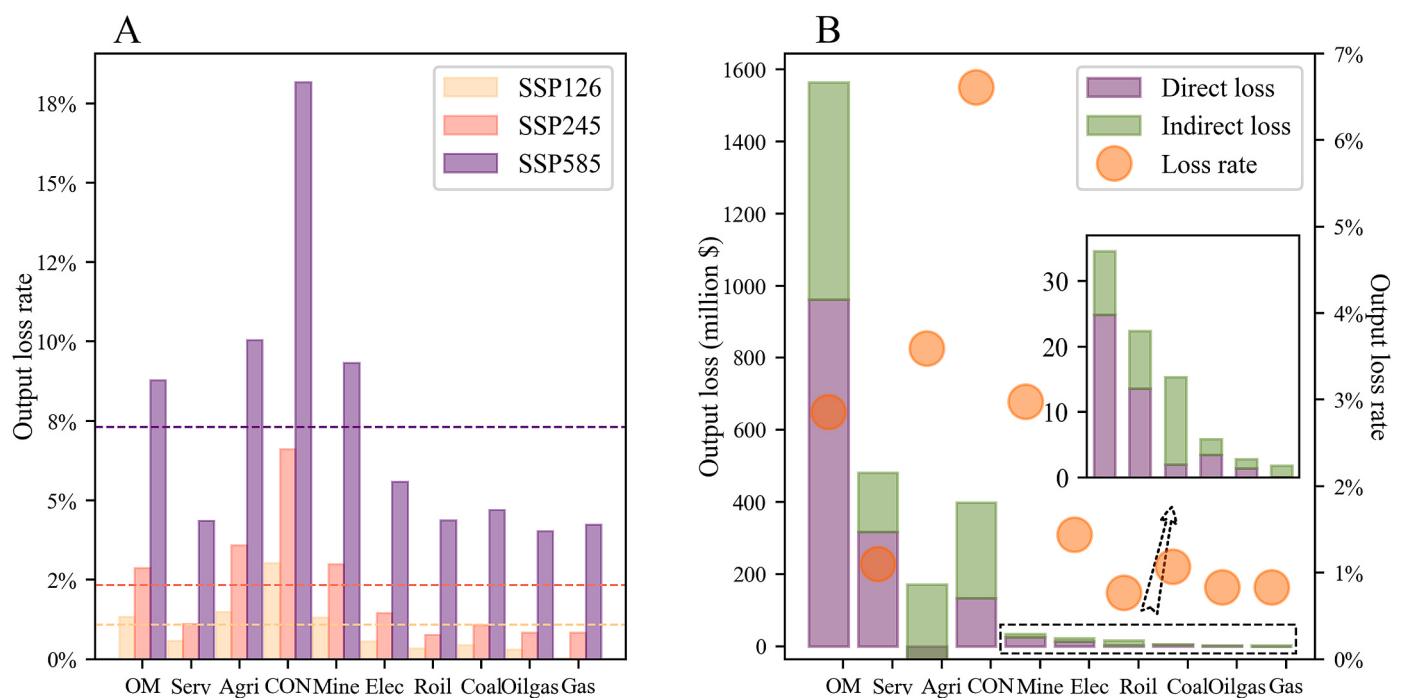


Fig. 2. Sectoral output loss and its components by 2100: A. Sectoral output loss rate under three scenarios; B. Sectoral direct and indirect loss under SSP245 scenario. Note: Agri = agriculture; CON = construction; Elec = electricity; OM = manufacturing; Roil = processing of petroleum, coking, processing of nuclear fuel; Serv = service.

(Institute of Climate Change and Sustainable Development of Tsinghua University, 2021) to convert these benefits into an amount of carbon emission reduction, they could support to reduce approximately 0.1%–0.3% of national carbon emission in 2020.

3.1.2. Distribution of economic losses across sectors

Economic costs are unevenly distributed across sectors (Fig. 2A). Due to higher heat exposure and sensitivity, labor-intensive sectors experience larger costs in comparison to the capital-intensive sectors. The labor-intensive sectors (including construction, agriculture, mining, and other manufacturing) are expected to undergo an output loss rate of 3.3% (2.9%–5.7%) under SSP245 scenario by the end of this century, 2 times higher than loss in the capital-intensive sectors. Without any climate change mitigation, the output loss rate in labor-intensive sectors would reach 9.6% (8.1%–12.9%) and that in the capital-intensive sectors would be 4.4% (3.1%–6.8%). Construction is expected to be the most affected, with a projected 6.6% (6.2%–10.5%) loss rate under SSP245 scenario by 2100, followed by the agriculture sector. However, the loss rate of service sector is 1.1% (0.8%–2.5%) under SSP245 scenario by 2100. If the 2 °C temperature target is achieved, the loss in construction would decrease to 3.0% (2.9%–8.2%) by the end of this century.

The analysis revealed costs amplification resulting from supply chains and intertemporal resource allocation. This highlights the importance of considering indirect loss when assessing economic impacts. We further decomposed the economic loss into the direct loss (direct sectoral output loss due to labor productivity loss) and the indirect loss (efficiency loss from distorted resource allocation due to

supply chains). In a near term (2020–2040), the largest fraction of the costs is the direct loss. National direct loss accounts for a significant majority (approximately 51.6%–61.1%) of the total GDP loss, but presents a declining trend over time. In contrast, the indirect loss is projected to become a major cost in the long term (2041–2100), with the share of national indirect loss would increase from 38.9% to 67.8%. The changes in share of indirect loss over time indicate that initial economic losses can result in long-term economic costs in a cumulative manner. The share of direct and indirect loss varies significantly across different sectors (Fig. 2B). The indirect impacts caused by supply chains and intertemporal resource allocation incurs an additional 0.73% output loss in service sector, accounting for 66.0% of its total loss by 2100 under SSP245 scenario. Conversely, in agriculture sector, the indirect impacts result in a 0.76% increase in output, which means agriculture sector can avoid 21% of its output loss with these indirect impacts by 2100 under SSP245 scenario. This is largely attributed to the low-price elasticity of demand of agricultural commodities.

3.2. Provincial analysis

3.2.1. The characteristics of loss distribution among provinces

The impact of climate change on labor productivity will be distributed unevenly across regions. According to Fig. 3, regions located in low latitudes are more affected by heat than high-latitude regions. By 2100, the potential labor productivity loss in low-latitude regions, including Hainan, Guangxi, Fujian, Guizhou, Guangdong, and Jiangxi, is about 2.2–3.2 times higher than the national loss under SSP245 scenario. This discrepancy can be attributed to the fact that in low-latitude regions,

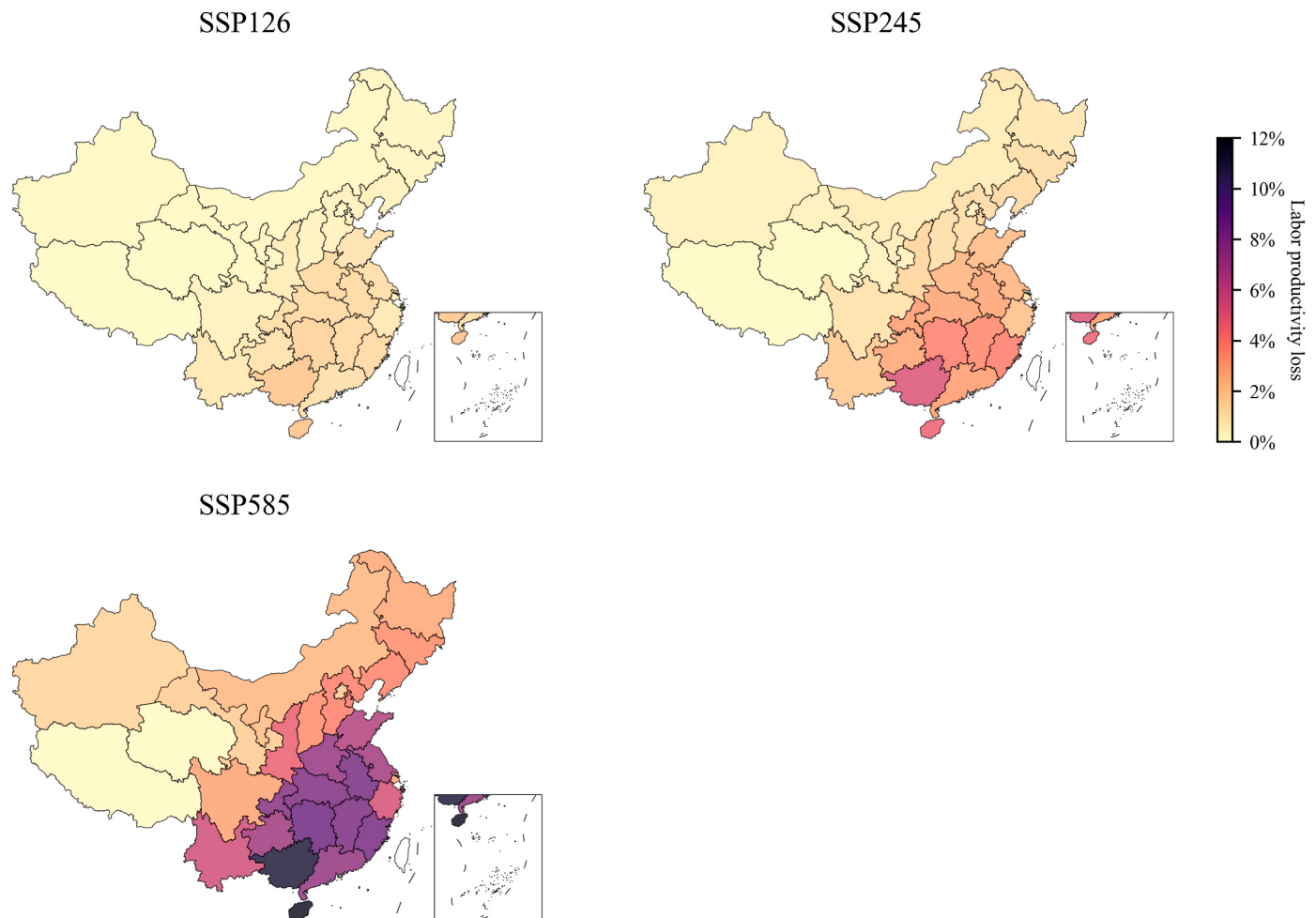


Fig. 3. Provincial heat-related labor productivity loss due to climate change by 2100 under different scenarios.

even a minor increase in temperature can result in a significant decrease in labor productivity due to the nonlinear relationship between temperature and labor productivity, as compared to high-latitude regions where the effect of the same degree of temperature rising on labor productivity is comparatively less severe. Of all low-latitude regions, Hainan and Guangxi are projected to be the most affected under all scenarios. By 2100, labor productivity loss in Hainan and Guangxi is estimated to reach 11.5% (8.1%–20.2%) and 11.0% (8.0%–14.5%) under SSP585 scenario, respectively, while the labor productivity loss in Qinghai, Gansu, Xizang is expected to be about 0.02%–1.5%. Even if the 2 °C temperature target is achieved, the labor productivity loss in low-latitude regions cannot be overlooked, with a loss of 1.8% (0.1%–6.5%) in Hainan and 1.8% (0.02%–6.3%) in Guangxi.

Not only is there an uneven distribution of labor productivity loss, but different economic structures also further exacerbate regional economic losses disparities. In relative terms (the loss rate), the highest provincial economic loss is concentrated in low-income regions located at low latitudes, and the lowest are concentrated in high-income regions and high-latitude regions. The economic costs in the low-income regions, including Guangxi, Hainan, Guizhou and so on, are 4.4–8.1 times of that in high-income regions and high-latitude regions (Fig. 4A) by 2100 under SSP245 scenario. By 2100, economic loss is estimated to reach 7.3% (7.4%–12.8%) in Guangxi, 4.5% (4.2%–9.1%) in Hainan, and 4.4% (3.5%–10.6%) in Guizhou under SSP 245 scenario. In these regions, the direct economic loss accounts for more than 60% of the total provincial loss. Even if taking aggressive mitigation to achieve 2 °C temperature target, these regions would still undergo large economic loss because of large share of labor-intensive sectors and high temperature. Under SSP126 scenario, the economic loss in Guangxi and Hainan would reach about 3.4% (2.0%–11.4%), 2.0% (1.4%–7.3%), respectively. Thanks to the high share of capital-intensive sectors, the economic loss in high-income regions, including Beijing and Shanghai, is estimated to be about 0.9%–1.1% by 2100 under SSP245 scenario. The majority of loss in these regions are caused by indirect impacts from industrial chains, with approximately 83.5% being indirect loss in Beijing, and 94.2% in Shanghai by 2100 under SSP245 scenario. Moreover, the proportion of indirect losses in Fujian, Guangdong, Ningxia,

Qinghai, Shanxi is expected to exceed 90%. The high-latitude regions are also expected to have small economic costs attributed to the small labor productivity loss, with an economic cost of 1.0%–1.2% by 2100 under SSP245 scenario. However, the annual growth rate of economic loss in these regions is much higher, because of faster temperature rise. Under SSP245 scenario, the annual growth rate would be 6.4% in Xinjiang, and 5.8% in Gansu. It would exceed 6.6% under SSP585 scenario. Furthermore, during our sensitivity analysis, we discovered that altering model parameters such as the projected trajectory of future economic development, the elasticity of substitution between labor and capital, the elasticity of substitution among labor types, and labor mobility did not alter the previously discussed distribution pattern of economic losses. Additionally, for these regions with the largest economic losses, increasing the elasticity of substitution between labor and capital yielded the most significant reduction in economic losses when compared to other model parameter changes. Under SSP245_KE scenario, economic losses in these regions could potentially decrease by approximately 30.2%–57.9% compared to the SSP245 scenario.

When estimating economic loss in monetary terms, the loss in absolute terms is particularly large in populous and wealthy coastal regions (Fig. 4B). These regions include Jiangsu, Guangdong, Shandong, and Zhejiang, showing a cumulative economic loss of \$882.1 (707.1–1825.2) billion, equivalent to two times of China's R&D investment in 2022, from 2020 to 2100 under SSP245 scenario. Henan, which is among the most populous, is also suffer large economic loss, about \$181 (150.5–398.9) billion cumulative loss. The economic loss in Jiangsu, Guangdong, Shandong, Zhejiang, and Henan accounts for about 27% of the national loss. Despite of the largest economic loss in absolute terms, aggressive carbon emission would avoid the largest economic loss in these regions. Despite these regions experiencing the largest economic loss in absolute terms, aggressive reduction of carbon emissions would avoid the largest economic loss for them. If the 2 °C temperature target is achieved, the benefits by avoiding economic loss compared with SSP245 scenario in these regions accounts for about 45% of national benefits, with largest benefits in Guangdong, about \$86 billion. The cumulative economic loss in high-latitude regions is relatively small, accounting for accounting for only 1.7 percent of

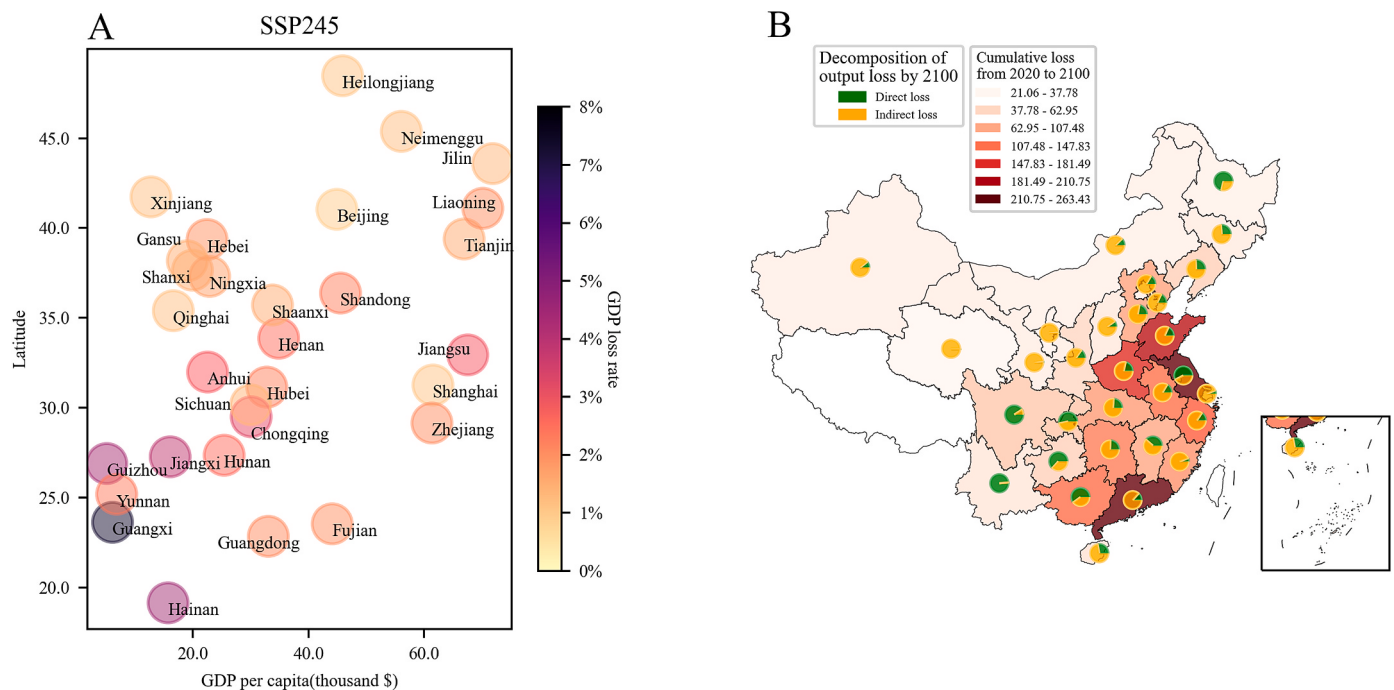


Fig. 4. Provincial GDP loss and its components under SSP245 scenario: A. The provincial GDP loss rate by 2100; B. The provincial cumulative GDP loss from 2020 to 2100 and loss's component by 2100.

national loss.

3.2.2. Economic losses across sectors and labors

There are notable variations in the economic costs across various sectors as well. By 2100, the projected provincial sectoral losses range from 0.8% to 5.3% under SSP245 scenario, and from 0.5% to 1.9% under SSP126 scenario. The construction sector is the most affected in all regions, especially severe in low-latitude regions. By 2100, the output loss of construction sector is expected to be 13.7% in Guangxi, and 10.1% in Hainan. Additionally, the findings indicate that high-latitude regions, which is less affected by heat, would gain comparative advantages in labor-intensive sectors among regional trade, which benefits regional exports and thus cover the loss. By 2100, exports of

manufacturing products from Qinghai to Guangxi would increase by about 2.9%, and exports from Ningxia to Guangxi would increase by 1.9% under SSP245 scenario. The agricultural output in Gansu is expected to increase 0.1% (Fig. 5A) attributed to a 1.9% increase in exports by 2100 under SSP245 scenario. However, no sector in any region would benefit from impact of climate change on labor productivity if we take no mitigation measures. Under SSP585 scenario, the agricultural sector in Gansu is expected to lose up to 1.6% by the end of this century. If achieving 2 °C temperature goal, the range of regions and sectors that are expected to experience an increase in sectoral output would be expanded. For example, there is expected to be a 0.02% increase in agriculture sector in Xinjiang.

The impact of climate change on wage exists significant variations

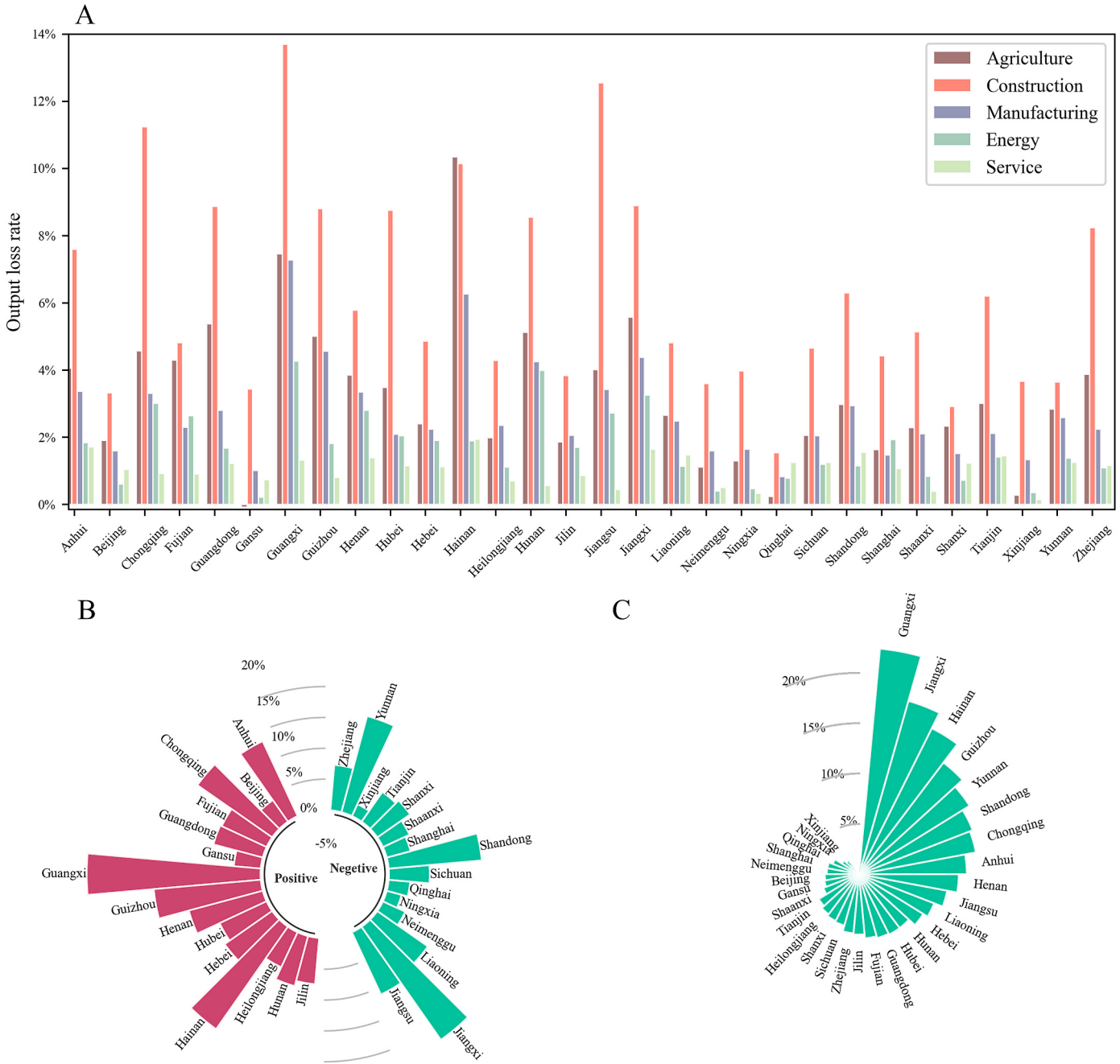


Fig. 5. Changes in sectoral output and wages by 2100 under SSP245 scenario: A. sectoral output loss rate; B. wage change for high-sensitive group; C. wage loss rate for low-sensitive group.
Note: Positive in figure B means the increase of wage, and negative means the decrease.

across different types of labors and regions. The worker's wage of low-sensitive group is expected to decrease across all regions, with largest loss found in low-latitude regions, with 22.5% in Guangxi, and 16.2% in Hainan by 2100 under SSP245 scenario (Fig. 5C). In low-latitude regions, the total wage of two groups is estimated to increase by 1.4%–7.0%, which indicates a potential increase of production costs. While for high-sensitive group, there are both increase and decrease in wage (Fig. 5B). The increase is expected to be mainly concentrated in the low-latitude regions where high-sensitive group would experience large labor productivity loss, and the decrease in high-latitude regions. By 2100, the wage of high-sensitive group would decrease by 3.8% in Qinghai, and 2.1% in Ningxia, while it would increase by 8.3% in Guangxi, 6.2% in Hainan, and 5.0% in Jiangxi under SSP245 scenario. It is because producers reduced their output to reach a new market equilibrium after the shock of labor productivity loss, resulting in decreased demand for labors both in low-sensitive group and high-sensitive group in high-latitude regions, which further led to decreased wages. However, for low-latitude regions, in addition to reducing output, producers had to increase additional input of labor in high-sensitive group due to their large labor productivity loss. This increase in demand for labor in high-sensitive group would consequently increase their wages.

4. Discussion

In this study, we estimated heat-related labor productivity loss and its economic costs at the provincial level in China under three climate change scenarios, with considering province-specific location and economic structure, indirect impacts from the industrial chain, and heterogeneity of intra-industry labors. The sensitivity analyses demonstrated the robustness of our findings (please found in the supplemental information). The results of this study provided a better understanding of regional impacts of climate change through labor productivity and valuable information into the design of mitigation and adaptation strategies.

The results indicated the potentially significant benefits from reducing emissions dramatically by avoiding heat-related labor productivity loss. By the end of this century, limiting global temperature rise within 2 °C could reduce labor productivity loss and economic loss by more than half compared to a 3 °C temperature rise. Considering that this study solely focuses on economic loss from heat, it's worth noting that larger benefits by mitigation could be expected when considering more impacts of other extreme weather events, such as floods, typhoons, and so on. The national economic loss by 2100 (about 2.3% under SSP245 scenario) is higher than the estimate of the 0.3%–1.3% by Liu et al. (2021), partly because of more indirect impacts (e.g., cumulative effects of capital loss, and price mechanism) and no adaptation considered in this study. Given that the indirect loss exceeded half of the total costs, neglect of such broader economic loss, which is often the case in existing studies, can lead to substantial underestimation. Moreover, previous studies have predominantly estimated economic impacts due to heat-related labor productivity loss at national scales (Liu et al., 2021; Orlov et al., 2019). This study showed the distribution patterns of economic loss across sectors and regions. As highly dependent on labor and sensitive to heat, the labor-intensive sectors would undergo higher loss than capital-intensive sectors. Therefore, we recommended improving mechanization and increasing adaptations in labor-intensive sectors.

At provincial level, low-income regions in low latitudes, mostly located in southwest China (including Guangxi, Hainan, and Guizhou), would experience the largest economic loss, estimated to be 4.4–8.1 times of high-income regions and high-latitude regions given a 3 °C rise in global temperature. These regions would still face significant economic loss even if the global temperature rise is controlled within 2 °C. Therefore, low-income regions in low latitudes are crucial to prioritize and promptly implement adaptation measures. Given the low level of economic development and lack of investment in adaptation in these regions, national financial supports are recommended to promote

adoption and application of adaptation measures in low-income regions in low latitudes. Furthermore, the results revealed that enhancing the substitutability of capital for labor can significantly reduce the economic losses in these regions, highlighting the significance of mechanization in mitigating heat-related labor losses. It should be noted that a free flow of capital among regions assumed in the CHEER model allows low-income regions pay higher prices to attract investments to compensate for labor productivity losses. Given the challenges low-income regions may face in attracting investments, we strongly recommend that governments implement fiscal policies aimed at drawing investment.

However, the largest avoided economic loss (or benefits) in monetary terms through mitigation would accrue not to the low-income regions but rather to the populous and wealthy coastal regions (including Jiangsu, Guangdong, Shandong, Zhejiang, and Henan), which are home to around 33% of the national population yet gain 45% of the total national benefits if 2 °C temperature target is achieved. Considering that the populous and wealthy coastal regions contribute to about 30% of the national carbon emissions, we strongly recommend that they incorporate the impacts on labor productivity into decision-making to address climate change and take more responsibilities to achieve national carbon neutrality. The high-latitude regions would experience a small economic loss, but the annual growth rate is much higher than other regions because of faster temperature rise. High-latitude populations have relatively poor thermal infrastructure and thermal tolerance compared to other regions (Villeneuve et al., 2021). Given no heterogeneity of thermal tolerance across regions, the growth rate of economic loss in high-latitude regions is expected to be higher. The rapidly increasing risk will cause the government and public to fail to react, therefore we suggested that high-latitude regions develop heat response plans in advance, and enhance public heat risk education.

At individual level, high-sensitive group in low-latitude regions would have an increase in wage, because large productivity loss increase demand for these particular laborers. The same result also can be found in Saeed's empirical research on West Africa (Saeed et al., 2022) and Shayege's empirical research on South Africa (Shayege et al., 2021). By 2100, for wage of high-sensitive group, there is an 8.3% increase in Guangxi, 6.2% in Hainan, and 5.0% in Jiangxi under SSP245 scenario. However, increased wages may not actually improve their quality of life as greater heat-related health risks would increase their medical expenditure. Moreover, this may potentially lead to increased production costs and worsen the shortage of these laborers. Conversely, others would experience a significant wage decrease, especially those with less sensitivity in low latitude regions. The key to reducing wage loss for those with less sensitivity is to minimize output loss which is primarily influenced by larger heat impacts on vulnerable workers. Therefore, we recommended that managers and others with low sensitivity to heat assist the vulnerable workers in reducing heat exposure. This can not only directly mitigate heat risks faced by more-sensitive groups but also indirectly reduce wage losses of less-sensitive group.

Several limitations in this study should be noted. First, this study did not consider the heterogeneity of thermal tolerance across regions and populations by adopting the same exposure-response function for all regions because of lacking investigation data. The finer-grained exposure-response function should be further examined. Second, this study only analyzed heat risks under different climate change mitigation efforts, and lacked consideration of climate adaptation measures, which could effectively reduce labor productivity loss (Morabito et al., 2020; Takakura et al., 2018). Effective adaptations necessitate careful planning. However, uncertainty of the impacts of climate change makes it difficult to identify adaptation requirements and strategies (Refsgaard et al., 2013; Bhawe et al., 2016). Additionally, the economic impacts of adaptation measures are complicated, for example, nature-based solutions may bring additional economic benefits (e.g. job creation) (Majumdar et al., 2023) and air conditioning use will increase electricity consumption (Davis and Gertler, 2015a, 2015b). We will address this aspect in future work by incorporating adaptation measures into the

model. Third, we didn't consider that companies may resort to forced overtime as a measure of offsetting labor productivity loss because of the limitation of the CGE model, which may reduce the estimated economic loss. Nevertheless, extended work hours may result in severer health issues which may cause the larger economic loss.

5. Conclusion

Ensuring occupational health safety is an important part of the fight against climate change and the promotion of economic development. By considering the province-specific location and economic structure and the heterogeneity of intra-industry labors, this study is the first comprehensive estimation for future economic impacts of heat-related labor productivity loss across different provinces, sectors and labor types in China. This study provides a better understanding of the magnitude and distributional patterns of heat impacts on labor productivity and the economy at the provincial level, and impacts on wages for two types of labor by taking heterogeneous labor within sectors into the modelling work. The study revealed an uneven distribution of economic losses across regions, sectors, and labor types. The study uncovered substantial economic costs resulting from heat-related labor productivity loss without ambitious carbon emission reduction. The study also highlighted the significant potential benefits from reducing emissions dramatically by avoiding heat-related labor productivity loss. These findings underscore the crucial importance of pursuing ambitious carbon emission reduction strategies. The low-income regions in low latitudes were found to experience the largest economic loss. Even if global warming is limited to 2 °C, these regions would still experience substantial economic loss. Moreover, wages of high sensitive group (including clerks, service workers, farmers, and other unskilled labor) would increase because larger labor productivity loss could increase labor demand for them. Conversely, others would experience a significant wage decrease, especially those with less sensitivity in low latitude regions. In light of these findings, we recommend that government provide national financial supports for low-income regions in low latitudes to promote their adoption and application of adaptation measures. Additionally, these regions are crucial to prioritize and promptly implement adaptation measures, such as providing cooling centers, enhancing workers training and education for heat. For workers, we recommend that managers assist the vulnerable workers in reducing heat exposure, such as providing cooling facilities, adjusting work schedules.

Credit author statement

Conceptualization, Mengzhen Zhao, Wenjia Cai; Methodology, Mengzhen Zhao and Mengke Zhu; Investigation, Mengzhen Zhao; Formal analysis, Mengzhen Zhao and Mengke Zhu; Writing – original draft, Mengzhen Zhao; Writing – review & editing, Chi Zhang, Wenjia Cai, Mengzhen Zhao, and Yuyou Chen; Supervision, Wenjia Cai and Chi Zhang.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (72091514); China Meteorological Administration Climate

Change Special Program (CMA-CCSP); the National Natural Science Foundation of China (72104029); the Youth Innovation Team of China Meteorological Administration (CMA2023QN15); the Wellcome Trust (209734/Z/17/Z); project funded by China Postdoctoral Science Foundation (2023M740252). We also thank the technical support from Bo Lu (China Meteorological Administration) and Zhenping Zhao (Chinese Center For Disease Control And Prevention).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2023.119707>.

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