Journal of Cleaner Production 322 (2021) 129083

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Upholding labor productivity with intensified heat stress: Robust planning for adaptation to climate change under uncertainty

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ARTICLE INFO

Handling editor:Bin Chen

Keywords:
Climate projection
Labor productivity
Optimization
Uncertainty
Adaptation
Heat stress

ABSTRACT

The intensification of heat stress in a changing climate poses great threats to both human health and labor productivity. It is of great practical importance to assess the impacts of climate-induced heat stress on labor productivity and to develop effective adaptation strategies. In this paper, an integrated optimization-based productivity restoration modeling framework is proposed for the first time to develop the optimal policies for adaptation to climate change. To address underlying uncertainties associated with climate and labor management systems, we take into account ensemble projections from five global climate models (GCMs) under two Representative Concentration Pathways (RCP2.6 and RCP8.5) and inexact system costs. The system costs, including direct and indirect costs such as management costs, energy costs, and labor costs, are presented as interval numbers due to inherent uncertainty caused by population growth, technology development, and other social-economic factors. Uncertain information can be effectively communicated into the optimization processes in this study to generate optimal and reliable decision alternatives. We find that the increased Wet-Bulb Globe Temperature (WBGT) will lead to a large reduction in labor capacities over China except for the Tibetan Plateau under both RCPs by the end of the 21st century. The less developed regions tend to achieve the minimum system cost by having labor productivity recovered through working overtime due to the relatively low cost of overtime. This could result in more heat-related work injuries in the less developed regions. Since the less developed regions are not heat-prone areas in China, the changing climate would be a more dangerous threat and cause more damages to these regions where the residents are less acclimatized to heat stress. Moreover, we obtain a range of minimum system costs from 1.86 to 8.97 billion dollars under RCP2.6 and from 9.42 to 32.31 billion dollars under RCP8.5 (about 0.2% of China's GDP in 2019, 0.01% of China's GDP projected in 2100 under a sustainable socio-economic development scenario) for the restoration of labor productivity in a warming climate. We argue that urgent actions are needed to mitigate global warming impacts on labor productivity.

1. Introduction

As one key consequence of ongoing global warming, a combination of extremely high temperature and relative humidity has been posing threats to human life and activities associated with climate conditions that exceed the human thermoregulatory capacity (Dunne et al., 2013; Fischer and Knutti, 2013). Exposing to such heat stress greatly reduces labor productivity (the loss of productive work time) and may also increase work injuries under extreme conditions (Diffenbaugh et al., 2007; Dukesdobos, 1981; Dunne et al., 2013; Pal and Eltahir, 2015). As an important driver of economic success, any changes in the labor capacity have a direct impact on national outputs, individual incomes, and sustainable development goals (Matsumoto, 2019; Zhao et al., 2016). A growing body of studies has estimated the reduction in labor capacity and the related economic impacts (Kjellstrom et al., 2009; Lee et al., 2018; Li et al., 2016). It is well known that negative changes in labor productivity can be potentially reversed by adaptation measures. The main unknown is how to restore the reduced labor capacity with the lowest cost through optimized planning within the socio-economic and environmental contexts. The cost-effective labor productivity restoration has played a crucial role in the mitigation and adaptation to global warming, which is mainly using air conditioning or making workers

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https://doi.org/10.1016/j.jclepro.2021.129083
Received 26 January 2021; Received in revised form 21 July 2021; Accepted 17 September 2021
Available online 18 September 2021

work overtime (Day et al., 2019). One of the most difficult challenges related to productivity restoration is the effective treatment of uncertainty in the adaptation management while considering the changing climate and socio-economic changes. To develop the optimal adaptation strategies for dealing with the issue of labor productivity reduction, we need not only to tackle the uncertainty in the future climate but also to incorporate the uncertain information into the productivity restoration process.

Labor productivity management is mostly carried out for labor planning and scheduling, which generally deals with the determination of schedule patterns and assigns workers to various tasks relating to availability, allocation, and transition. Both labor scheduling and planning aim to balance the relatively low-level and short-term labor demand and availability. Primarily, there are two categories of labor planning/scheduling models widely used, including descriptive (or exploratory) models and normative models (Bastian et al., 2020; Borba et al., 2019; Lavergne et al., 2019; Song and Huang, 2008). Descriptive models are defined as analytical tools to predict how the labor stream would respond to various conditions. Typical examples of descriptive models include Markov (cross-sectional) models (Di Francesco et al., 2016; Dimitriou and Georgiou, 2019; Knorzer, 2000), semi-Markov models (Bastian et al., 2020; Chattopadhyay and Gupta, 2007; Song and Huang, 2008), and renewal models (Chen et al., 2018; De Feyter et al., 2017). Normative models are the optimization tools used to prescribe policies in order to achieve an ideal balance in the labor management system under given criteria. The ideal balance can be obtained with a certain degree of satisfaction in the objective function, such as personnel flow, labor size, and related costs. To meet various needs in service levels and labor requirements, dynamic programming within a Markov framework is also used to generate optimal recruitment and transition patterns (Dimitriou and Tsantas, 2010).

Previous studies were mainly focused on the balance between labor demand and availability over a short period of time, which ignored the long-term climate change impacts on labor productivity. The model inputs and parameters were also required to be deterministic in previous studies, which failed to address uncertainties that inherently exist in climate and management systems. Since various information related to technology development, environmental and socio-economic situations are imprecise, they are often given as interval numbers in real-world planning problems over a long period of time. In this paper, we deal with a long-term labor planning problem faced by decision-makers who seek to address the issue of the labor productivity reduction induced by global warming under uncertainty. To our best knowledge, we, for the first time, develop an integrated optimization-based productivity restoration modeling framework for cost-effectively restoring the reduced labor productivity caused by the intensified heat stress under global warming. The proposed framework takes into account the importance of uncertainties existing in the main factors determining system costs and the evolution of global warming in three steps. First, changes in heat stress are projected through an ensemble of global climate models (GCMs) projections under two Representative Concentration Pathways (RCPs). Second, changes in productive working time are obtained based on the relationship between the projected heat stress and labor capacity. Third, the working time intervals are used as constraints in an interval programming model developed to determine the optimal adaptation plans with minimum system costs under different climate change scenarios.

The rest of the paper proceeds as follows: Section 2 presents the methods and datasets used to obtain the changes in the labor capacity and to formulate the interval programming model. A comprehensive understanding of the impacts of climatic factors on the management system provides the basis to conduct the optimization of adaptation options to achieve the minimum system costs. Section 3 exhibits the results of heat stress, reduced labor capacity, and the optimal solutions obtained from the interval programming model. This section demonstrates the practical significance of the newly developed framework to assess the impacts of global warming on labor productivity and to provide the adaptation plans for decision-makers to minimize the system cost. Section 4 concludes the novelty of this study, the main findings, and the associated implications.

2. Methods and data

2.1. Climate projection, heat stress index, and labor productivity assessment

Projections from five GCMs, including CanESM2, IPSLCM5A-MR, HadGEM2-ES, CSIRO-MK3.6.0, MIROC5, were selected to assess heat stress over China (details on the selection of GCMs are provided in the Supplementary Information Table S1). Note that since the daily average value is typically lower than the hourly average value, hourly climatic variables are essential for studying extreme situations such as heat stress. Thus, hourly mean surface air temperature and relative humidity were selected to calculate the time series of heat stress over the reference period from 1981 to 2005. Projections of two climatic variables were used to calculate the changes in heat stress over the period from 2076 to 2100. We chose two RCPs, namely the most warming scenario in which CO_2 concentrations will keep increasing through 2100 (RCP8.5) and the aggressive mitigation scenario that limits warming to below 2 °C (RCP2.6), to explore climate system outcomes under different warming scenarios (Taylor et al., 2012).

An increasing number of studies have been focusing on the combined effect of air temperature and relative humidity, which are considered as “well-established” risk factors for human health and are towards amplifying heat stress on the human body (Liu et al., 2018; Wang and Zhu, 2020; Zhu et al., 2019; Zhu et al., 2017). As a result, a large number of thermal indices were created to address the combined effect and to measure heat stress posed on the human body (Fischereit and Schlunzen, 2018; Havenith and Fiala, 2016; Morabito et al., 2014). Among various indices available, the WBGT (Wet-Bulb Globe Temperature) has the advantages of being well-validated and high usability for quantifying heat stress (Budd, 2008; Willett and Sherwood, 2012). We used the simplified WBGT method adopted by the Australian Bureau of Meteorology for the valid air temperatures ranging from 0 °C to 100 °C. The WBGT was approximated without considering the direct exposure to sunlight and wind. This is because we focus on studying a relatively low limit of heat stress in optimally sheltered daytime, shaded daytime, and nighttime conditions.

$$e_{sat} = \exp\left(\begin{array}{l} 18.8764 - \dfrac{2991.2729}{T^2} - \dfrac{6017.0128}{T} - 0.0285 \times T + 1.7838 \times 10^{-5} \times T^2 - 8.4150 \times 10^{-10} \times \\ T^3 + 4.4413 \times 10^{-13} \times T^4 + 2.8585 \times 10^{-2} \times \ln(T) \end{array}\right) / 100 \tag{1a}$$

$$e = RH \times e_{sat} \tag{1b}$$

$$WBGT = 0.567 \times T + 0.393 \times e + 3.94 \tag{1c}$$

where T is the hourly surface air temperature (°C), RH is the hourly relative humidity, e is the simultaneous vapor pressure (hPa), and e_{sat} is the saturation vapor pressure (hPa).

Labor capacity is the occupational capacity to safely carry out continuous labor under environmental pressure. The labor capacity is assumed to be 100% for a healthy and acclimatized worker to safely perform sustained labor under non-extreme conditions. The time interval for analysis is about 1 h exposure to heat stress. A 50% labor capacity indicates that a worker needs to take a rest for 30 min during each 1-h work-rest cycle. 3-hourly data (which is readily available in the CMIP5 dataset) was used to calculate the average labor capacity weighted by exposure. According to Dunne's study, a single metric was developed to measure the relationships between WBGT and three different types of labor work (light, moderate, and heavy labor) (Dunne et al., 2013). The empirical metric is based on the assumption of heavy labor corresponding to roughly 200% of moderate labor, and of moderate labor corresponding to roughly 200% of light labor. The empirical relationship for heavy work is estimated as

$$LC = 100\%,\ WBGT \leq 25^{\circ}\mathrm{C} \tag{2a}$$

$$LC = \left[1 - 0.25 \times max(0,\ WBGT - 25)^{\frac{2}{3}}\right] \times 100\%,\ 25^{\circ}\mathrm{C} < \mathrm{WBGT} < 33^{\circ}\mathrm{C} \tag{2b}$$

$$LC = 0\%,\ WBGT \geq 33^{\circ}\mathrm{C} \tag{2c}$$

where LC is the labor capacity (%), and $WBGT$ is the Wet-Bulb Globe Temperature (°C). It should be noted that the unhealthy and unacclimatized workers due to their ages and inferior physical conditions are not considered in this study. The differences in capacity reductions caused by the nature of work (extent of exposure to heat in the work) are also not considered due to the data limitation and for the simplification of model formulation.

The Bureau of Labor Statistics commonly uses four strength levels (light, moderate, heavy, and very heavy) to describe the job requirements for performing physical activities with different durations and weight classes (China, 2020; Gong et al., 2016). For the reference period from 1981 to 2005, 57% of civilian workers in China's economy performed light level labor. 32.3% of workers were involved in moderate level activities. 9.6% and 1.1% of workers performed heavy and very heavy level activities, respectively (Liu et al., 2015; Qi et al., 2015). To be consistent with the classification in Equation (2), we use the value of 10.7% (9.6% + 1.1%) to represent the total percentage of civilian workers required in the heavy level activity in China. For every 3 h, the labor capacity can be reduced to some extent when the WBGT exceeds the threshold for a specified labor type. The daily labor capacity reduction weighted by exposure can be accumulated for both baseline and future periods. Thus, we can subtract the accumulated labor capacity reduction for the baseline period from the reduction for the future period. Under normal conditions, the working hour is 8 h per day when the labor capacity is 100%. Assuming a constant heat stress effect on the hourly change in labor capacity for all working hours, we define the annual productivity loss/working hour loss as the 25-year averaged labor capacity reduction multiplied with the population of workers involved in a given labor type.

2.2. Model formulation

Under a warming climate, labor productivity across different regions could be influenced to a different extent due to their unique climate situations. Moreover, local contexts influence the rank of the effectiveness of adaptation measures. It is thus essential to examine regional climate impacts on labor productivity across different regions categorized by geographical complexities. In this paper, we select China's land area as the study area (as shown in Fig. 1). To better depict regional climate impacts on labor productivity, China is delineated into nine climate divisions based on temperature and precipitation characteristics, including 1. Cold and humid zone; 2. Warm and arid zone; 3. Plateau and arid zone; 4. Warm and semi-arid zone; 5. Plateau and semi-humid zone; 6. Cool and humid zone; 7. Warm and humid zone; 8. Hot and humid zone; 9. Subtropical and humid zone.

Over the 25-year planning horizon from 2076 to 2100, various adaptation options are available to restore the labor capacity to the reference period. Working overtime, occupational shifts, work practice & education programs, air conditioning, shades, outdoor portable cooling devices, and labor relocations are the most common measures to

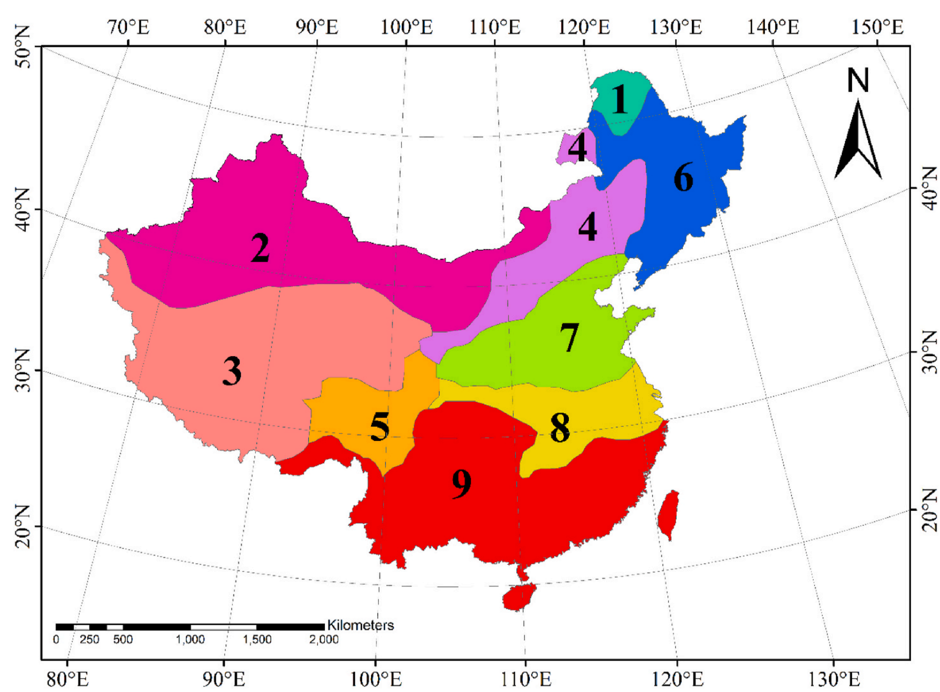

Fig. 1. Nine climate divisions delineated according to temperature, precipitation, and humidity differences.

mitigate the negative impacts on workers. Parts of labor will be substituted by the other agents such as capital and auto-robots for the consideration of wage stickiness. Hence, labor-intensive industries are most vulnerable to the increased heat stress. Such industries might have to lay off or cut wages to workers to deal with the difficult situation. To prevent hazards and seek high income, geographically relocating labors to the regions with less heat stress is foreseeable in a long run (Wang and Luo, 2014; Zhang and Song, 2003; Zhao, 1999). Relocating the bases of industries is complex (labor costs, supplements, industry chain, political influences, and so on) and is out of the scope of this study due to data limitations. It is worthy to design a framework to identify effective solutions for reducing labor productivity under intensified heat stress in the future. Compared with labor relocation, applying air conditioning and working overtime are more affordable and realistic options for all industries. Each adaptation option has a specific treatment capacity restricted by processing efficiencies and national safety regulations. The increased frequency of high nighttime temperatures could reduce the effectiveness of the adaptation by working overtime to restore the lost working hours. For the days with nighttime temperatures over the threshold of labor capacity reduction, the passive cooling mechanism can be applied with operating costs and capital investments for operating at night. Most passive cooling measures such as air conditioning are energy and carbon-emission intensive solutions. Compared with air conditioning, working overtime is the adaptation measure with fewer carbon footprints and lower energy costs. Since more working hours are allocated to the passive cooling options, more associated environmental costs are needed.

Within the national context of China, a large number of working hour losses due to the intensification of heat stress have a direct and significant impact on the economy (Zhao et al., 2016). Various adaptation options are available to alleviate the situation or even compensate for the working hour losses. Systematic planning of upholding labor productivity is complicated and affected by many factors such as technology, as well as economic, social, and environmental developments at a national level. Moreover, considerable uncertainty exists in the cost of implementing each adaptation measure, which includes direct capital investments/payments and indirect costs such as operation, maintenance, and management costs. Thus, it is necessary to effectively incorporate uncertain information into the systematic planning of labor productivity restoration to identify the optimal adaptation measures with the lowest cost. The scientific community has a consensus on two specific adaptation options that are cost-effective for restoring working hour losses based on the rules of thumb (Day et al., 2019). Specifically, working overtime, as the most commonly used active measure, can make up the lost productive hours in the daytime; air conditioning, which is the most widely used passive adaptation option, is effective in smoothing outdoor/indoor temperature peaks and reducing working hour losses. It is suggested that optimizing the application of working overtime and air conditioning has the largest systematic impact on restoring the lost working hours at a regional scale. For the seven regions in China, we obtain the data of economic costs for air conditioning and working overtime presented as intervals over the planning horizons of 25 years. These intervals address the uncertainty of implementing adaptation measures by incorporating the ranges in the population weight, economic development, and air-conditioning penetration rate. We use the provincial-level air-conditioning penetration rates (Supplementary Information Table S2), averaged market values of air conditioners, energy consumptions for passive cooling mechanisms reported in the China Statistics Yearbook for the baseline period (China National Bureau of Statistics, 2020) and socio-economic scenarios (Zhang et al., 2016) to estimate the running costs and capital investments on the application of air conditioning in the future. Our study makes use of the yearly provincial population projections in China under Shared Socioeconomic Pathways from 2010 to 2100 to obtain the provincial-scale long-term forecasting database of national regulations, population, and GDP (Gross Domestic Product) (Chen et al., 2020). Then, we used the China Population and Employment Statistics Yearbooks from 1981 to 2005 to calculate the changes in population and estimate the managing costs and payments for working overtime (as shown in Table 1) (China National Bureau of Statistics, 2007).

Table 1
Costs of air conditioning and working overtime for three labor types in the planning horizon.

Regions	Labor Types	Air Conditioning (10^5\$/hr)		Overtime (10^5\$/hr)	
		Running Costs	Costs	Managing Costs	Payments
1	Moderate	[2.212, 4.699]	[34.368, 39.293]	[5.321, 6.987]	[34.222, 37.150]
	Light	[1.555, 3.373]	[33.768, 37.798]	[4.742, 6.063]	[30.099, 34.370]
	Heavy	[0.253, 1.757]	[30.125, 34.082]	[2.650, 5.504]	[28.678, 32.055]
2	Moderate	[4.442, 7.525]	[50.359, 55.330]	[10.636, 12.391]	[43.173, 46.082]
	Light	[4.843, 6.749]	[41.250, 45.697]	[9.822, 12.333]	[39.324, 42.671]
	Heavy	[2.793, 4.864]	[41.248, 45.857]	[7.695, 9.996]	[37.022, 40.647]
4	Moderate	[7.648, 9.678]	[46.197, 50.890]	[11.904, 13.140]	[47.936, 53.448]
	Light	[4.753, 6.687]	[44.254, 49.009]	[10.301, 12.738]	[43.984, 47.712]
	Heavy	[2.782, 3.741]	[38.328, 42.799]	[9.170, 11.873]	[40.791, 45.045]
6	Moderate	[8.366, 10.256]	[42.154, 46.782]	[11.747, 13.801]	[60.035, 62.890]
	Light	[5.176, 7.393]	[40.534, 45.798]	[11.455, 13.140]	[55.055, 60.035]
	Heavy	[5.788, 6.765]	[40.273, 44.147]	[10.307, 11.518]	[53.433, 56.522]
7	Moderate	[10.268, 12.336]	[54.211, 58.881]	[14.524, 18.398]	[71.858, 76.969]
	Light	[7.508, 9.236]	[43.607, 48.469]	[14.685, 18.169]	[71.796, 75.127]
	Heavy	[6.286, 7.861]	[39.896, 44.783]	[11.845, 14.163]	[67.985, 73.384]
8	Moderate	[9.491, 11.795]	[55.002, 60.140]	[14.144, 17.495]	[73.208, 76.980]
	Light	[6.467, 9.986]	[52.105, 56.502]	[15.306, 19.123]	[71.811, 75.638]
	Heavy	[5.867, 7.622]	[43.593, 47.252]	[11.881, 15.949]	[71.099, 76.367]
9	Moderate	[11.819, 14.726]	[59.386, 63.834]	[15.229, 19.236]	[87.022, 90.044]
	Light	[8.800, 10.641]	[53.264, 58.395]	[17.208, 21.014]	[82.160, 85.972]
	Heavy	[7.792, 9.048]	[45.839, 49.708]	[12.426, 15.044]	[77.167, 81.507]

In this study, the productivity restoration process is considered as an interval system. In the productivity restoration management system, the interval decision variables represent the number of working hour losses across different regions with various adaptation options under each RCP scenario. The objective is to achieve the minimum system cost for restoring labor productivity by optimally allocating the number of working hour losses to adaptation options. The adaptation options can be divided into two categories, including passive measures (e.g., air conditioning, outdoor shades, and personal cooling devices) and active measures (e.g., working overtime, occupational choices, and work practice programs). The constraints account for the underlying relationships between decision variables and restoration restrictions. The detailed interval programming model is formulated as follows:

Objective function for minimizing the total labor system costs with considering uncertainties in direct and indirect costs:

$$Min y^{\pm} = \sum_{i=1}^{u}\sum_{j=1}^{v}\sum_{k=1}^{w} x_{ijk}^{\pm} \times \left(CI_{jk}^{\pm} + OC_{ijk}^{\pm}\right) + \sum_{i=1}^{u}\sum_{j=1}^{n}\sum_{k=1}^{w} TR_{ik}^{\pm} \times x_{ijk}^{\pm} \times NCI_{ik}^{\pm} + \sum_{i=1}^{u}\sum_{k=1}^{w}\left[\left(\sum_{j=1}^{n} TR_{ik}^{\pm} \times x_{ijk}^{\pm}\right) \times \left(\sum_{j=n+1}^{v} NOC_{ijk}^{\pm}\right)\right] - \sum_{i=1}^{u}\sum_{j=1}^{n}\sum_{k=1}^{w} x_{ijk}^{\pm} \times EC_{ijk}^{\pm} \tag{3a}$$

Constraints on passive methods capacity (mainly concerns the cooling efficiency and capacity in the working places):

$$\sum_{i=1}^{u}\sum_{j=n+1}^{v}\sum_{k=1}^{w} x_{ijk}^{\pm} + \sum_{i=1}^{u}\sum_{j=1}^{n}\sum_{k=1}^{w} TR_{ik}^{\pm} \times x_{ijk}^{\pm} \le PC^{\pm} \tag{3b}$$

Constraints on active methods capacity (mainly concerns the working schedule alternations):

$$\sum_{i=1}^{u}\sum_{j=1}^{n}\sum_{k=1}^{w} x_{ijk}^{\pm} \le AC^{\pm} \tag{3c}$$

Constraints on the allocation of working hour losses capacity (accumulated working hour losses in the labor system):

$$\sum_{j=1}^{v} x_{ijk}^{\pm} = WC_{ik}^{\pm}, \forall i, k. \tag{3d}$$

$$x_{ijk}^{\pm} \ge 0, \forall i, j, k. \tag{3e}$$

where:

$y^{\pm}$ is the total system cost (unit: $);

$x_{ijk}^{\pm}$ is the number of working hour loss in the region i allocated to the adaptation option j (options from 1 to n are the active measures; options from n+1 to v are the passive ones) for the labor type k (unit: hr);

$CI_{jk}^{\pm}$ is the capital investment for implementing the adaptation option j for the labor type k (unit: $/hr);

$OC_{ijk}^{\pm}$ is the operating/managing cost for implementing the adaptation option j for the labor type k in the region i (unit: $/hr);

$TR_{ik}^{\pm}$ is the rate of hot nights when the nighttime WBGT is over 25 °C and passive cooling mechanisms are needed in the region i for the labor type k (unit: %). Since workers who are working overtime at night are awake, the threshold of 25 °C from the summer day index is used to calculate the working hour loss;

$NCI_{ik}^{\pm}$ is the capital investment for implementing the lighting system for the labor type k in the region i during overtime/nighttime (unit: $/hr);

$NOC_{ijk}^{\pm}$ is the operating/managing cost for implementing the passive cooling option j for the labor type k in the region i during overtime/nighttime (unit: $/hr);

$EC_{ijk}^{\pm}$ is the environmental cost saved by not using the passive cooling mechanism j for the labor type k in the region i (unit: $/hr);

$PC^{\pm}$ is the total capacity of implementing passive methods for reversing the working hour loss (unit: hr);

$AC^{\pm}$ is the total capacity of implementing active methods for reversing the working hour loss (unit: hr);

$WC_{ik}^{\pm}$ is the accumulated working hour loss for the labor type k in the region i (unit: hr).

Solutions of the interval programming model include the objective function value $y^{\pm}$ and relevant decision variables $x_{ijk}^{\pm}$, $\forall i, j, k$. The objective function value is expressed as $y^{\pm} = [y^{-}, y^{+}]$ in which the lower bound y^{-} and the upper bound y^{+} are the minimum possible value and the maximum possible value of the optimized system cost, respectively. The lower and upper bounds of the objective function correspond to the values of decision variables . that can be expressed as $x_{ijk}^{\pm} = [x_{ijk}^{-}, x_{ijk}^{+}]$, $\forall i, j, k$. The variation of decision variables within their corresponding lower and upper bounds leads to the adjustment of the objective function value within the interval of system costs. These interval solutions provide meaningful insights into the decision-making process to achieve cost-effective labor productivity restoration under different RCP scenarios. For a given RCP scenario, the interval programming model can be solved as follows. For detailed procedures for solving the interval programming model, please refer to Fan et al. (2012):

Lower bound of the objective function:

$$Min y^{-} = \sum_{i=1}^{u}\sum_{j=1}^{v}\sum_{k=1}^{w} x_{ijk}^{-} \times \left(CI_{jk}^{-} + OC_{ijk}^{-}\right) + \sum_{i=1}^{u}\sum_{j=1}^{n}\sum_{k=1}^{w} TR_{ik}^{-} \times x_{ijk}^{-} \times NCI_{ik}^{-} + \sum_{i=1}^{u}\sum_{k=1}^{w}\left[\left(\sum_{j=1}^{n} TR_{ik}^{-} \times x_{ijk}^{-}\right) \times \left(\sum_{j=n+1}^{v} NOC_{ijk}^{-}\right)\right] - \sum_{i=1}^{u}\sum_{j=1}^{n}\sum_{k=1}^{w} x_{ijk}^{-} \times EC_{ijk}^{+} \tag{4a}$$

Constraints on passive methods capacity:

$$\sum_{i=1}^{u}\sum_{j=n+1}^{v}\sum_{k=1}^{w} x_{ijk}^{-} + \sum_{i=1}^{u}\sum_{j=1}^{n}\sum_{k=1}^{w} TR_{ik}^{-} \times x_{ijk}^{-} \le PC^{+} \tag{4b}$$

Constraints on active methods capacity

$$\sum_{i=1}^{u}\sum_{j=1}^{n}\sum_{k=1}^{w} x_{ijk}^{-} \le AC^{+} \tag{4c}$$

Constraints on the allocation of working hour losses capacity:

$$\sum_{j=1}^{v} x_{ijk}^{-} = WC_{ik}^{-}, \forall i, k. \tag{4d}$$

$$x_{ijk}^{-} \ge 0, \forall i, j, k. \tag{4e}$$

Let $x_{ijk}^{-} opt$ be the solution of the model given in function (4a)-(4e).

Upper bound of the objective function:

$$Min y^{+} = \sum_{i=1}^{u}\sum_{j=1}^{v}\sum_{k=1}^{w} x_{ijk}^{+} \times \left(CI_{jk}^{+} + OC_{ijk}^{+}\right) + \sum_{i=1}^{u}\sum_{j=1}^{n}\sum_{k=1}^{w} TR_{ik}^{+} \times x_{ijk}^{+} \times NCI_{ik}^{+} + \sum_{i=1}^{u}\sum_{k=1}^{w}\left[\left(\sum_{j=1}^{n} TR_{ik}^{+} \times x_{ijk}^{+}\right) \times \left(\sum_{j=n+1}^{v} NOC_{ijk}^{+}\right)\right] - \sum_{i=1}^{u}\sum_{j=1}^{n}\sum_{k=1}^{w} x_{ijk}^{+} \times EC_{ijk}^{-} \tag{5a}$$

Constraints on passive methods capacity:

$$\sum_{i=1}^{u}\sum_{j=n+1}^{v}\sum_{k=1}^{w} x_{ijk}^{+} + \sum_{i=1}^{u}\sum_{j=1}^{n}\sum_{k=1}^{w} TR_{ik}^{+} \times x_{ijk}^{+} \le PC^{-} \tag{5b}$$

Constraints on active methods capacity:

$$\sum_{i=1}^{u}\sum_{j=1}^{n}\sum_{k=1}^{w} x_{ijk}^{+} \le AC^{-} \tag{5c}$$

Constraints on the allocation of working hour losses capacity:

$$\sum_{j=1}^{v} x_{ijk}^{+} = WC_{ik}^{+}, \forall i, k. \tag{5d}$$

$$x_{ijk}^{+} \ge 0, \forall i, j, k. \tag{5e}$$

$$x_{ijk}^{+} \ge x_{ijk}^{-} opt, \forall i, j, k. \tag{5f}$$

2.3. Computational procedure for the novel framework

As shown in Fig. 2, the proposed modeling framework for optimally restoring labor productivity in adaptation to climate warming involves four main components, including data collection, projection of future global warming, estimation of potential labor capacity reduction, and identification of optimal adaptation strategies for labor productivity restoration. Through the integration of the ensemble of GCMs, the function of potential labor capacity reduction, and the optimization-based productivity restoration modeling, the most cost-effective

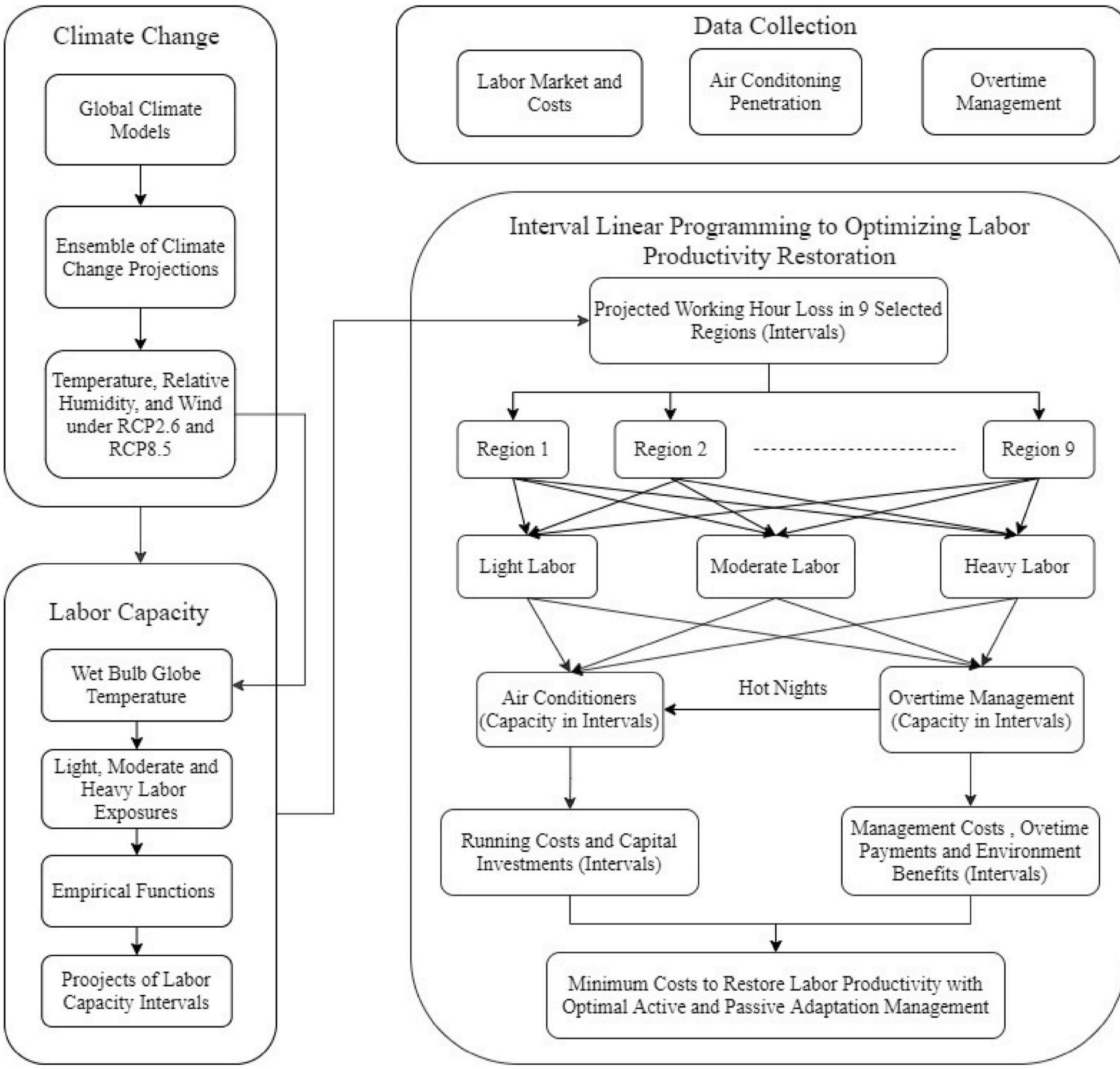

Fig. 2. Flow chart of the integrated optimization-based productivity restoration modeling framework.

solution can be generated to restore the working hour loss with the minimum system cost under different climate change scenarios. Specifically, the ensemble of five GCMs projections under two RCP scenarios is first used to explore the uncertainties in climate modeling and to generate the daily time series of heat stress. Second, the empirical relationship between heat stress and labor capacity is employed to predict the future working hour losses for each labor type under two RCPs. Third, the interval programming model is developed to provide decision supports for optimal productivity restoration based on the predicted working hour losses under uncertainty. Large-scale applications of air conditioners will boost electricity consumption and lead to more CO2 emitted to the atmosphere. Using more active measures such as working overtime rather than air conditioners could save energy costs. In this paper, the environmental costs involved in adaptation options are incorporated into the modeling framework by calculating the electricity costs for using air conditioners. The proposed framework can not only quantify the global warming impact on labor productivity but also generate optimal solutions for decision-makers to restore labor productivity under uncertainty.

3. Results

3.1. Projection of future changes in WBGT and heat stress

Fig. 3 shows the projected changes in the WBGT derived from the GCM ensemble for the end of the 21st century relative to the reference period under RCP8.5 (for results under RCP2.6, please refer to the Supplementary Information Fig. S1). For five GCMs, the WBGT is projected to increase across China with different magnitudes and spatial distributions under both RCPs. Under RCP8.5, all models show that the WBGT would increase by more than 5 °C for most parts of China. Among the five models, CSIRO-Mk3-6-0 and MIROC5 simulate the smallest increase in the WBGT. In comparison, CanESM2 and HadGEM2-ES have their simulations with the largest change (up to 9 °C) in the WBGT. Moreover, there are large variations in the spatial distribution of the WBGT change due to the model uncertainty. As shown in Fig. S1, all models show the increases of WBGT by higher than 1 °C all over China under RCP2.6 which is 4 °C lower than the results under RCP8.5. There are also considerable differences between magnitudes and spatial

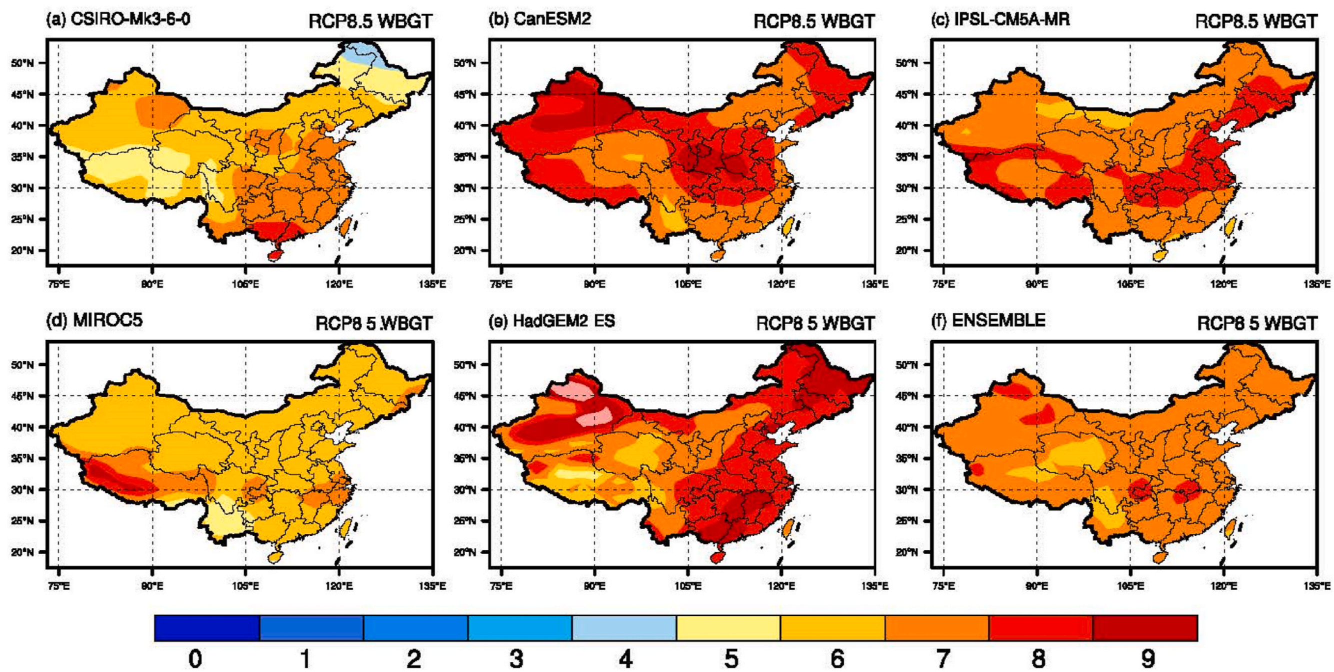

Fig. 3. Projected changes in WBGT (°C) for five GCMs and the ensemble mean under RCP8.5 for the end of the 21st century relative to the baseline period.

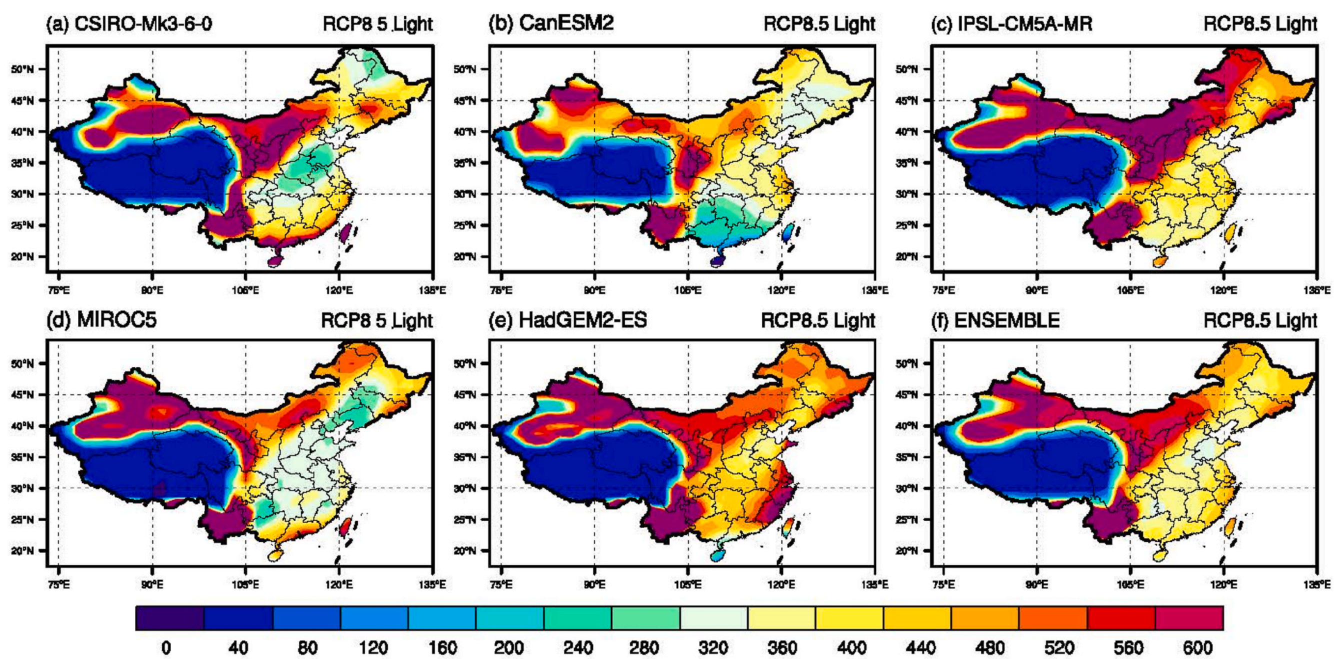

Fig. 4. Projected working hour losses (hour) in light labor for five GCMs and ensemble mean under RCP8.5.

distributions of the WBGT changes under different RCPs; nevertheless, we find an intensification of heat stress across the whole country derived from the ensemble means of the WBGT changes under both RCP2.6 and RCP8.5.

3.2. Projection of working hour losses

Figs. 4–6 show the projected changes in working hour losses for light, moderate, and heavy labor in China for the 2076–2100 period relative to the baseline period under RCP8.5 (please refer to the Supplementary Information Figs. S2–S4 for results under RCP2.6). By the end of the 21st century, most regions show large decreases in the accumulated labor capacity of light, moderate, and heavy labor under both RCPs. As mentioned in Section 2.1, the reduction in the labor capacity can be used to calculate the working hour loss by accommodating a population of civilian workers. In opposite to the spatial distribution of WBGT, the working hour loss for a specific labor type does not show large geographical differences among all GCMs. For all five models, the working hour loss would be less than 40 h per year in Tibet (region 3) and the western part of the Sichuan Province (region 5) for all three labor types under both RCPs. The largest reduction in the working hour appears in the Yunnan Province (region 9) with an annual value of over 600 h. We also find that the working hour loss exhibits a consistent geographical difference between inland areas (regions 1, 2, and 4) and

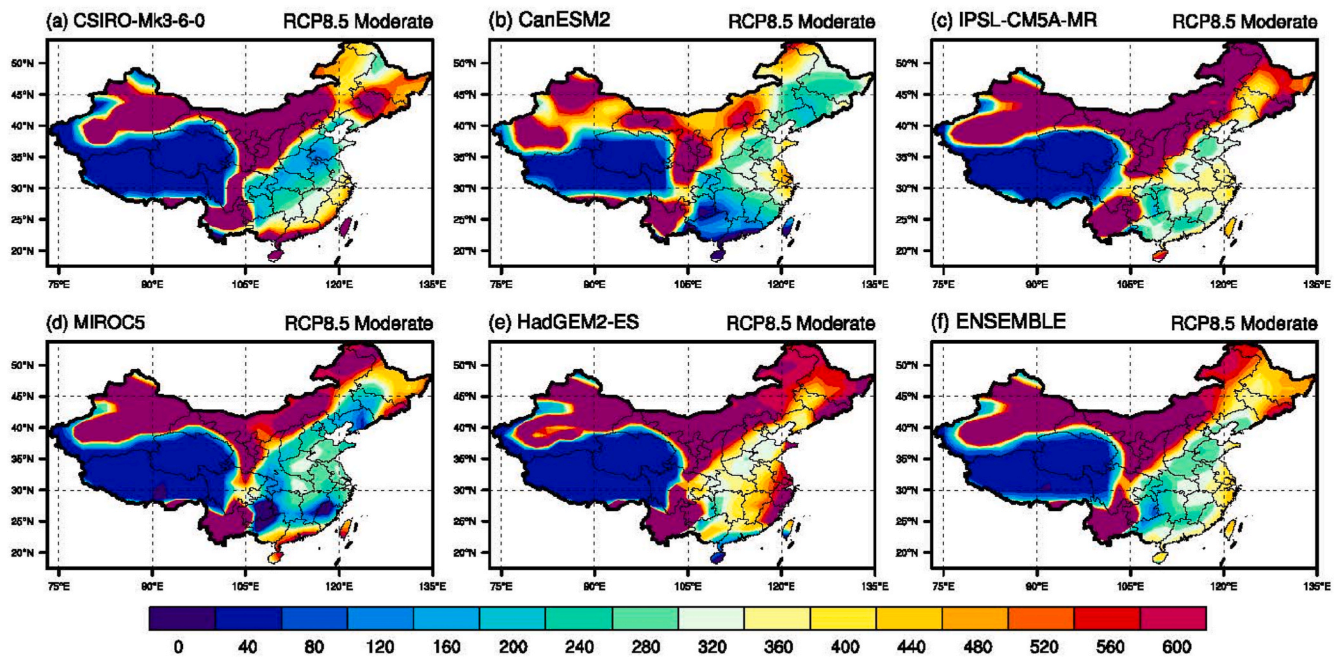

Fig. 5. Projected working hour losses (hour) in moderate labor for five GCMs and ensemble mean under RCP8.5.

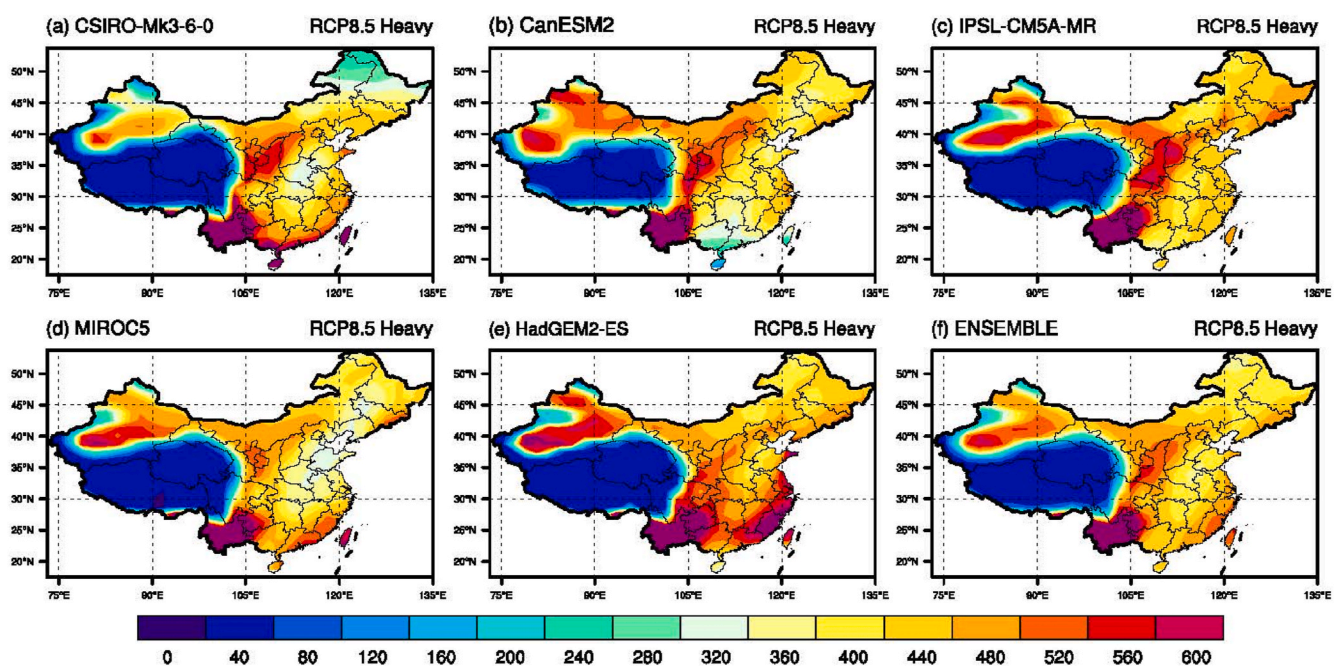

Fig. 6. Projected working hour losses (hour) in heavy labor for five GCMs and ensemble mean under RCP8.5.

monsoon affecting areas (regions 6, 7, 8, and 9) for light, moderate, and heavy labor activities. Except for the Yunnan Province, the inland areas have a greater working hour loss than the monsoon affecting areas. Based on the findings from our previous studies (Wang and Zhu, 2020; Zhu et al., 2017; Zhu et al., 2019), the reason why there is a distinct difference between the two areas is that the inland areas tend to have more dry days than the monsoon areas with the temperature rising rapidly. This results in more prolonged heatwaves taking place in the inland areas than the monsoon areas. Despite the variations caused by the model uncertainty, moderate labor activities have the largest reduction in the annual working hour loss under RCP2.6 and RCP8.5. Light labor activities have the second-largest reduction, and heavy labor activities have the smallest. However, this does not imply that moderate activities are the most vulnerable to the intensification of heat stress. When we examine the global warming impacts on individuals (as shown in Supplementary Information Fig. S5), we find that heavy labor activities have the lowest threshold (25 °C) of the labor capacity reduction, while moderate activities have the second-lowest (28 °C) and light activities have the highest (30 °C). The greatest loss in the productive working hour for moderate labor activities results from the combination of the percentage of civilian workers involved and the individual labor capacity's sensitivity to the increased heat stress.

The ensemble of multi-model simulations addresses the model uncertainty residing in GCMs by generating a plausible range of climate

Table 2
Intervals of area-averaged working hour losses for three labor types under RCP2.6 and RCP8.5.

Regions	RCP2.6			RCP8.5		
	Moderate	Light	Heavy	Moderate	Light	Heavy
1	[108, 307]	[81, 222]	[61, 186]	[371, 714]	[282, 549]	[227, 411]
2	[135, 257]	[122, 204]	[81, 171]	[574, 811]	[480, 618]	[339, 474]
3	[0, 0]	[0, 0]	[0, 1]	[0, 12]	[0, 15]	[0, 16]
4	[85, 319]	[85, 226]	[66, 191]	[399, 736]	[405, 593]	[413, 440]
5	[0, 0]	[0, 0]	[0, 2]	[0, 14]	[0, 19]	[0, 22]
6	[115, 236]	[119, 172]	[103, 168]	[254, 512]	[325, 455]	[351, 438]
7	[93, 186]	[124, 167]	[130, 171]	[244, 453]	[304, 452]	[357, 462]
8	[74, 130]	[118, 148]	[123, 175]	[228, 466]	[304, 456]	[372, 453]
9	[149, 216]	[150, 223]	[150, 237]	[273, 654]	[357, 606]	[444, 585]

projections. The integration of an ensemble of multi-model projections and the functions used to quantify the relationships between heat stress and labor capacity as well as the population of workers involved for different labor types can lead to variations in working hour losses for nine regions under two RCP scenarios. As shown in Table 2, the ranges of working hour losses for three labor types are area-averaged and interpreted as intervals (with known lower and upper bounds, and unknown probability distribution) for each region under RCP2.6 and RCP8.5. For regions 3 and 5, the upper bounds of the working hour loss intervals are less than 22 h per year. Hence, the working hour losses are too small to be considered for implementing adaptation options to restore them with the minimum system costs for both regions. Losses in the working hours for the remaining seven regions are allocated to adaptation options to develop optimal plans for labor productivity restoration. Fig. 7 shows the ranges between the lower and upper bounds of future working hour losses projected under RCP2.6 and RCP8.5. Despite the types of labor activities, we find that the ranges derived from the ensemble of GCMs projections under RCP8.5 are larger than those under RCP2.6 for all the seven regions. It indicates that the system optimization of productivity restoration can deal with larger uncertainty under RCP8.5 than RCP2.6. If aggressive actions are taken to mitigate the climate change impacts, not only the working hour losses can be limited but also the ranges of working hour losses can be narrowed. For each type of labor activity, we also find that moderate activities have larger ranges than the other two types of activities for most regions under both RCPs (except regions 8 and 9 under RCP2.6, and region 7 under RCP8.5). Extra attention should thus be given to moderate labor activities when adaptation strategies are developed under uncertainty.

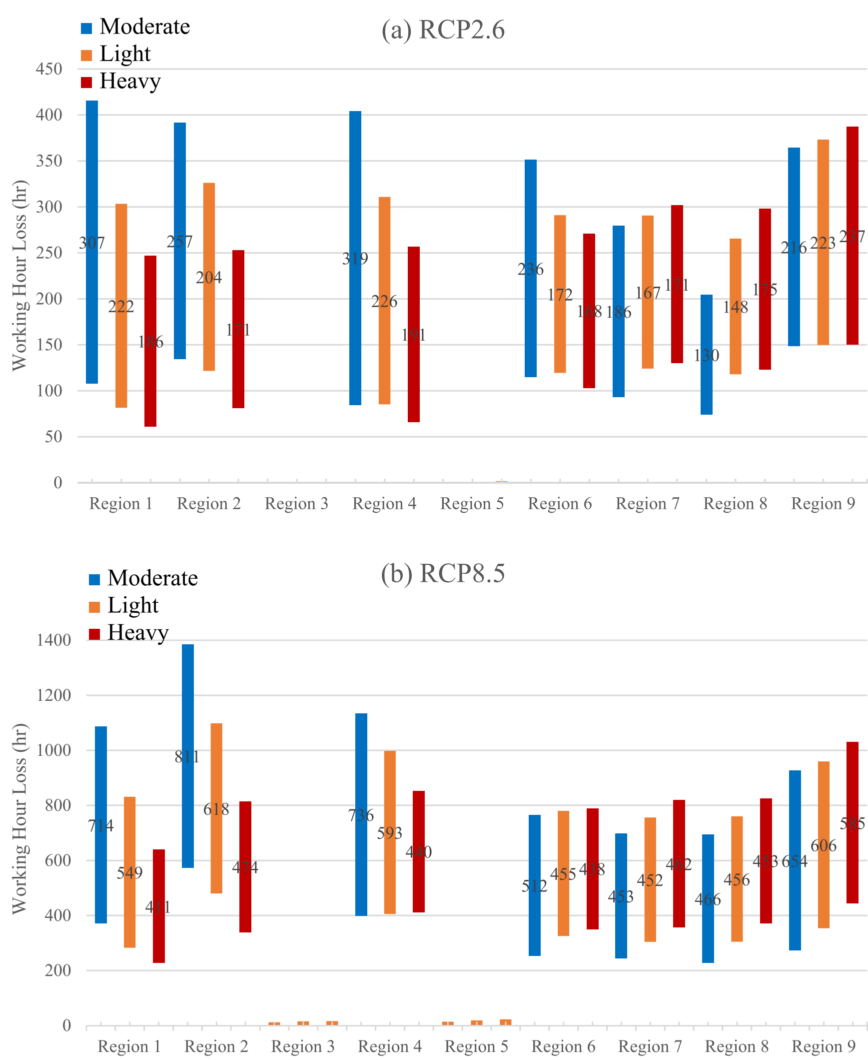

Fig. 7. Ranges between the lower and upper bounds of future working hour losses for three labor types under RCP2.6 (a) and RCP8.5 (b).

3.3. Optimal adaptation measures for restoring labor productivity under uncertainty

We find that the regions with dense populations and developed economies (i.e., regions 7, 8, and 9) have higher management costs and payments for working overtime than the other regions. As for the capital investments on air conditioning, they are directly connected to the local air-conditioning penetration rate while there is no big difference in the market values and the electricity consumption of air conditioning among all regions. A high penetration rate indicates the wide application of air conditioners and the low cost for scale expansions. Regions with a hot and humid climate such as regions 7, 8, and 9 have relatively high air-conditioning penetration rates and, therefore, have low capital investments in adaptation to the amplified heat stress under global warming. Moreover, a high penetration rate indicates high running costs and environmental costs resulting from large energy consumption and carbon footprint. By choosing different combinations of working hour allocations within their corresponding intervals and by considering the constraints of processing capacities in adaptation options, a set of feasible interval solutions can be generated by solving the objective function in the interval programming model and reflecting the underlying uncertainties in both global warming and the productivity restoration management system. Please refer to the Appendix for the detailed solving procedure for productivity restoration through the interval programming model applied to the study area.

Table 3 shows the interval solutions for achieving the optimal labor productivity restoration with the minimum costs under two RCP scenarios. It indicates that the objective function, constraints, and decision variables can be expressed in the form of intervals. For each RCP scenario, the decision alternatives interact with the economic costs for adaptation measures and the constraints relating to processing capacities for three labor types over seven regions. It should be noted that solutions become deterministic when the values of lower and upper bounds are equivalent. For instance, the values of $x^{\pm}_{111}$, $x^{\pm}_{112}$, $x^{\pm}_{113}$, $x^{\pm}_{213}$, $x^{\pm}_{911}$, $x^{\pm}_{912}$, $x^{\pm}_{913}$ under RCP2.6 and $x^{\pm}_{111}$, $x^{\pm}_{113}$, $x^{\pm}_{212}$, $x^{\pm}_{213}$, $x^{\pm}_{813}$, $x^{\pm}_{911}$, $x^{\pm}_{913}$ under RCP8.5 are deterministic, which indicates that these decision variables are insensitive to the uncertainties in model parameters and constraints. We find that all deterministic decision variables are the lost working hours processed by the air conditioning measure. Considering the adaptation measure's processing capacity and its varying cost, decision-makers tend to use the air conditioning up to its limit because it has a lower cost than working overtime. Under RCP2.6, a total of [1,590, 1848] hours are allocated to the option of air conditioning, while [682, 2464] hours are allocated to the working overtime option for all three labor activities across seven regions. Under RCP8.5, a total of [2,811, 2949] hours are processed by the air conditioning measure, while [4,489, 8389] hours are compensated by working overtime (Supplementary Information Figs. S6 and S7). For both RCP scenarios, the air conditioning measure is used up to its corresponding limit due to the relatively low cost compared to the working overtime option. For each labor type, it is consistent that more hours are allocated to air conditioning than to working overtime when the working hour loss is relatively small (under RCP2.6) and below the measures' processing limitation. When the number of hours is too large to being processed by air conditioning, more hours would be allocated to the working overtime measure across all three labor activities under RCP8.5 than under RCP2.6. The positive outcome of implementing the working overtime measure to restore productivity is that the carbon footprint of using air conditioners can be saved.

As shown in Figs. 8 and 9, each region has its preference to address working hour losses due to capacity limitations and cost differences in implementing adaptation options. On one hand, regions with lower air-conditioning penetration rates and less developed economies (such as regions 1, 2, and 4) tend to have the minimum system cost by restoring their working hour losses through working overtime rather than through air conditioning under both RCP scenarios. This is because these regions have relatively high costs for applying air conditioning and low costs for working overtime across all three types of labor activities. On the other hand, regions 7, 8, and 9 which have well-developed economies and high penetration rates of air conditioning tend to restore more of their productivity reductions through air conditioning than working overtime. Working overtime as an adaptation option is most likely to take place at night to compensate for the productivity reduction occurring during the daytime over the planning horizon. It should be noted that the overtime hours are also needed to be processed by air conditioning due to extreme hot nights. We highlight that the inland areas (less developed regions) suffer more working hour losses than the monsoon affecting areas and tend to use the working overtime measure rather than air conditioning to save costs. In the proposed interval programming model, the sub-models for y^{-} and y^{+} aim to determine the lower and upper bounds of the system cost, respectively, under a specific scenario. By solving the objective function of the interval programming model, the optimal minimum system cost $y^{\pm}$ used to fully restore the working hour losses of light, moderate, and heavy labor activities is [1860.75, 8970.59] million dollars under RCP2.6 and [9421.84, 32,309.99] million dollars under RCP8.5. It can also be seen that the value of the upper-bound system cost under RCP2.6 is smaller than the value of the lower-bound system cost under RCP8.5.

4. Discussions

Due to the lack of health data for the study area, we did not consider the costs for preventing and covering work injuries and fatalities caused by the increased heat stress in our study. Nevertheless, we should be aware that the frequency of work injuries may increase due to long-time

Table 3
Optimal solutions (interval numbers) for achieving labor productivity restoration with the minimum cost for three labor activities under RCP2.6 and RCP8.5.

Regions	Scenarios	Air Conditioning (hr)			Overtime (hr)		
		Moderate	Light	Heavy	Moderate	Light	Heavy
1	RCP2.6	[0, 0]	[0, 0]	[0, 0]	[28.5, 227.5]	[81, 222]	[61, 186]
	RCP8.5	[134, 134]	[0, 0]	[0, 0]	[237, 580]	[282, 549]	[227, 411]
2	RCP2.6	[68.4, 68.4]	[23.3, 105.3]	[0, 0]	[66.6, 188.6]	[98.8, 102.8]	[81, 171]
	RCP8.5	[9.6, 9.6]	[20, 158]	[0, 0]	[564.4, 801.4]	[460, 463]	[339, 474]
4	RCP2.6	[85, 103.4]	[85, 113.8]	[66, 108.5]	[0, 215.6]	[0, 112.2]	[0, 82.5]
	RCP8.5	[194, 194]	[211.9, 211.9]	[202.5, 202.5]	[203, 540]	[193.1, 381.1]	[210.5, 237.5]
6	RCP2.6	[97.3, 97.3]	[113.3, 113.3]	[103, 114.3]	[17.8, 138.8]	[5.8 58.8]	[0, 53.8]
	RCP8.5	[184.5, 184.5]	[198.8, 198.8]	[203, 203]	[69.5, 327.5]	[126.3, 256.3]	[148, 235]
7	RCP2.6	[93, 118.2]	[114.5, 114.5]	[105.3, 105.3]	[0, 67.8]	[9.5, 52.5]	[24.7, 65.7]
	RCP8.5	[227.4, 227.4]	[199.5, 199.5]	[159.1, 159.1]	[16.6, 225.6]	[104.5, 252.5]	[197.9, 302.9]
8	RCP2.6	[74, 123.8]	[115.1, 115.1]	[103.6, 103.6]	[0, 6.3]	[2.9, 32.9]	[19.4, 71.4]
	RCP8.5	[196, 196]	[161.7, 161.7]	[163, 163]	[32, 270]	[142.3, 294.3]	[209, 217]
9	RCP2.6	[86, 86]	[100.5, 100.5]	[77, 77]	[63, 130]	[49.5, 122.5]	[73, 160]
	RCP8.5	[76.7, 76.9]	[161, 161]	[106.4, 106.4]	[196.3, 577.1]	[193, 445]	[337.6, 478.6]

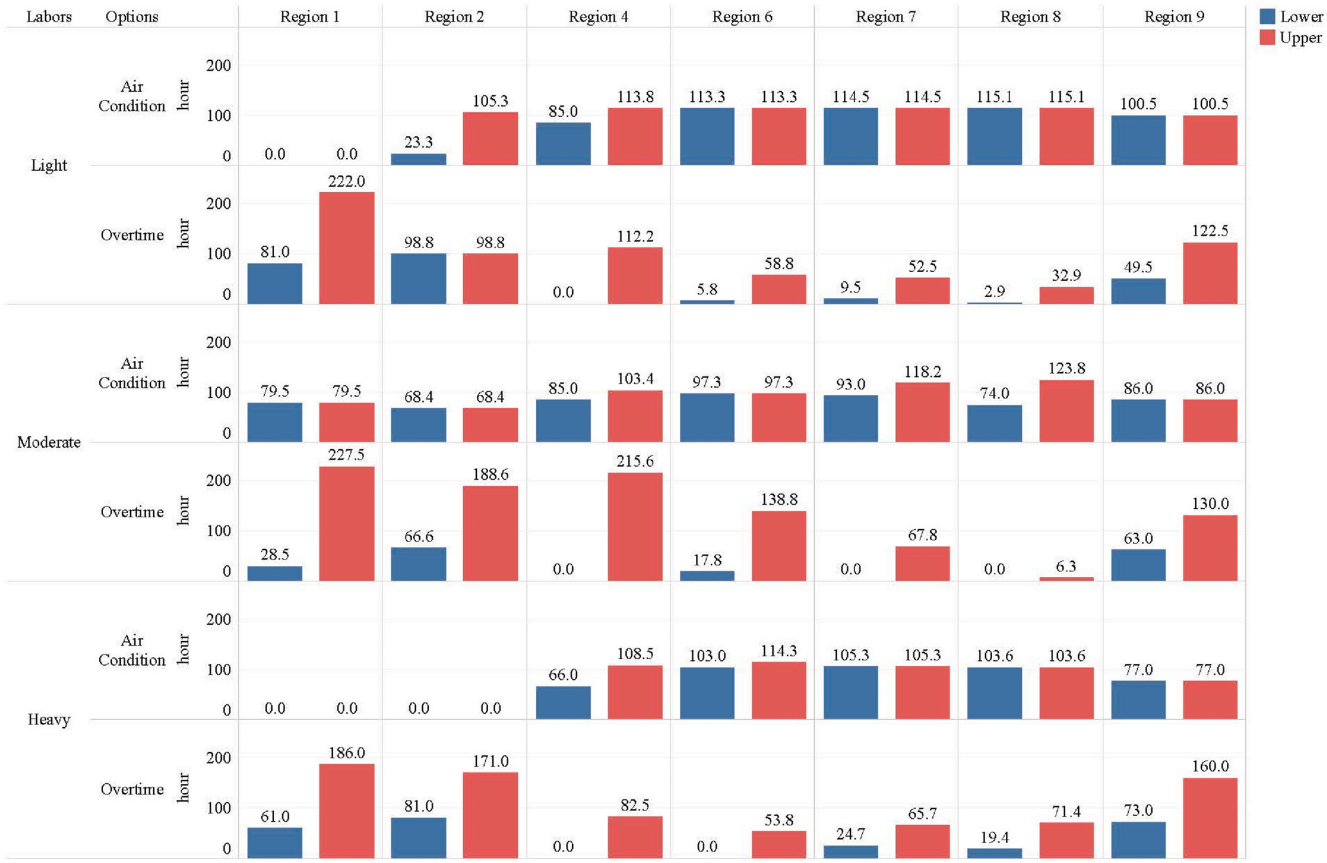

Fig. 8. Optimal decision alternatives for upholding labor productivity with the minimum cost for three labor activities under RCP2.6.

working under heat stress. We also find that the developed regions are more heat-prone areas. For the same increment in the WBGT, the developed regions have a higher frequency of extreme heat days than the less developed regions. It is well known that poorer households tend to reside in more heat-prone areas over the world (Park and Heal, 2013). They are more likely to suffer from health-related problems in the workplace affected by global warming. Contrary to the global distributional impacts, there will be more heat-related work losses in the areas (less developed regions) without heat stress in China. It makes workers in these regions more vulnerable to climate change than those workers in the developed regions due to the low air-conditioning penetration rate, which further enlarges inequities between the developed and the less developed regions. According to the World Bank's statistics and Shared Socioeconomic Pathways scenarios, the gross domestic product (GDP) of China is 14,342,903.01 million dollars in 2019 and 235,000, 000.00 million dollars in 2100 under Shared Socioeconomic Pathways 1 (The World Bank, 2020; van Vuuren et al., 2017). We find that it would cost the nation 32.3 billion dollars which are about 0.2% of China's GDP in 2019 and 0.014% of China's GDP projected in 2100 under the SSP1 scenario to restore the labor productivity level to the baseline period without sound mitigation and adaptation to global warming. Considering the increased labor demands and development needs, actions are thus urgently needed for China to deal with climate change impacts on labor productivity. Consequently, the government needs to take urgent actions to avoid adverse situations by increasing the air-conditioning penetration rate and by reducing the related costs of implementing air conditioning in the inland areas/less developed regions.

5. Summary and conclusions

In this paper, an integrated optimization-based productivity restoration modeling framework is developed for the first time to restore labor productivity with the minimum system cost in the context of global warming. The proposed framework consists of an ensemble of GCMs projections, estimation of potential labor capacity reduction, and an interval programming model, which facilitates the long-term and systematic planning of productivity restoration in an uncertain environment. Specifically, five GCMs projections under RCP2.6 and RCP8.5 are adopted to provide the daily time series of air temperature and relative humidity in order to calculate heat stress represented by the WBGT. The ensemble of GCMs also helps to explore the ranges in the projected heat stress under global warming. The daily WBGT is then used to predict the changes in labor productivity/working hour loss in a changing climate through the empirical relationship between heat stress and labor capacity. Moreover, an interval programming model is formulated to provide optimal adaptation strategies to achieve the minimum system cost under uncertainty. In general, the proposed framework has advantages of (i) quantifying global warming impacts on labor productivity; (ii) adequately incorporating various uncertainties inherent in climate projection, labor capacity estimation, and identification of adaptation options into the systems analysis; (iii) helping decision-makers to identify and implement the cost-effective adaptation strategies for upholding labor productivity under climate change.

The proposed framework has been applied to examine climate change impacts on labor productivity and the related costs for implementing optimal adaptation strategies in China. Our findings indicate that the intensification of heat stress will lead to large decreases in the labor capacity all over China except for regions 3 and 5 (the Tibetan Plateau) under both RCPs by the end of the 21st century. Most regions exhibit that moderate labor activities are suffering greater losses in working hours than light or heavy activities for the combination of labor capacity reduction and population of involved workers. With the plausible range of working hour losses based on the ensemble of multi-model projections, a variety of decision alternatives of working hour allocation

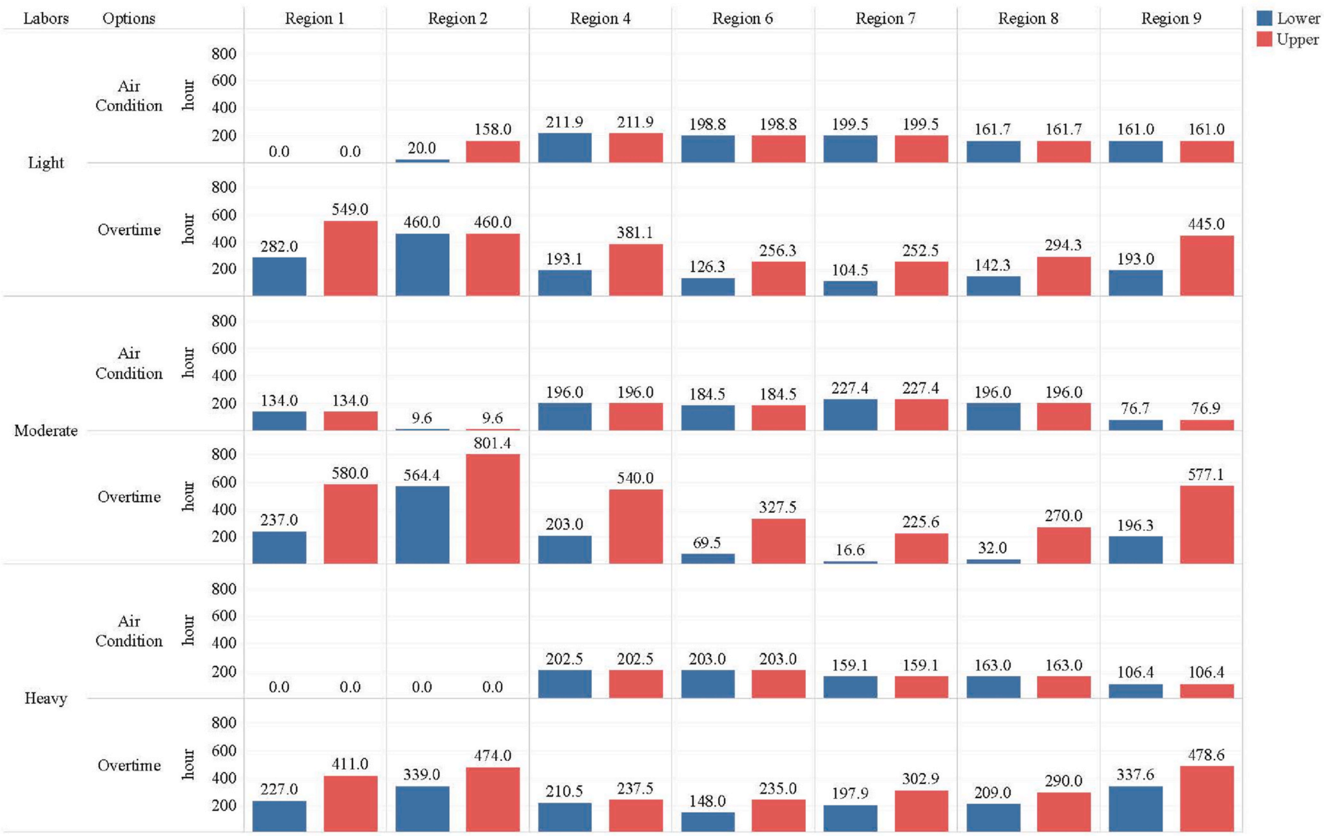

Fig. 9. Optimal decision alternatives for upholding labor productivity with the minimum cost for three labor activities under RCP8.5.

to adaptation options are obtained through the established interval programming model with uncertain parameters and constraints. We find that regions with dense populations, developed economy, and relatively high air-conditioning penetration rates (i.e., regions 7, 8, and 9) have higher costs of working overtime and lower costs of air conditioning than the other regions. As a result, these regions tend to have their productivity restored through air conditioning rather than through working overtime to achieve the minimum system cost. Other less developed regions tend to have more working hours restored through the working overtime option than through air conditioning due to their low air-conditioning penetration rates and low costs for working overtime. Since the less developed regions are not the heat-prone areas in China, residents in these regions will be less adaptive to the intensified heat stress. This can result in more heat-related injuries taking place in the less developed regions and enlarged inequities between the developed and the less developed regions. In addition, the minimum system costs estimated for productivity restoration of light, moderate, and heavy labor activities are [1.86, 8.97] billion dollars under RCP2.6 and [9.42, 32.31] billion dollars under RCP8.5. It is noteworthy that the value of the upper-bound system cost under RCP8.5 is about 0.2% of China's GDP in 2019. Considering the increased labor demands and development needs, aggressive mitigations and adaptations are urgently needed to alleviate climate change impacts on the labor productivity level.

Our study has significant implications for supporting decision-makers to make informed adaptation plans in terms of labor productivity in the context of global warming. Future studies would be undertaken to conduct high-resolution regional climate model projections for improving the simulation of geographical features and extreme events. We will investigate the potential impacts of the improved characterization of geographical features and extreme events on the optimization processes and will compare the conclusions against those derived from GCMs. Furthermore, the proposed framework of Chinese labor productivity is applicable to other countries for designing global climate policies. It should be noted that there are several limitations in our study. The relationship between heat stress and labor capacity reduction is estimated based on the empirical, epidemiological exposure-response function which is developed based on limited studies. Different regions could have different responses to the exposure. More comprehensive studies on quantifying the relationship between heat stress and labor capacity reduction should be conducted with considering partitions of outdoor/indoor activity, workers' experience, adaptation effectiveness, and others. The negative effects of adaptation measures are also not studied thoroughly. For instance, more installations of air conditioners could increase outdoor temperature and potentially exacerbate the urban heat island effect. Plus, more electricity consumption for proactive cooling measures could lead to more CO2 emissions. Developing an effective adaptation policy balanced with climate mitigation will be a promising direction in future studies.

CRediT authorship contribution statement

Jinxin Zhu: Conceptualization, Methodology, Validation, Formal analysis, Writing – original draft. **Shuo Wang:** Conceptualization, Writing – review & editing, Supervision, Investigation, Project administration, Funding acquisition. **Dagang Wang:** Validation, Writing – review & editing. **Xueting Zeng:** Writing – review & editing. **Yanpeng Cai:** Writing – review & editing. **Boen Zhang:** Writing – review & editing.

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.

Acknowledgments

CMIP5 data used in this paper are freely available at https://esgf-node.llnl.gov/projects/cmip5/. We acknowledge and thank the climate modeling groups (listed in Supplementary Information Table S1) in the World Climate Research Programme's Working Group on Coupled Modelling (which is responsible for CMIP5) for generating their model outputs and making them available. This research was supported by the National Natural Science Foundation of China (Grant No. 51809223) and the Hong Kong Research Grants Council Early Career Scheme (Grant No. 25222319). The authors declare no competing financial interests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.129083.

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