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Future growth pattern projections under shared socioeconomic pathways: a municipal city bottom-up aggregated study based on a localised scenario and population projections for China

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ABSTRACT

Precise multi-scenario projections of future economic outputs based on localised interpretations of global scenarios and major growth drivers are important for understanding long-term economic changes. However, few studies have focussed on localised interpretations, and many assume regional uniformity or use key parameters that are recursive or extrapolated by mathematical methods. This study provides a more intuitive and robust economic framework for projecting regional economic growth based on a neoclassical economic model and shared socioeconomic pathways (SSPs) scenarios. A non-uniform version of SSP2 (the middle-of-the-road scenario) was developed, and more detailed population projections for China were adopted using municipal-level data for 340 districts and parameter settings based on China's recent development. The results show that China's GDP will vary substantially across SSPs by 2050. Per capita GDP ranges from 19,300 USD under SSP3 (fragmentation) to 41,100 USD under SSP5 (conventional development). Per capita GDP under SSP1 (sustainability) is slightly higher than under SSP2, but lower on average than under SSP5. However, SSP1 is a better choice overall because environmental quality and equity are higher. Per capita GDP growth will generally be higher in relatively low-income regions by 2050, and the upper-middle-income provinces will become China's new engine for economic growth.

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1. Introduction

The level of global environmental change, especially climate change, depends on the scale of economic activities and technologies used. Therefore, scenarios of future

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human impacts on the global environment are built on projections of economic output (Leimbach et al., 2017). The increasing demand for such projections is hindered by a shortage thereof regarding the development of the global economy, particularly the lack of multi-scenario projections based on local interpretations. However, it is not easy to integrate multiple growth drivers into a consistent framework to generate economic scenarios, understand the dynamics and effects of these drivers in the medium and long terms, and thus identify possible future growth patterns (Pedde et al., 2020; Riahi et al., 2017).

As long-term economic projections are highly uncertain (Vlah Jerić et al., 2020), international economic institutions such as the IMF (2020) and World Bank (2020a) tend to base their outlooks on short-term working hypotheses. In general, previous efforts to develop global environmental scenarios have generated economic output scenarios by assuming an exogenous regional growth rate of GDP or productivity (Gallopín & Raskin, 2002; IEA, 2009; Kemp-Benedict et al., 2002; Nakićenović & Swart, 2000; Raskin et al., 2002), or by using complicated models involving mathematical recurrence or trend extrapolation in the projection of major growth drivers (Hertel, 1999; Huang et al., 2019; Jiang et al., 2018; Leimbach et al., 2017; Lejour et al., 2006).

The GDP projection framework in this study is based on the shared socioeconomic pathways (SSPs) recently proposed by the Intergovernmental Panel on Climate Change (O'Neill et al., 2014; van Vuuren et al., 2014), and a well-understood neoclassical economic model developed by Abramovitz (1956) and Solow (1957). Basic SSPs describe plausible alternative trends in the evolution of society and natural systems over the 21st century at the world and large world region levels. They consist of two elements: a narrative storyline and set of quantified measures of development. The SSP storylines use five pathways to describe the challenges faced at levels of social and economic development in terms of mitigation and adaptation to climate change. The scenarios are discussed in more detail in Section 2; however, the five pathways are SSP1 (sustainability), SSP2 (middle-of-the-road), SSP3 (fragmentation), SSP4 (inequality), and SSP5 (conventional development). The scenarios can be used as reference cases for climate change analysis as they provide transparent underlying narratives for determining model parameters and an internally consistent basis for detailed local- and regional-scale designs based on GDP scenarios (Kriegler et al., 2012; O'Neill et al., 2014, 2017). The neoclassical production function represents a technological relationship that expresses the level of output as a function of the level of inputs such as labour and capital. Over the last century, many studies have focussed on finding a specific form of production function. The results showed that if the elasticities of output to factor inputs are constant and technical progress is Hicksian-neutral, then a Cobb–Douglas production function would provide the best statistical fit for the empirical data (McCombie & Thirlwall, 1995). While the neoclassical growth theory is certainly being challenged by endogenous growth theory (Aghion & Howitt, 1998), which represents the new generation of economic growth research, the Solow–Swan model and Cobb–Douglas function remain relevant and commonly used tools to explore historical and future economic growth paths. Therefore, the Cobb–Douglas function was adopted as the basic analytical tool in this study.

The research of Leimbach et al. (2017) was used to guide the scenario generation method in terms of the main driving forces of GDP growth. However, for the projection of capital accumulation, a different, more intuitive and robust method is adopted instead of mathematical recursive equations or trend extrapolation. In terms of data selection and parameter setting, many previous studies adopted global averages to set Chinese parameters (Crespo Cuaresma, 2017; Dellink et al., 2017; Leimbach et al., 2017) or their parameter sources were ambiguous (Huang et al., 2019; Jiang et al., 2018). In contrast, in this study, the assumptions and calculations of the key parameters are based on localised historical data and theoretical economic reasoning. In particular, in terms of population data, the team's existing research results on population projections under different SSPs were used¹ (Guo et al., 2019). The population projection data are not only accurate at the municipal administrative level, but also reflect the slow growth and basic stability of the fertility rate since China proposed the 'Comprehensive Two-Child' policy in 2015, and importantly, the ageing trend of China's society, which is expected to continue deepening in the future. In addition, considering China's vast territory and significant regional development differences, this study develops an alternative version of SSP2, in which the challenges of mitigation and adaptation are on average moderate in each region, but vary greatly within regions rather than being more uniformly middle-of-the-road, as assumed in the SSP2 narrative presented in most SSP studies (O'Neill et al., 2017). Therefore, the projection in this study is not a simple function fitting or trend extrapolation, but a long-term scenario simulation based on the reality of economic development and the historical background of China to reflect feedback on the internal laws of the economic development process under different development patterns in the future.

After nearly 40 years of rapid economic growth, with an average annual GDP growth rate of 9.45% from 1979 to 2018, China, the largest developing country in the world, is facing great pressures. These stem from an economic downturn, environmental governance issues, and the need for economic transformation and upgrading (Matyushok et al., 2021; National Bureau of Statistics, 2019; Zhang et al., 2020). The Chinese government is committed to shifting away from its original extensive economic development pattern and transforming it into an environmentally friendly, resource-saving, high-quality, sustainable development pathway, although this is not easy given the size of China's economy (Li & Li, 2019). As one of the most influential countries worldwide, China's choice of development pattern will profoundly impact global economic development and climate change. The projections in this study provide a valuable framework for the discussion of the future and a reflection on possible actions for China in the context of climate change.

In this study, a long-term GDP projection framework is established, with technological progress as well as human and physical capital formation as the major drivers of growth under the five SSPs. GDP projections are generated based on a sound understanding of the drivers of economic growth and scenario generation. Section 2 describes the method used to generate GDP projections in detail. Section 3 presents and evaluates five GDP scenarios based on refining, projecting, and aggregating the GDP of 340 districts in China at the provincial and national scales. Section 4 presents the conclusions and discussion.

2. Methods and materials

2.1. SSP narratives

The underlying SSP narratives depict the following five typical global situations differentiated by climate change mitigation and adaptation challenges (Kriegler et al., 2012; O'Neill et al., 2014, 2017).

SSP1 (sustainability): The world has made progress in sustainability, and the rapid development of low-income regions means that the emphasis on economic growth shifts toward a broader emphasis on human well-being and better environmental conditions, even at the expense of somewhat slower economic growth over the long term. The world faces low mitigation and adaptation challenges.

SSP2 (middle-of-the-road): The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Moderate challenges arise in terms of both mitigation and adaptation.

SSP3 (fragmentation): This path involves a fragmented world with regional conflicts and competitiveness. The world is characterised by a high degree of poverty and faces significant mitigation and adaptation challenges.

SSP4 (inequality): This path describes a highly unequal world in which large numbers of poor people in various regions face significant adaptation challenges, whereas advanced wealthier regions have developed alternative technologies to reduce their mitigation challenges.

SSP5 (conventional development): Under this path, the world is growth-oriented and uses conventional technologies (especially energy conversion technologies based on fossil fuels). Therefore, it faces significant mitigation challenges.

2.2. Cobb–Douglas production model

The Cobb–Douglas function is widely used by economists because it has the advantages of algebraic tractability and provides a fairly good approximation of the production process (Cobb & Douglas, 1928). Its basic form is:

$$Y(t) = A(t)K(t)^\alpha L(t)^{1-\alpha} \quad (1)$$

where Y is output (GDP), A is total factor productivity (TFP), K is capital stock, L is labour inputs, α is the output elasticity of capital, and t represents time. In this equation, technological progress is Hicksian-neutral; that is, capital and labour can expand equally in the production of technological innovations. Another advantage of the Cobb–Douglas production function is that the estimated elasticity corresponds approximately to the actual factor income share (McCombie & Thirlwall, 1995). Figure 1 depicts the relationships between the key determinants of the model. The calculations and reasoning underlying the main growth drivers in future scenarios are described in detail below.

2.2.1. Labour and human capital

Labour inputs are derived from SSP population projections (Kc & Lutz, 2017). There are three components of labour inputs in the Cobb–Douglas function: the number of

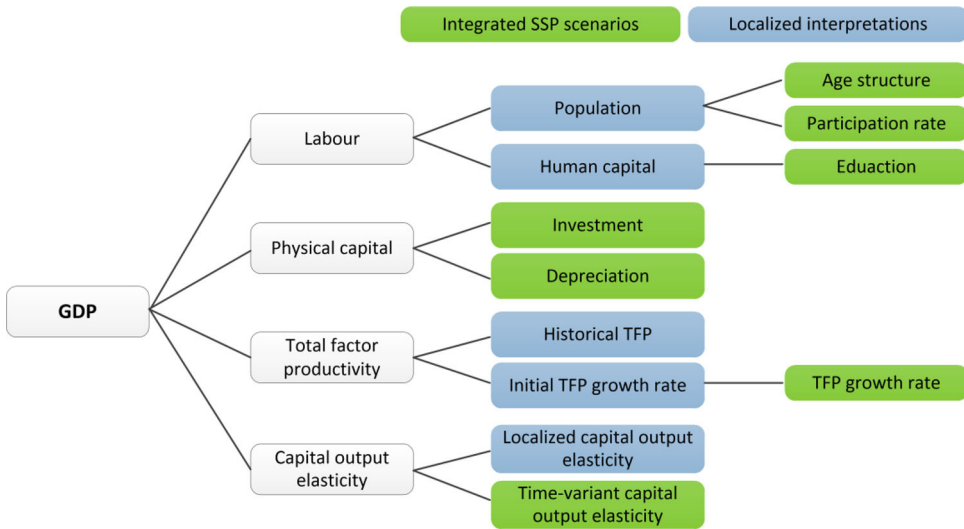


Figure 1. Schematic overview of the Cobb–Douglas production model under the SSP scenarios. Source: Prepared by the authors.

working age people (WAP), labour force participation rate (LFPR), and education levels (H):

$$L(t) = \sum_q H(t) * LFPR(q, t) * WAP(q, t) \tag{2}$$

Equation (2) also includes a time index t and index q , which distinguishes two age groups: those aged 15–64 years (q_1) and 65 and above (q_2). Each working age group has a specified LFPR based on historical development trends in China for the different age groups and the latest data from the sixth national census. On this basis, it is assumed that the LFPR for the population aged 65 years and above is constant at the 2015 level (20%) under the different SSPs, as it is expected to have only a second-order effect. The LFPR of the population aged 15–64 years in the base period 2015 was 77%. It is assumed that the LFPR for this group has different levels that converge across the SSP scenarios of future development, as shown in Table 1. In particular, it is assumed that the high economic growth under SSP5 is supported by a high LFPR (q_1). In the case of SSP3, where the development pathway is opposite to that of SSP5, a very low LFPR (q_1) is assumed. SSP1 and SSP2 have moderate LFPR levels. Under SSP1, a well-functioning labour market allows for a higher participation rate, but people also have a strong preference for leisure time. Thus, the ultimate convergence target is slightly lower than that under SSP2, and the convergence time is longer. In addition, it is assumed that under SSP2, regions, which are grouped according to different income levels, reach different convergence levels according to their own development pace, and the LFPR (q_1) in high-income regions decreases faster than it does in low-income regions. SSP4 describes a fragmented and highly unbalanced world in which LFPR (q_1) is generally lower than that under SSP5. Barriers to interregional labour mobility are likely to exist, especially in middle-income and low-income areas.

Table 1. Quantitative settings for the labour force participation rate of the population aged 15–64 years (LFPR (q_1)) under different SSPs.

Pathway	SSP1	SSP2	SSP3	SSP4	SSP5
Convergence target (%)	68	LM: 70 UM: 70 HI: 70	60	LM: 71 UM: 74 HI: 78	80
Convergence time (Years)	120	LM: 120 UM: 100 HI: 80	80	LM: 200 UM: 150 HI: 100	100

Note: Under SSP2 and SSP4, the convergence target and convergence time differs across regions depending on their income levels, which are grouped into three categories,² lower-middle income and below (LM), upper-middle income (UM), and high income (HI).

Source: According to Kc and Lutz (2017), Leimbach et al. (2017), O'Neill et al. (2017) and authors' assumptions.

Therefore, the LFPR (q_1) in these areas is far lower than that in high-income areas, and the convergence time is longer (Leimbach et al., 2017; O'Neill et al., 2017).

The data underlying the projections for the total and working age populations of China's 340 administrative units under different SSPs for 2015–2050 were derived from the team's existing research results (Guo et al., 2019). By multiplying the LFPR by the corresponding WAP, the actual number of working people in the population is obtained. The next step is to consider the quality differences in the labour force due to different levels of education. The mean years of schooling (*MYS*) of the WAP were used as a measure of education. Given the availability of data, the *MYS* of the WAP for 31 provinces (excluding Hong Kong, Macao, and Taiwan) is used to express the *MYS* of the WAP in the municipal administrative units included in each province. The *MYS* of each province in 2015 was obtained from the China Human Capital Index Report 2017 (Li, 2017). Following Psacharopoulos (1994) and Hawkworth (2006), education can be calculated using the following equation:

$$H = \begin{cases} e^{0.134 \cdot MYS}, & MYS \leq 4 \\ e^{[0.536 + 0.101 \cdot (MYS - 4)]}, & 4 < MYS \leq 8 \\ e^{[0.94 + 0.068 \cdot (MYS - 8)]}, & MYS > 8 \end{cases} \quad (3)$$

In general, education-based human capital measurement should be a monotonic increasing function of the overall education level (Koman & Marin, 1997). Referring to the historical *MYS* trend for China's labour force over the past 30 years (1985–2015), the linear growth method is used to determine changes in the years of education in the future, as shown in Table 2. Under SSP1 and SSP5, there is a high level of educational investment to improve human capital and accelerate population transformation. The *MYS* increased significantly every year. In the fragmented SSP3 world, all regions focus on realising energy and food security goals at the expense of broader development. Therefore, investment in education will be greatly reduced, and a very low annual growth in years of education is assumed. Under SSP2, regions invest in education according to their own economic capacity, but the progress is generally slow with an average growth of 0.06 years in *MYS*. A key assumption under SSP4 is that investment in education is generally low and highly unequal, which is exacerbated by limited access to education in low-income areas (Cornia, 2012; OECD, 2011).

Table 2. Quantitative settings for mean years of schooling (*MYS*) under different SSPs.

Pathway	SSP1	SSP2	SSP3	SSP4	SSP5
Annual variation (years)	0.1	LM: 0.04 UM: 0.06 HI: 0.08	0.02	LM: 0.03 UM: 0.04 HI: 0.07	0.1
2050 national average target (years)	13.6	LM: 11.5 UM: 12.2 HI: 12.9	10.8	LM: 11.2 UM: 11.5 HI: 12.6	13.6

Source: According to OECD (2011), Cornia (2012) and authors' assumptions.

2.2.2. Physical capital stock

Estimating capital stock is a difficult and important problem in economic and statistical analyses. Owing to different estimation methods and application directions, scholars have estimated different results for capital stock through China's history (Chow, 1993; Jefferson et al., 1992; Shan, 2008; Young, 2003; Zhang et al., 2004). Following Shan's (2008) method, the perpetual inventory method was used to estimate the current capital stock of China and its provinces in 2015:

$$K(t+1) = (1-d) \cdot K(t) + I(t) \quad (4)$$

where t is a time indicator and d is the depreciation rate. Shan's (2008) estimation result is used, and 10.96% is assumed as the depreciation rate in the provincial estimation. Investment I increases the stock of physical capital K , which represents the total regional capital formation. These data were taken from the Statistical Yearbook of China.

In contrast to Leimbach's (2017) research, this study does not use the mathematical method of a recurrence equation to project future capital stock because it has no practical economic basis, making the results unconvincing. Investment I is further decomposed into $Y(t) \cdot i$ (Equation (5)). In the long-term projection, depreciation rate d and investment rate i are described according to different development pathways and regional development levels:

$$K(t+1) = (1-d) \cdot K(t) + Y(t) \cdot i \quad (5)$$

The experience of economic development in Western developed countries and in Asia's more developed countries and regions indicates that the relationship between economic growth and the investment and depreciation rates changes over time. First, a short-term effect is related to the early stages of economic development. Regions with rapid economic growth have high levels of investment, and the frequency and degree of capital utilisation increase, leading to an increase in the depreciation rate (Attanasio et al., 2000; Dosi et al., 1995). Second, in the long term, the economic development level increases, as does the level of technology. Large-scale investment in the early stages of economic development is no longer required. The economic growth rate is not as high as in the early stage of development, but resource efficiency is constantly improving and the growth pattern is more environmentally and resource friendly. This results in a decrease in depreciation rate (Chenery & Syrquin, 1975; Chenery et al., 1986).

Table 3. Quantitative settings for the depreciation rate (d) under different SSPs.

Pathway	SSP1	SSP2	SSP3	SSP4	SSP5
Convergence target (%)	9.2	LM: 10.8 UM: 10.3 HI: 9.8	11.9	LM: 11.1 UM: 11.5 HI: 12.3	12.8
Convergence time (Years)	150	LM: 100 UM: 100 HI: 100	50	LM: 150 UM: 120 HI: 100	100

Source: According to authors' assumptions.

As the change in the depreciation rate is sensitive to the estimation of capital stock, a long convergence time for the depreciation rate is set under different paths, as shown in Table 3. Under SSP1, technology yields high resource efficiency in each region, which leads to high capital utilisation efficiency and a low depreciation rate, but this occurs over a long period. SSP2 is the pathway closest to the real world. It is assumed that the average depreciation rate of the different income-level regions under SSP2 is 10.3% and that the average convergence time is 100 years. SSP5 is a scenario involving high inputs, high output, and high losses. To ensure continued high growth, the depreciation rate was maintained at a high level of 12.8%. Under SSP4, high-income areas have greater access to loans and greater economic opportunities. Thus, they can achieve a higher depreciation rate at a higher speed. However, owing to the weak political power and limited economic development opportunities in the other regions (Bénabou, 2000; Vindigni, 2002), the depreciation rate is low, not because of the improvement in resource efficiency, but because of the low level of resource utilisation. Owing to regional competition and fragmentation, even social unrest and conflict, technological progress is slow and the depreciation rate high under SSP3, with the depreciation rate converging to a higher level at a faster speed.

Over the past half century, China's investment rate has been rising despite fluctuations, and it has reached a level far higher than the world average (in 2015, China's investment rate was 45.6% compared with the world average of 24.5%) (World Bank, 2020b), which was essential at this stage of China's economic and social development. China's rapid economic growth in the past 40 years benefitted from large-scale investment initially; however, with the transformation of its economic structure, the investment rate began to decline, and economic growth gradually shifted from relying on investment to relying on scientific and technological progress. Over a long period, only the average growth rate is important in determining fluctuations in the investment rate (Dornbusch et al., 2011). Therefore, based on the experience of developed countries and the historical trend in China's investment rate, this study makes assumptions concerning the investment rates for the different development pathways. To maintain high growth, it is necessary to maintain a high investment level under SSP5. Under this pathway, although the investment rate drops by 0.31% on average every year, it remains at 34.8% in 2050. Under SSP3, the investment rate decreases by 0.69% every year, not because of technological improvements, but because of the technological stagnation caused by regional competition and fragmentation, and a lack of interregional cooperation, which leads to a significant decline in regional investment capacity. Under SSP4, the decline in the investment rate is generally large and highly unequal between regions. Compared with other regional groups, high-

Table 4. Quantitative settings for the investment rate (i) under different SSPs.

Pathway	SSP1	SSP2	SSP3	SSP4	SSP5
Annual variation (%)	-0.54	LM: -0.44 UM: -0.47 HI: -0.5	-0.69	LM: -0.61 UM: -0.52 HI: -0.37	-0.31
2050 national average target (%)	26.7	LM: 30.2 UM: 29.2 HI: 28.1	21.5	LM: 24.3 UM: 27.4 HI: 32.7	34.8

Source: According to World Bank (2020b), Dornbusch et al. (2011), O'Neill et al. (2017) and authors' assumptions.

income regions have more investment opportunities and stronger economic capacity; thus, their investment rate remains high in the future. Under SSP1, owing to technological progress and breakthroughs, there is less dependence on investment, and it is assumed that the investment rate will drop by an average of 0.54% every year. SSP2 is the pathway closest to the current development track. The overall investment rate declines at a moderate rate under SSP2. High-income regions are likely to achieve scientific and technological breakthroughs, their resource efficiency is high, and there is less dependence on capital investment (Gil-Alana et al., 2020; O'Neill et al., 2017; Philipson, 2020). Thus, for high-income regions, the investment rate declined faster than in the other two regional groups.

2.2.3. Total factor productivity

TFP measures the quality of a country's economic development. A higher TFP means more output can be produced with the same amount of resource input. If TFP does not increase, eventually diminishing marginal returns will result in stagnation despite the accumulation of factor inputs (Krugman, 1994; Young, 1995). Even with unlimited resources, it would be impossible to promote economic growth, let alone with limited resources. In this study, the TFP for GDP projections is based on the assumption that the empirically observed growth pattern involves an exponential growth trajectory (Leimbach et al., 2017). Therefore, the long-term TFP projection value A_L can be estimated using the following formula:

$$A_L(t) = A_{his}(2015) * \prod_{i=2016}^t [1 + g_L(t)] \quad (6)$$

where t denotes time, $A_{his}(2015)$ denotes the historical TFP data for the base period in 2015, and $g_L(t)$ is the projected value of the TFP growth rate in period t in the future. The calculation of historical TFP $A_{his}(t)$ is based on the inverse of the Cobb–Douglas function, as follows:

$$A_{his}(t) = \frac{Y(t)}{K(t)^{\alpha(t)} L(t)^{1-\alpha(t)}} \quad (7)$$

Therefore, the initial TFP value for 2015 for the 340 municipal administrative regions in China can be calculated using Equation (7) and GDP for the base period of 2015, which is published in the statistical yearbook of each region. The initial

Table 5. Quantitative settings for capital output elasticity (α) under different SSPs.

Pathway	SSP1	SSP2	SSP3	SSP4	SSP5
Convergence target (Scalar)	0.65	0.65	0.55	0.60	0.75
Convergence time (Years)	100	150	150	100	250

Source: According to Leimbach et al. (2017), O'Neill et al. (2017) and authors' assumptions.

values of the capital stock and labour inputs of each region were calculated (see sections 2.2.1 and 2.2.2). Denoting capital output elasticity by α , most developed countries have a capital output elasticity of approximately one third (Dornbusch et al., 2011; Leimbach et al., 2017). However, China's long-term dual economic structure has led to an unbalanced distribution of factors, involving low labour remuneration and rising capital income. Most studies estimate that the elasticity coefficient of capital output for China falls within a range of 0.6 to 0.8 depending on the measurement methods used (Chen, 2012; Fan & Guo, 2019; Guo & Jia, 2005; Li & Zeng, 2009; Zhang & Shi, 2003). In this study, α was set at 0.7, which is assumed the base period α value for 2015. Unless long-term economic growth is being analysed, it is generally considered that the elastic parameter in the Cobb–Douglas function is constant (Dornbusch et al., 2011). Therefore, although a time-variant elasticity of capital output is assumed in this study, the convergence time is very long (Table 5). Under SSP1 and SSP2, the convergence targets for α are obviously reduced owing to a more balanced distribution of factors. However, compared with SSP1, under SSP2, progress in realising structural transformation and increasing education investment is slow and takes longer to achieve. Slow convergence and a low capital output elasticity of 0.55 are assumed for SSP3, which simulates a fragmented and retrogressive world with a significant decrease in capital intensity (Leimbach et al., 2017). A slightly better long-term level of 0.6 and faster convergence are assumed for SSP4. The SSP5 scenario is characterised by high international cooperation and high-speed economic growth, which requires the continuous promotion of large amounts of capital accumulation. It is assumed that α can grow to a high level of 0.75 over a long period (O'Neill et al., 2017).

Regarding the TFP growth rate g_A , while China's TFP growth rate has been relatively stable, until its accession to the World Trade Organization in 2001, it fluctuated at various stages because of the immature market economy (Fan & Guo, 2019; Li & Zeng, 2009). Thus, following Leimbach's (2017) approach, the initial value of g_A is determined as a weighted average of the growth rates of historical TFP $A_{his}(t)$ from $t = 2003$ to 2015 as follows:

$$g_A = \frac{\sum_t \left(t \cdot \log \frac{A_{his}(t)}{A_{his}(t-1)} \right)}{\sum_t t} \quad (8)$$

Considering the availability of data, the values for g_A for each of the 31 provinces were used to represent the g_A of each municipal administrative unit in each province. Table 6 shows the TFP growth rate assumptions for the future based on the research of Leimbach et al. (2017) and Dellink et al. (2017). SSP3 has a very low TFP growth rate in the future, and the transition time between historical and future trends

Table 6. Quantitative settings for TFP growth rates (g_A) under different SSPs.

Pathway	SSP1	SSP2	SSP3	SSP4	SSP5
Convergence target (%)	0.9	LM: 0.9 UM: 1.0 HI: 1.1	0.2	LM: 0.3 UM: 0.5 HI: 1.0	1.2
Convergence time (Years)	50	LM: 100 UM: 100 HI: 100	20	LM: 100 UM: 80 HI: 50	50

Source: According to Leimbach et al. (2017), Dellink et al. (2017) and authors' assumptions.

(20 years) is shorter than those of all other scenarios, because this pathway involves the most drastic deviation from the historical development path. Owing to the large and effective amounts of technological investment and spillovers, the TFP growth rate under SSP1 and SSP5 is high and the convergence time is moderate. Under SSP2, current trends continue longer than under the other SSPs, with a convergence time of 100 years and an average target of 1.0%. SSP4 shows a highly unequal world, with serious technological and trade barriers between high-income and other regions. Compared with high-income regions, all other regions have longer convergence times and lower TFP growth rates.

2.3. Conditional convergence model

The issue of convergence is important when discussing the generation of long-term climate scenarios and projections of economic growth (Kemp-Benedict, 2012; McKibbin et al., 2009). Recognising this, this study adopted a framework based on the conditional convergence hypothesis applied in a neoclassical growth framework, which is adapted from recent work by the Economics Department of the Organisation for Economic Co-operation and Development (Johansson et al., 2013):

$$E(t) = E_A^L + (E(0) - E_A^L) \cdot e^{-\Delta t \beta} \quad (9)$$

where $E(t)$ represents the convergence value in the convergence time t , E_A^L represents medium- to long-term convergence targets, $E(0)$ represents the initial value, and β represents the convergence control parameters in a specific scenario. The framework adopted reflects the convergence trends in per capita output growth, technological progress, and other aspects among economic regions with similar structural characteristics (Barro & Sala-I-Martin, 2004), which makes it more suitable in terms of the newly added non-uniform version of SSP2 and severely unbalanced SSP4 pathway. The specification of the convergence assumption is derived from the more detailed SSP narratives discussed in the previous sections.

3. Analysis of the results

3.1. Comparison of statistics and projection data for 2015–2019

The simulation effect of the Cobb–Douglas model can be tested by comparing the results of the GDP projection results with the statistical data for China (nationally and for typical provinces) for 2015–2019. The SSP2 scenario was selected because it

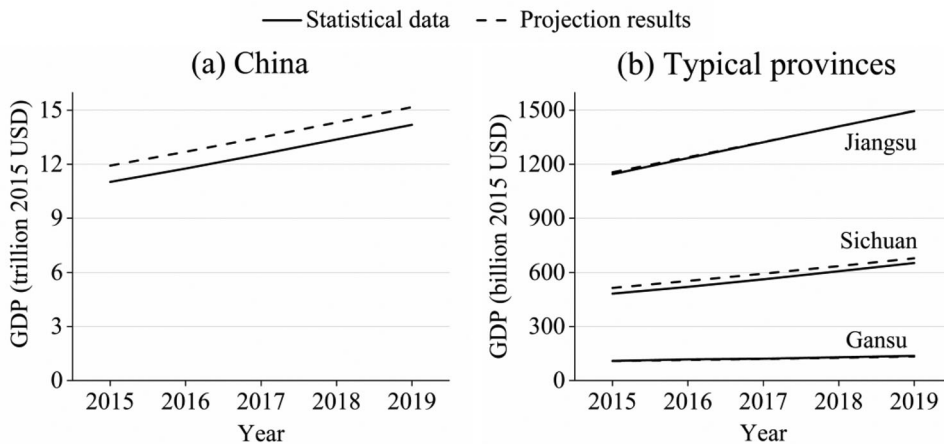


Figure 2. Comparison of GDP statistics and SSP2 projection results for China (nationally and for typical provinces) for 2015–2019. Source: Prepared by the authors, according to authors' calculations and the statistical yearbook of each region.

is a moderate projection scenario in which social, economic, and technological trends do not deviate significantly from the historical model. As Figure 2(a) shows, according to the statistics, China's average GDP for 2015–2019 is 12.6 trillion USD (expressed in constant 2015 USD throughout), beginning the period at 11.0 trillion and totalling 14.2 trillion USD in 2019. The average annual GDP projected by the model for the same period is 13.5 trillion USD, with totals of 11.9 and 15.2 trillion USD in 2015 and 2019, respectively. The average error for statistical and predictive data was 7.5%, the error range was 7–8%, and the error standard deviation was 0.5%. As the method of calculating GDP at the national level for the base period of 2015 in this study is the sum of the GDP statistics of the 340 prefecture-level administrative regions (11.9 trillion USD), rather than the national data published by the national statistics (11.0 trillion USD), there are differences in the statistical calibre of the initial value, resulting in a large range of errors. Nevertheless, from the perspective of the growth trend and standard deviation of the error, the simulation results of the model are consistent with reality.

Based on the World Bank's classification of per capita incomes in 2015, Jiangsu, Sichuan, and Gansu were selected as representatives of high-income, upper-middle-income, and relatively low-income provinces, respectively, to observe the simulation effect of the projection model (Figure 2(b)). For 2015–2019, the annual average GDP statistics of Jiangsu, Sichuan, and Gansu were 1,320, 570, and 120 billion USD, respectively, and the annual average GDP projected by the model in the same period was 1,320, 600, and 120 billion USD, respectively. The average errors were 0.29%, 5.45%, and 1.90%, respectively, and standard deviations of the error 0.34%, 1.00%, and 0.89%, respectively. Jiangsu and Gansu had good simulation results. Although the growth trend is consistent, the error in Sichuan Province is relatively high. This is due to the difference between the sum of the initial GDP for the 21 regions included in Sichuan Province (510 billion USD) and estimate of the provincial statistical yearbook (480 billion USD). The above results show it is feasible to use the

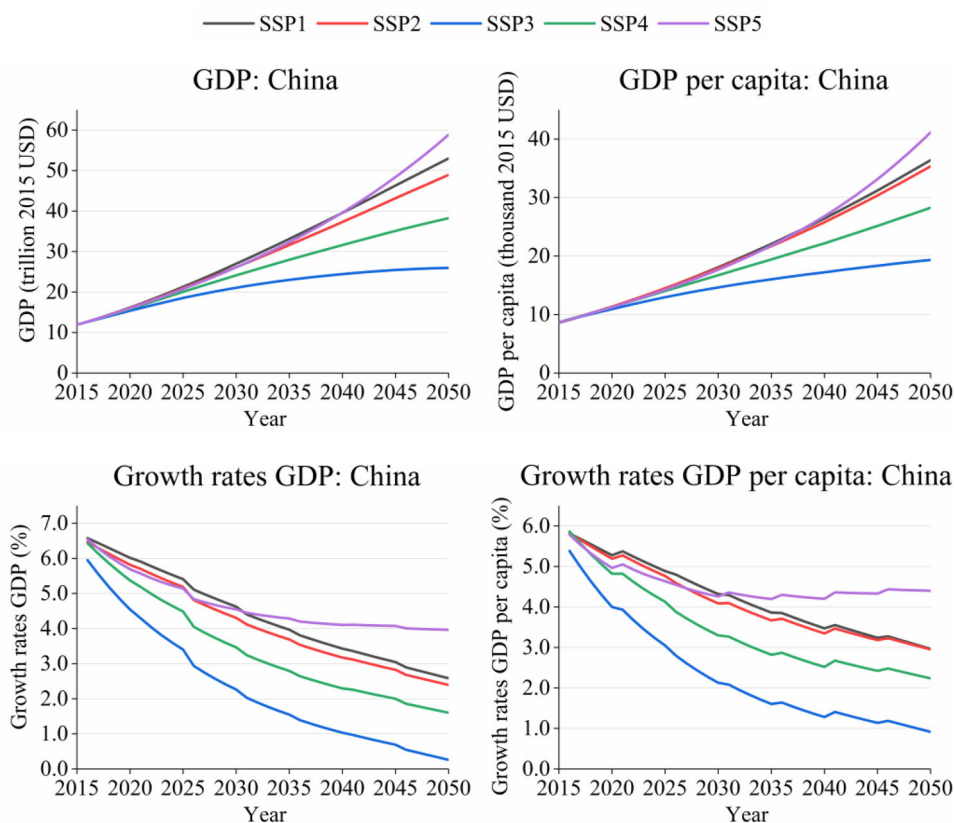


Figure 3. China's GDP and per capita GDP levels and associated annual growth rates³ for the five SSPs. Source: Prepared by the authors, according to authors' calculations.

Cobb–Douglas model to refine and project the GDP of 340 regions in China and to aggregate the GDP at the national and provincial levels, and that the parameters of the model are reasonable.

3.2. Projection of China's GDP and per capita GDP under different SSPs

The following two subsections present the main results from the SSP projections by analysing the change in trends for total GDP and per capita GDP levels at the national and provincial levels for 2015–2050 under the five SSPs. The GDP and per capita GDP levels were calculated in constant 2015 USD.

As illustrated in Figure 3, China's GDP levels varied substantially across SSPs by the middle of the century. The range varies from 26.0 trillion USD under SSP3 to 58.8 trillion USD under SSP5. This pattern is similar for per capita GDP levels, which range from 19,300 USD for SSP3 to 41,100 USD under SSP5.

The narrative focus of SSP5 is conventional economic development. By 2050, China's GDP growth is expected to be nearly five times that of 2015. In this case, by the middle of this century, the per capita GDP growth rate remains above 4.5% per

year, on average, resulting in a per capita GDP nearly four times that of 2015 by 2050. Over the first 10 years, the growth rate at the national level under SSP5 is lower than that under SSP1 or SSP2, because SSP5 involves a higher depreciation rate and faster convergence.

SSP3 and SSP4 are the scenarios with the lowest levels of international cooperation and trade. Although GDP per capita is higher under SSP4 than under SSP3, both are at the bottom of the range. Under these scenarios, China's per capita GDP growth will drop significantly to 0.9% and 2.2% per year, respectively. The drop in China's growth begins almost immediately under SSP3, whereas it is more gradual under SSP4. In particular, SSP3 involves very low per capita GDP growth (by 2050, it has done little more than doubled) based on the assumption of low growth rates for the main economic drivers.

The growth rate under SSP1 and SSP2 is moderate, with per capita GDP levels that are 4.2 times and 4.1 times that of 2015, respectively, by 2050. In the first decades, SSP1 involves higher growth because of the faster convergence of the TFP growth rate, but the growth rate of per capita GDP under SSP1 drops to the same level as SSP2 by 2050. Considering the higher population projection of SSP1, per capita GDP diverges less than the absolute GDP levels between SSP1 and SSP2.

3.3. Changes in per capita GDP and growth rates of provinces under different SSPs

The changes in GDP per capita and growth rates in the different provinces vary under different SSPs. Figure 4 shows the spatial distribution of the annual average GDP per capita of each province under the different SSPs for 2015–2050. For almost all provinces, the average annual per capita GDP under SSP5 was higher than under SSP2, SSP3, and SSP4. For some relatively low-income provinces, the average annual per capita GDP under SSP5 is less than that under SSP1. The per capita GDP level was the lowest under SSP3. It is very close for SSP1 and SSP2, with the latter being slightly higher, with the exception of Beijing, Shanghai, and Jiangsu. The SSP4 showed significant regional differences. The per capita GDP of high-income regions such as Beijing, Shanghai, and Tianjin is much higher than that of relatively low-income regions such as Gansu, Heilongjiang, and Shanxi. In general, the spatial distribution of the average annual per capita GDP of the 31 provinces from 2015 to 2050 was high in the east and low in the west.

Figure 5 shows the spatial distribution of the annual average per capita GDP growth rates of the provinces under different SSPs for 2015–2050. In contrast to per capita GDP, the annual average per capita GDP growth rates under SSP5 are higher than those of the other pathways for all provinces. In addition, the growth rates of high-income regions such as Beijing, Shanghai, and Guangdong are lower than those of Yunnan, Tibet, Guangxi, and other relatively low-income regions. This is because the high-income regions follow a relatively stable growth path, with annual growth declining in the coming decades, whereas the annual growth rate of most relatively low-income regions will continue to rise over the initial 10 years, demonstrating a typical hump-shaped growth pathway. As a result, the spatial distribution of the

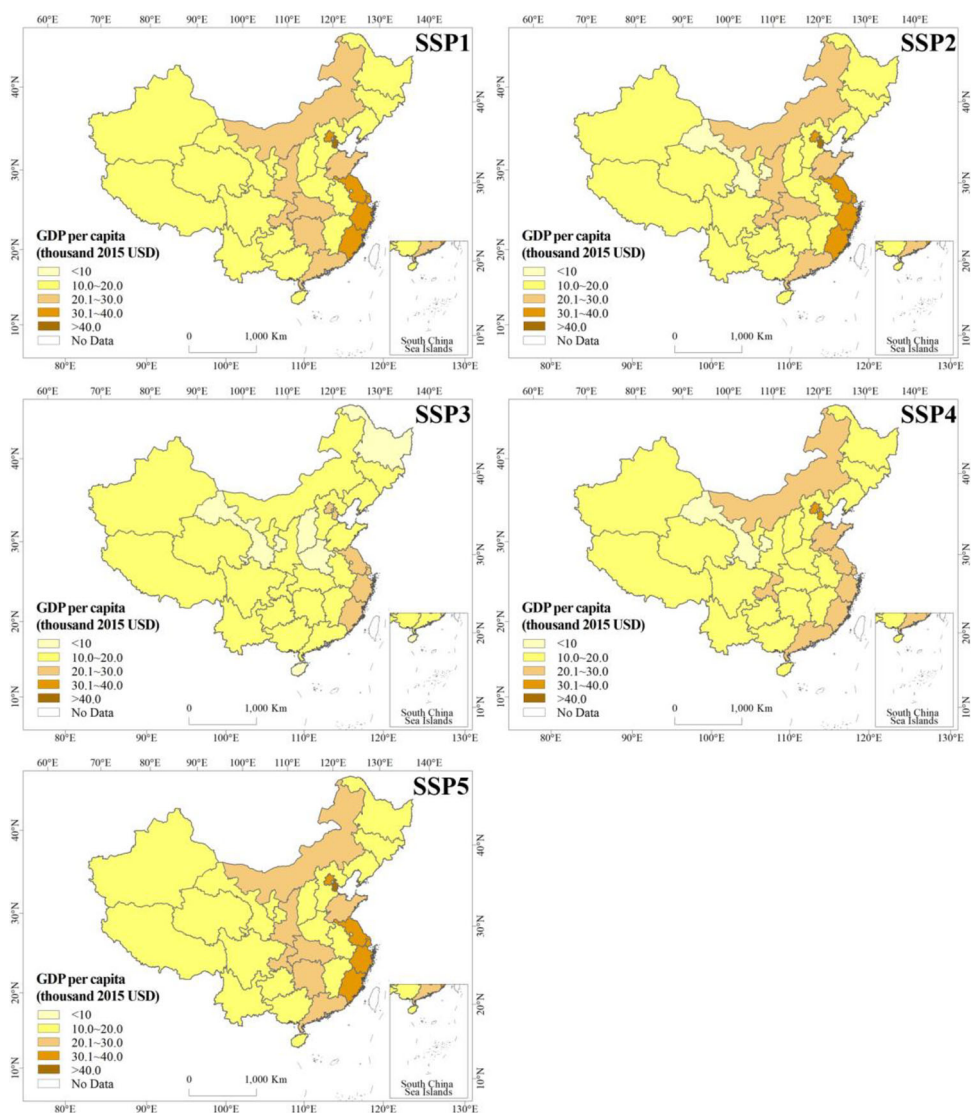


Figure 4. Spatial distribution of annual average per capita GDP in different provinces of China under different SSPs for 2015–2050. Source: Prepared by the authors, according to authors' calculations.

annual average per capita GDP growth rates of 31 provinces presents the opposite situation to that of the annual average per capita GDP.

Table 7 shows the comparison between the top 10 provinces in terms of per capita GDP in 2015 and those under different SSPs in 2050. Compared with 2015, the ranking of the different income regions changed significantly by 2050. In particular, the proportion of high-income regions in the top 10 provinces declined significantly. In 2015, 7 of the top 10 regions were high-income regions, whereas in 2050, SSP2 (50%) and SSP4 (50%) accounted for the highest proportion of high-income regions. Under SSP3, only three high-income provinces (Tianjin, Inner Mongolia,

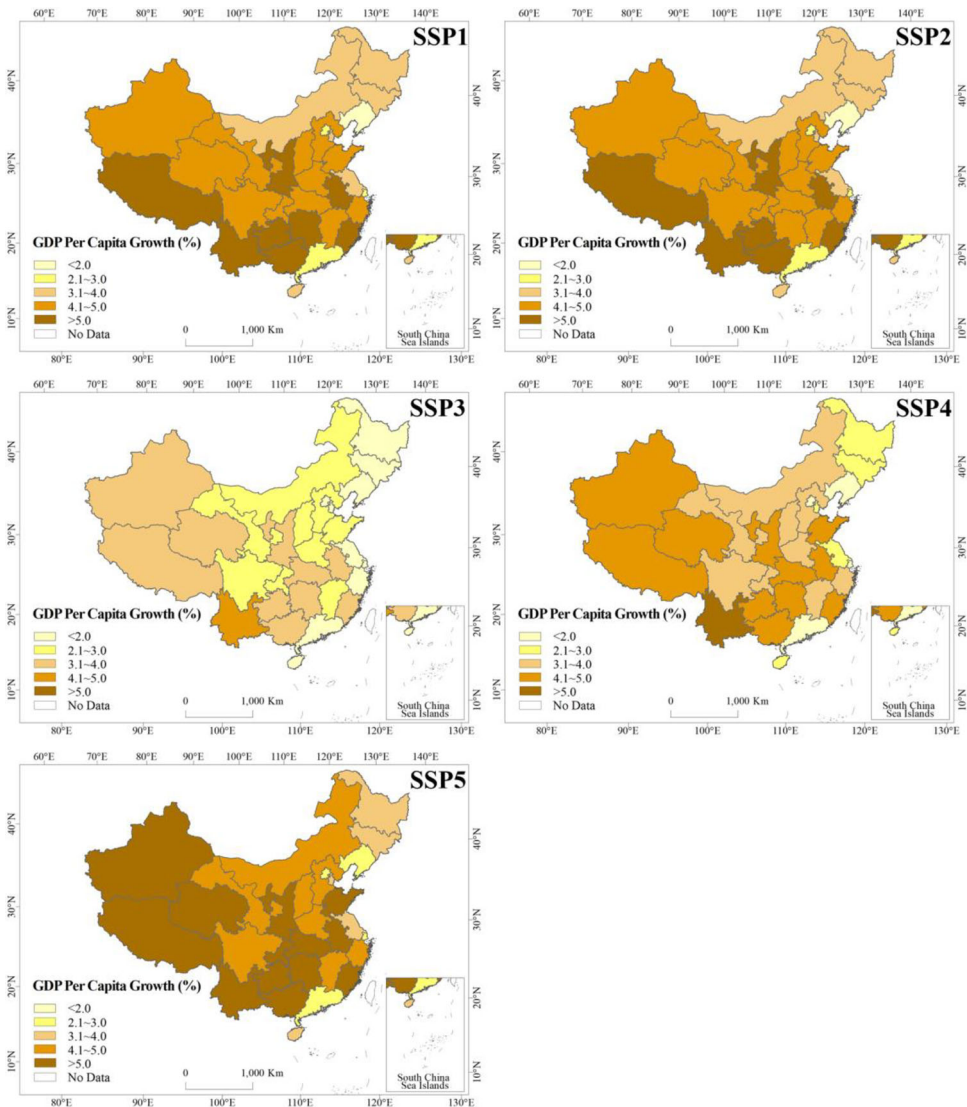


Figure 5. Spatial distribution of the annual average per capita GDP growth rates in different provinces of China under different SSPs for 2015–2050. Source: Prepared by the authors, according to authors' calculations.

and Zhejiang) ranked in the top 10. Other high-income regions declined significantly in terms of ranking. Guangdong and Shanghai do not rank in the top 10 under any pathways, whereas Beijing ranks in the top 10 under SSP2 and SSP4, although it is in one of the last two positions of the top 10. In contrast, the ranking progress of the upper middle-income regions is highly significant, with Fujian ranking second under various pathways in 2050, rising from the 8th position in 2015, and Shandong ranking third, up from 10th in 2015. In addition, Shaanxi, Chongqing, Ningxia, Hubei, and Xinjiang are in the top 10 for the first time under various pathways by 2050, indicating that China's upper-middle-income regions are

Table 7. Comparison between the top 10 provinces in terms of per capita GDP in 2015 and in 2050 under different SSPs.

Pathway		2015		2050-SSP1		2050-SSP2	
Ranking	Province	GDP per capita (thousand 2015 USD)	Province	GDP per capita (thousand 2015 USD)	Province	GDP per capita (thousand 2015 USD)	GDP per capita (thousand 2015 USD)
1	Tianjin	20.4	Tianjin	66.9	Tianjin	66.1	
2	Beijing	18.4	Fujian	65.9	Fujian	63.2	
3	Shanghai	17.3	Shandong	53.9	Shandong	52.7	
4	Jiangsu	14.3	Inner Mongolia	51.1	Zhejiang	49.9	
5	Inner Mongolia	13.1	Zhejiang	51.1	Inner Mongolia	49.4	
6	Zhejiang	12.6	Shaanxi	47.5	Jiangsu	45.6	
7	Guangdong	11.9	Chongqing	46.4	Shaanxi	44.9	
8	Fujian	11.1	Ningxia	45.9	Chongqing	43.8	
9	Liaoning	10.3	Jiangsu	45.4	Beijing	43.3	
10	Shandong	10.3	Hubei	43.1	Ningxia	43.0	

Pathway		2050-SSP3		2050-SSP4		2050-SSP5	
Ranking	Province	GDP per capita (thousand 2015 USD)	Province	GDP per capita (thousand 2015 USD)	Province	GDP per capita (thousand 2015 USD)	GDP per capita (thousand 2015 USD)
1	Fujian	33.2	Tianjin	51.4	Fujian	79.3	
2	Tianjin	32.8	Fujian	48.1	Tianjin	77.5	
3	Shandong	27.8	Shandong	41.7	Shandong	63.5	
4	Ningxia	27.5	Inner Mongolia	39.2	Zhejiang	60.3	
5	Inner Mongolia	26.9	Zhejiang	37.6	Inner Mongolia	58.1	
6	Shaanxi	26.4	Ningxia	37.0	Jiangsu	53.4	
7	Zhejiang	24.2	Shaanxi	36.7	Shaanxi	53.1	
8	Chongqing	23.4	Jiangsu	35.1	Chongqing	52.8	
9	Hubei	23.0	Hubei	34.4	Hubei	50.5	
10	Xinjiang	22.2	Beijing	33.6	Ningxia	49.6	

Note: Excluding the Hong Kong, Macao and Taiwan regions.

Source: Authors' calculations.

beginning to contribute to growth by 2050 and will become a new engine of growth for the Chinese economy.

4. Discussion

The advantages of this method are obvious in that it is both intuitive and robust. It replaces the complicated mathematical model and need for specialised operational skills with intuitive economic reasoning, and avoids the unsoundness of results caused by the correlation of key variables. The projection results are slightly more optimistic than most global projections, which is probably because the parameters used in this study align with China's actual economic development such as its high capital output elasticity, rather than being based on global averages. A more detailed version of SSP2 and population projection data at the municipal level provides more precise and non-uniform results. However, it should not be forgotten that there are large uncertainties involved in the long-term projection of economic growth, including major external shocks such as natural disasters, military conflicts, or discovery of valuable resources. These problems cannot be solved in the five SSP scenarios with internally consistent assumptions. Nevertheless, the projections are suitable as a reference for quantitative analysis that relies on long-term economic baselines because they reflect different combinations of underlying growth drivers. While these localised

interpretations are constructed specifically for China, the framework can also be used for other countries and regions.

5. Conclusions

This study provided an improved framework of practical economic significance for the projection of regional economic growth, rather than using a recursion or extrapolation method. The new method is based on a neoclassical economic model and recently developed scenarios of SSPs including an alternative non-uniform version of SSP2. This study adopted more detailed population projection data for China at the municipal level and parameter settings aligned with China's development reality. GDP data for 340 districts were refined, projected, and aggregated at the provincial and national scales.

China's GDP levels varied substantially across the SSPs by the middle of this century, ranging from 26.0 trillion USD under SSP3 to 58.8 trillion USD under SSP5. This pattern is similar for per capita GDP levels, which range from 19,300 USD under SSP3 to 41,100 USD under SSP5. The performance of SSP1 and SSP2 is similar, with the former being higher, although on average, both are lower than in SSP5. Nevertheless, given its better environmental quality and higher level of equity, SSP1 is likely a better choice of pathways than SSP5.

The spatial distribution of the average annual per capita GDP of 31 provinces for 2015–2050 is characterised by a pattern high in the east and low in the west, whereas the distribution of the average annual per capita GDP growth rates presents the opposite situation. By 2050, the per capita GDP growth rates in high-income regions are generally lower than those in relatively low-income regions, and the proportion of high-income (upper-middle-income) provinces in the top 10 provinces by per capita GDP levels has declined (improved) significantly. Thus, the results indicate that China's upper middle-income provinces begin to make a general contribution to growth around the middle of this century and will become a new engine for China's economic growth in the future.

Notes

1. The population projection data covered 340 administrative units, including four municipalities and 336 prefecture-level and non-prefecture-level cities, excluding the Hong Kong, Macao and Taiwan regions.
2. According to the World Bank's classification of income levels for world economies in 2015, the 340 administrative units in China can be classified into 61 regions with lower middle incomes and below (LM), 230 regions with upper middle incomes (UM), and 49 regions with high incomes (HI) (<http://data.worldbank.org/about/country-and-lending-groups>).
3. The growth curve of GDP and per capita GDP shows zigzag fluctuations, which is largely due to the structure of the population projection data, which are based on 5-year age groups derived from the initial age grouping structure of the Sixth National Population Census (<http://www.stats.gov.cn/tjsj/pcsj/rkpc/6rp/indexch.htm>).

Disclosure statement

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