An integrated assessment of provincial economic damages from climate change in China

Abstract

Assessments of climate change damage at the provincial scale are crucial to designing climate policies in China, ensuring the efficiency and fairness of provincial mitigation strategies. While extensive research has addressed climate damages at the global and national scale, few studies have estimated China's subnational economic damages from different sectors and evaluated the equilibrium impacts. Here, we develop an integrated assessment framework that combines climate projections, econometric analyses, process-based emulators, and a provincial computable general equilibrium model. We use this framework to construct estimates of economic damages from three channels – labor productivity, energy demand, and agriculture yield – in China's provinces under two climate change scenarios (Shared Socioeconomic Pathway (SSP) 126 and 245) for 2060. The collective impacts of the three damage channels result in national GDP changes of -5.0% and -3.3% in 2060 under the SSP245 and SSP126 scenarios, respectively. Importantly, these damages are distributed unequally across provinces, exhibiting a discernible north-south pattern: northern provinces experience relatively modest loss rates, while central and southern provinces incur more substantial losses.

1 Introduction

China is actively promoting a greener economy to mitigate climate change. Currently, the national targets for emissions reduction are allocated to each province. Policymakers need to have information about the provincial costs and benefits of emissions reduction. Several studies have explored the considerable disparities in costs for reducing emissions in various provinces due to different industrial and energy structures (Guo et al., 2023). However, the benefits of emissions reduction, or conversely, the "damages" from climate change, are often disregarded at the sub-national scale. Understanding the provincial benefits of emissions reduction is crucial for incentivizing provinces to take action, ensuring the fair distribution of emissions reduction responsibilities, and developing province-specific adaptation strategies.

While the literature has addressed climate damages at the global scale (Piontek et al., 2021), country scale (Kompas et al., 2018; T. Wang et al., 2020), or sub-national scales (Ciscar et al., 2011; Hsiang et al., 2017), the studies that comprehensively estimate climate damages of the China's provinces are limited. By using Earth System Models (ESMs), studies have assessed the physical risk of extreme events (e.g., flood, heat stress, etc) under different climate change scenarios among China's provinces (Wu et al., 2017). Some of them further evaluated direct economic damages (e.g., damaged houses) by applying loss curves to the events (Wu et al., 2019). These studies primarily focus on certain events and rarely consider the equilibrium economic impacts propagated across different regions and sectors. Wang et al. (2022) evaluated the social cost of carbon in China's provinces relying on rough estimates between temperature rise and economic growth. They did not distinguish the damage functions and sources between provinces. A recent study estimated the labor productivity impact of climate change for each province by using a Computable General Equilibrium (CGE) model but did not consider other damage channels (Zhao et al., 2024). In summary, the potential equilibrium impacts of climate change resulting from different damage channels among China's provinces remain unclear.

In this paper, we aim to develop an integrated assessment framework that resolves China's economy at a provincial scale, involves three damage modules, and captures the equilibrium impacts. Based on empirical evidence and emulators of process-based models, we construct three damage modules that incorporate the nonlinear relationships between climate variables and labor productivity, energy demand, and crop yield. We then employ the data from the Coupled Model Intercomparison Project phase 6 (CMIP6) to the damage modules and impose the damage shocks to a multi-sector multi-region CGE model that resolves China at the provincial scale. The framework is applied to answer two primary questions: How do the economic impacts of climate change vary across provinces? What are the total economic damages considering the spillover effects between regions and sectors?

2 Methods

We developed an integrated assessment framework that combines ESMs, damage modules, and a provincial CGE model (Figure 1). The ESMs project the climate variables at the grid scale, capturing the anomaly of climate conditions under various climate change scenarios. These climate variables are then fed into the damage modules to calculate the resulting changes in different sectors, including the change rates of labor productivity, energy demand, and crop yield. The grided losses are then aggregated to the provincial scale, serving as shocks to the parameters in the provincial CGE model. This framework allows for a thorough evaluation of the economic impacts of climate change at the provincial level, considering multiple sectors and their interconnected dynamics.

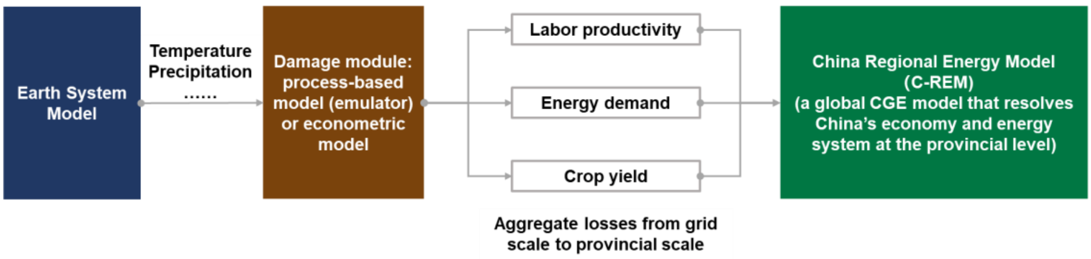

Figure 1 The structure of the integrated assessment framework.

We considered provincial economic damages under two emissions trajectories consistent with the Shared Socioeconomic Pathway (SSP) 126 and SSP245 scenarios in CMIP6. SSP126 is a low emissions pathway that we interpret as the case of China achieving carbon neutrality in 2060; SSP245 is a medium-to-high emissions pathway that we interpret as the case that China remains the carbon policy stringency before announcing the carbon neutrality target. We constructed two baseline scenarios, in which we imposed emissions constraints of the pathways, and two damage scenarios, in which we further imposed the climate damage shocks. The economic damages were estimated by comparing the damage scenarios with the corresponding baseline scenarios.

The climate data utilized in this study are sourced from six ESMs in CMIP6, including EC-Earth3-Veg-LR, MIROC6, FGOALS-g3, GFDL-ESM4, NorESM2-MM, and MPI-ESM1-2-HR. These models cover a range of Equilibrium Climate Sensitivity (ECS), representing the uncertainties from ESMs and making our analysis robust. We used the downscaled projection data of each model at

1/4-degree horizontal resolution from NASA Earth Exchange Global Daily Downscaled Projections (Thrasher et al., 2022) to fulfil the spatial resolution requirements of provincial assessment. Climate variables spanning from 2050 to 2080 were used to reflect the climate conditions in 2060.

We used the China Regional Energy Model (C-REM) to simulate the economic impacts. The model is a multi-sector, multi-regional, dynamic recursive CGE model that has been widely used in China's energy and climate policy studies (Li et al., 2018; Qu et al., 2020; Zhang et al., 2013). The model's regions include 30 provincial administrative areas of mainland China and 4 international regions. It has been updated to version 4.0 recently which employs the latest data from the Global Trade Analysis Project (GTAP) 11 database (Aguiar et al., 2022), incorporates negative emissions technologies, and extends projections to 2060.

To estimate labor productivity impact, we calculate the Wet Bulb Globe Temperature (WBGT) to measure heat stress, which is a good index incorporating humidity and temperature effects (Kjellstrom et al., 2018). The equation $(11),(2)$ shows the components of WBGT, where *RH* means relative humidity and *Ta* means temperature, with the spatial resolution of 1/4 degree and the time resolution of 1 day. We employed the "2+4+2" method, as outlined by (Kjellstrom et al., 2018), to approximately estimate the hourly WBGT based on the daily WBGT. Under the assumption of an 8-hour workday, in accordance with Chinese labor law, we considered that workers spend 2 hours under the average temperature, 2 hours under the maximum temperature, and 4 hours under the mean level of average temperature and the maximum temperature. Subsequently, the estimated WBGTs were put into the Exposure-Response Functions (ERFs) specially developed for China for different (eq.(3),(4)), which are adjusted by Chinese occupational health standards (Cheng et al., 2023). The parameters within these functions vary based on different work intensity levels, as outlined in

Table 1. Finally, the loss rates in each grid were weighted by the grid-level population projection developed for China (Chen et al., 2020) and aggregated to the provincial level. These loss rates were applied to the C-REM production functions as an increased demand of labor for a unit of sectoral output.

$$WBGT = 0.7 \times Tw + 0.3 \times Ta \tag{11}$$

$$\begin{aligned} Tw = Ta \times \arctan\left[0.151977 \times (RH + 8.313659)^{\frac{1}{2}}\right] + \arctan(Ta + RH) \\ - \arctan(RH - 1.676331) \\ +0.00391838 \times RH^{\frac{3}{2}} \times \arctan(0.023101 \times RH) - 4.6860352 \end{aligned} \tag{2}$$

$$y = 0.5\left[1 + \operatorname{erf}\left(\frac{WBGT - \mu}{\sigma\sqrt{2}}\right)\right] \tag{3}$$

$$\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x \exp(t^2)dt \tag{4}$$

Table 1 Function parameters for the Chinese ERF

Work Intensity Level	μ	σ
200W	35.129	3.503

300W	33.492	3.948
400W	32.492	3.948

Note: 400W corresponds to agriculture and construction, 300W corresponds to manufacturing and 200W corresponds to service.

To estimate energy demand impact, we adopted the empirical estimates of semi-elasticities between climate variables and energy demand in four kinds of economic sectors (De Cian & Sue Wing, 2019). These semi-elasticities measure the response of demand for electricity, natural gas, and petroleum associated with heating and cooling as a function of exposure extent to hot (>27.5 °C) and cold (<12.5 °C) days for tropical countries and temperate countries. We calculated the change of hot days and cold days in the future (relative to history) under SSP126 and SSP245 scenario, respectively. The change rates for different energy types in different sectors were then calculated by equation (5), where $\Delta Energy\_Consumption_{ijst}$ means the change rates of energy demand, β_{ijst} means the semi-elasticity estimates, and ΔDay_{it} means the change of hot or cold days, i means tropical or temperate region, j means energy type, s means sectors, and t means year. Finally, the grid-level change rates of energy demand were aggregated to the provincial level to be applied to the C-REM to modify the shift parameters in energy demand functions.

$$\Delta Energy\_Consumption_{ijst} = \beta_{ijst} \times \Delta Day_{it} \tag{5}$$

To estimate crop yield impacts, we adopted the emulators trained by the outputs from the Global Gridded Model Intercomparison Project (GGCMI) Phase 2 experiment (Franke et al., 2020). These emulators combine the advantageous features of statistical and process-based crop models, which can return the climatological-mean yield response of anomalies in temperature and water supply in the future compared to the historical level. We considered five crops (maize, rice, soybean, and spring and winter wheat) and calculated aggregated crop yield change rates for each province. The change rates were applied to the C-REM as changes in productivity in the agriculture sector.

3 Results

Firstly, we find that climate change will induce significant losses in labor productivity across China in 2060, with heterogeneous economic impacts among provinces. Figure 2 shows the loss of productivity across China in different scenarios and work intensities, the population with high exposure intensity (400W) accounts for the most of total losses (Figure 2 (a) and (d)). The medium exposure intensity (300W) (Figure 2 (b) and (e)) and low exposure intensity (200W) (Figure 2 (c) and (f)) show similar spatial distribution pattern with high exposure intensity, the loss of productivity is mainly in southern provinces, especially in Guangxi and Guangdong province. In addition, the loss rates in SSP 245 are significantly higher than SSP126. Under the SSP245 scenario, the national average loss rate of labor productivity for low-, middle- and high-intensity work will reach 0.97%, 1.71%, and 2.16%, respectively. These losses decrease by 17% under the SSP126 scenario. Provinces situated in lower latitudes experience more pronounced effects compared to those in higher latitudes. For instance, Guangxi and Guangdong suffer the most productivity losses among all the provinces, with rates approximately double the national average. These labor losses contribute to a national GDP decrease of 1.2% and 0.9% for the SSP245 and SSP126 scenarios, respectively. Provincial GDP losses vary from 0.3% (Heilongjiang) to 2.0% (Guangxi) under the SSP245 scenario and from 0.3% to 1.5% under the SSP126 scenario (Figure 4 (a) and (e)).

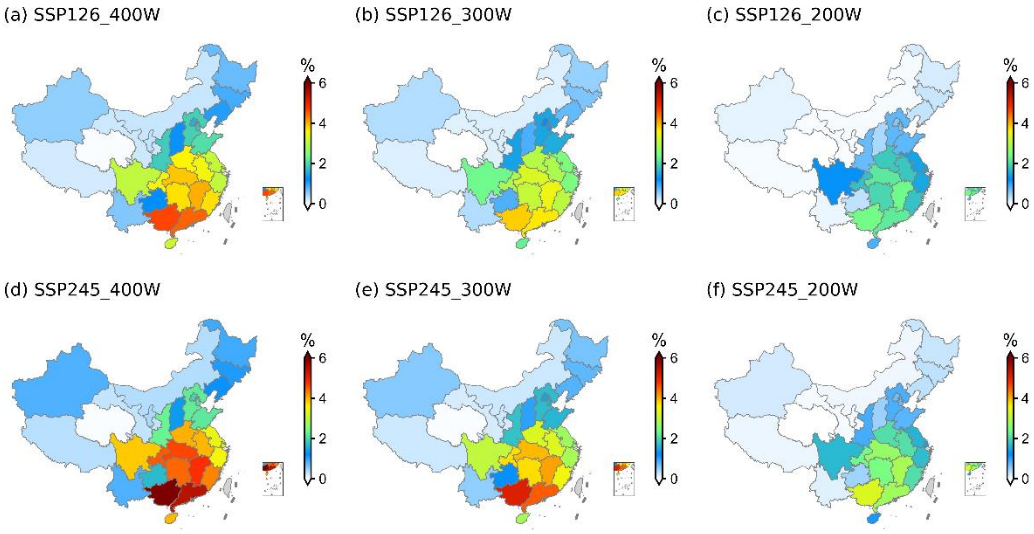

Figure 2 Provincial loss rates of labor productivity in different scenarios and work intensities.

Secondly, we find that the changes in energy demand are unevenly distributed among provinces and economic sectors under climate change. Provinces in temperate regions, particularly those in middle latitudes like Sichuan and Henan, commonly experience more significant shocks in energy demand as temperatures rise. Take electricity as an example, Figure 3 illustrates that the electricity demand will increase significantly across China, especially in central provinces, such as Sichuan, Henan. The commercial will be the largest contributor to the demand increase (Figure 3 (c) and (g)). Other sectors, agriculture, industrial and residential, also have increase in the demand for electricity, and the increase is mainly from central and southern regions in China, with the similar distribution pattern to commercial sector. Figure 3 also illustrates that the demand for electricity across China will be significantly higher in SSP 245 than in SSP 126. These shocks propagate across regions and sectors and the induced changes in provincial GDP range from +0.4% (Qinghai) to -2.7% (Tianjin) in 2060 under the SSP126 scenario (Figure 4 (b) and (f)).

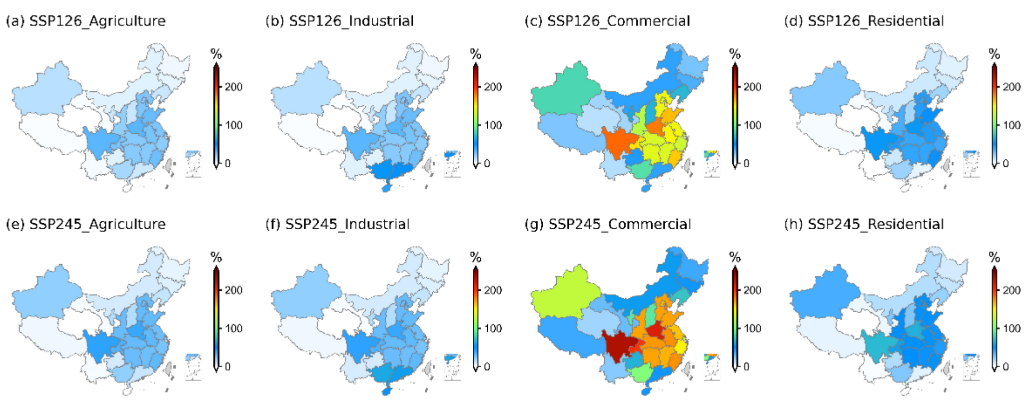

Figure 3 Provincial change rates of electricity demand in different scenarios and sectors.

Thirdly, we find that climate change leads to yield losses across most provinces, but certain regions experience increased yields for specific crops (Figure 4 (c) and (g)). The aggregated productivities of the agriculture sector at the provincial level exhibit changes ranging from -27% (Guangdong) to 0% (Gansu) under the SSP245 scenario and from -17% (Shanghai) to +12% (Shanxi) under the SSP126 scenario. Consequently, induced changes in provincial GDP span from -4.8% to +2.0% under the SSP245 scenario and from -7.4% to +0.7% under the SSP126 scenario.

The collective impacts of the three damage channels result in national GDP changes of -5.0% and -3.3% in 2060 under the SSP245 and SSP126 scenarios, respectively. The distribution of changes in provincial GDP reveals a general north-south pattern: northern provinces experience relatively modest loss rates or even gain (e.g., Gansu), while central and southern provinces exhibit larger loss rates, notably Hainan (Figure 4 (d) and (h)). Importantly, the magnitude of the equilibrium impact closely aligns with the simple sum of the results from the three channels at the national level, but discrepancies emerge at the provincial scale. This underscores the imperative need for the development of an integrated framework at the provincial scale.

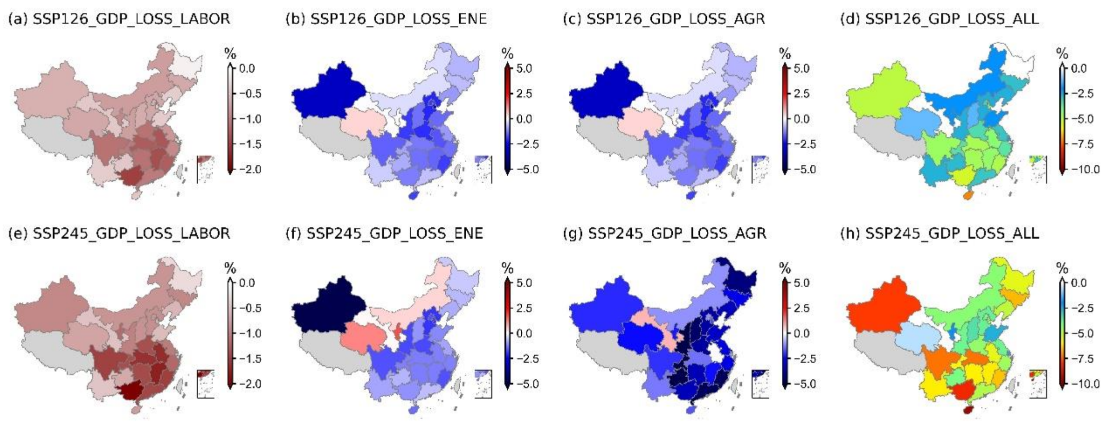

Figure 4 Provincial GDP loss rates for three damage channels and the collective impacts under SSP126 and SSP245 scenarios

4 Concluding remarks

Our study highlights that it is crucial to consider the economic damages from climate change at the provincial scale and introduce various damage channels into an integrated framework. This approach offers valuable policy implications for the formulation of effective mitigation and adaptation strategies for China's provinces.

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