

Article

The Spatio-Temporal Dynamic Mechanism of Multidimensional Population on Both Sides of the Hu Line in China Under Climate Change

Haibin Xia ^{1,2,3,*} , Qingchun Liu ⁴, Jie Yin ^{1,2,3}, Xiangyu Xie ^{1,2,3} and Feiran Sun ^{1,2,3}

¹ School of Geographic Sciences, East China Normal University, Shanghai 200241, China;

jyin@geo.ecnu.edu.cn (J.Y.); 51273901129@stu.ecnu.edu.cn (X.X.); frsun@geo.ecnu.edu.cn (F.S.)

² Key Laboratory of Geographic Information Science, Ministry of Education, Shanghai 200241, China

³ Institute of Eco-Chongming, Shanghai 200062, China

⁴ China Economic Research Institute, Shandong University of Finance and Economics, Jinan 250016, China; lqc7919@sdufe.edu.cn

* Correspondence: hbxia@geo.ecnu.edu.cn; Tel.: +86-54341210

Abstract

This paper discusses the dynamic mechanism of stability and the possibility for breakthrough of the Hu Line based on the relationship between population, socioeconomic development and the environment. Against the background of sustainable development and climate change, we used historical census data from China and comparative analysis of three versions (IIASA, NUIST and Tsinghua) of the Shared Socioeconomic Pathways (SSPs) to analyze multidimensional demographic characteristics such as population size, age and education on both sides of the Hu Line (China's population boundary). The study found that SSP scenarios and regional differences in the natural growth rate (defined by fertility and mortality) and urbanization rate jointly influenced the changes in the proportion on both sides of the Hu Line. In addition to the breakthrough of the population proportion on the west of the Hu Line, population quality deserves greater attention. The provinces on the east and west sides of the Hu Line can adopt different social and economic development paths to achieve sustained development of the population, economy, society, resources and environment. On the premise of sustained social and economic development, the total population will not rise or fall significantly, keeping the trend of aging under control, and enhancing the educational level. The central government should increase investment in basic education in the provinces west of the Hu Line and create more employment opportunities through the Belt and Road Initiative and the new urbanization strategy. In areas with abundant water resources on the west of the Hu Line, urbanization efforts should be rationally planned and advanced to gradually establish clusters of talent hubs. This will facilitate the effective conversion of human resources by retaining and attracting higher-education professionals to pursue employment and entrepreneurship opportunities.



Academic Editor: Jun (Justin) Li

Received: 18 September 2025

Revised: 5 July 2026

Accepted: 6 July 2026

Published: 5 August 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: the Hu Line; education; age; Climate Change Scenarios

1. Introduction

Since the 2015 Paris Climate Summit, research on population from a multidimensional perspective (structure and quality) has attracted increasing attention. Some scholars believe that even if the population proportion on both sides of the Hu Line has not changed significantly, if the quality of life of people on the western side of the Hu Line is effectively

improved, it can also be regarded as a breakthrough. This reflects that the understanding of the Hu Line has shifted from discussing population quantity distribution to population quality distribution.

The concept of the Hu Line originated from concerns about whether China's population was excessively concentrated and whether large-scale migration within the country remained possible. In 1935, Hu Huanyong published *The Distribution of China's Population*, introducing the well-known "Aihui–Tengchong" population boundary in China—later called the Hu Huanyong Line, or simply the Hu Line [1]. Using data from the Fourth National Census, Hu Huanyong observed in 1990 that the east–west population ratio had shifted from 96%:4% in 1935 to 94.4%:5.6%. This 1.6-percentage increase in the western share prompted the first systematic discussions on changes in the population balance across the Hu Line [2]. Subsequent studies have repeatedly confirmed the relative stability of the Hu Line using census data from later years [3–6].

Debates over the mechanisms behind the Hu Line began with the "population–grain" relationship [1,2]. Discussions of whether the Hu Line could be "broken" have largely focused on socioeconomic drivers. Many scholars argued that breakthrough was possible by improving development conditions or tapping substitute resources—such as urbanization, education and cultural investment, technological progress, and information development—and thus they tended to take an optimistic view [6–8]. From an environmental perspective, however, the focus on physical geographic constraints often invoked accusations of "environmental determinism," leading to greater support for the "stability" position [9].

The straightforward conclusion of the Hu Line contrasts sharply with the complex coupling of demographic, socioeconomic, and environmental factors that underlie it. With the aid of rich geospatial data and simulation models, scholars have explored its potential for future change. For example, Wang Lu et al. used a logistic model to project population distribution based on historical census data [10]. Others modeled future agricultural productivity [11], forest cover [12], environmental adaptability [13], and urban land expansion [14]. In these studies, the Hu Line served as an important spatial benchmark. Such "extended" research gradually reframed the Hu Line from being seen solely as a demographic boundary to being recognized as a boundary of national conditions. Nevertheless, little attention has been paid to how the constantly changing socioeconomic and environmental factors directly affect China's population distribution and thereby alter the country's east–west balance. A common approach has been to use projected changes in one or more geographic factors—expressed as indices—to linearly estimate potential future population changes [11,13].

In the debate over whether the Hu Line can or cannot be broken, some scholars have stressed that the issue should not be reduced to whether the population ratio on either side crosses a certain threshold. Instead, discussions must return to the central focus on people themselves [15]. As Premier Li Keqiang emphasized, new-type urbanization must be people-centered, with everything else serving the people (People's Daily Online, 28 November 2014). Accordingly, research on the Hu Line is shifting from issues of population quantity toward population quality.

The discussion surrounding the "breakthrough" and "stability" of the Hu Line should not be confined to examining whether the population ratio on either side of the line exceeds a certain threshold. Moreover, analyzing the Hu Line solely through the lens of socioeconomic factors or natural environments, or by focusing on isolated elements, is inherently biased. Today, climate change has become the defining theme of our era. As China currently ranks first globally in carbon emissions, pursuing sustainable development is an inevitable path for the nation's future. The exploration of the Hu Line's implications must

align with the demands of this new era. Against the backdrop of sustainable development and climate change, examining the evolutionary trends of China's historical and future populations provides a scientific research perspective for assessing the potential stability or breakthrough of the Hu Line.

This paper investigated the driving mechanisms that could reshape the Hu Line by examining the coupled dynamics of population, socioeconomic development, and the environment. Against the backdrop of sustainable development and climate change, we used historical census data and compared population scenario simulations from three versions of the Shared Socioeconomic Pathways (SSPs) developed by IIASA (International Institute for Applied Systems Analysis), NUIST (Nanjing University of Information Science and Technology), and Tsinghua (Tsinghua University). We analyzed changes in population shares on both sides of the line from multiple dimensions—size, age, and education—thereby contributing to the ongoing debate over whether the Hu Line can truly be broken.

2. The Driving Mechanisms Behind the Breakthrough of the Hu Line from a Multidimensional Population Perspective

China is currently experiencing relatively modest changes in population size but rapid shifts in population structure [16]. The country is transitioning from an agrarian society to an urban one, and from a land-dependent society to a highly mobile and dynamic one [17]. Excluding the effects of family planning, rapid urbanization and steadily rising educational attainment have raised living standards and life expectancy while reducing fertility intentions. Together, these factors have accelerated China's transition into an aging society [17,18]. Thus, the dynamic interplay of population size, demographic structure, and population quality forms the first major driving force behind potential changes to the Hu Line.

Socioeconomic development also reshapes population dynamics by influencing natural growth (via fertility and mortality rates) and mechanical growth (via migration). Improvements in public health and healthcare infrastructure lower mortality rates and extend life expectancy [19]. Poverty alleviation helps reduce infant mortality [20]. Meanwhile, investment in education and technology raises aspirations for child quality over quantity, lowering fertility intentions while boosting educational outcomes [21]. In this way, socioeconomic development alters birth, death, and migration rates across regions, creating the second driving force for potential breakthroughs of the Hu Line.

Socioeconomic transformation, including demographic change, also contributes to energy emissions at varying levels [22]. Using the PET model, O'Neill et al. found that beyond population size, demographic composition significantly influenced greenhouse gas emissions [23]. For instance, aging may reduce emissions by up to 20%, while urbanization could increase projected emissions by more than 25%. From a climate adaptation perspective, Shayegh showed that skilled individuals enjoyed greater mobility than unskilled ones [24]. As a result, when environmental conditions worsened, unskilled populations often struggled to adapt through migration. Populations of the same size but with different demographic and educational structures may therefore respond very differently to climate change [25,26].

Climate change, in this sense, functions as a threat multiplier [27]. It intensifies risks or amplifies existing vulnerabilities, indirectly shaping future population distribution. At the same time, migration and mobility become important adaptation strategies [27,28]. Thus, climate change constitutes the third major driving force of potential breakthrough of the Hu Line (Figure 1).

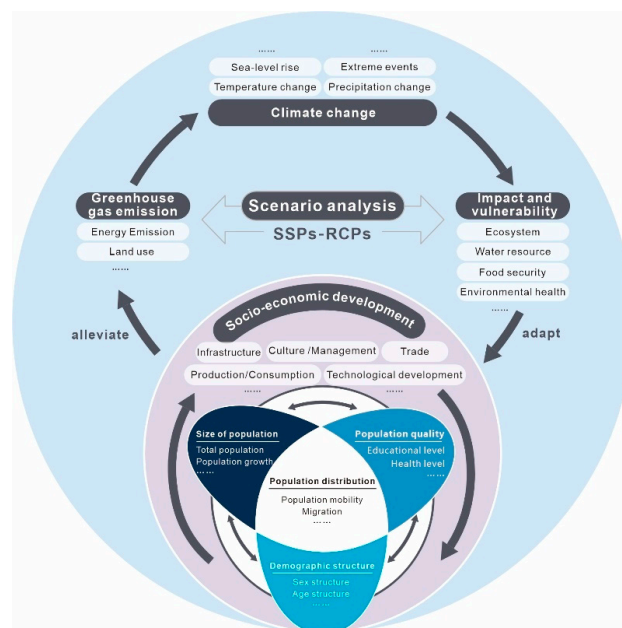


Figure 1. The coupling relationship between population, resources, environment, and socioeconomy in the context of climate change.

3. Comparative Analysis of Multidimensional Demographic Characteristics on Both Sides of the Hu Line

3.1. Population Distribution on Both Sides of the Hu Line

In 1935, the population distribution across the Hu Line was approximately 96% in the east versus 4% in the west [1]. At that time, China's population was estimated at 459 million [2]. By 2010, the population had grown to 1.34 billion. At the county level, the east–west population ratio in 2010 was 93.68% to 6.32% [4]. Using county-level data from The Distribution of China's Population (1935) and the Sixth National Population Census, we mapped population distributions with the point value method. In 1935, each point represented 20,000 people, while in 2010 each point represented 60,000 people to reflect the nearly threefold population growth (Figure 2). Figure 2 clearly shows that the basic pattern of population density—dense in the east, sparse in the west—remains unchanged, confirming the Hu Line's role as China's demographic boundary.

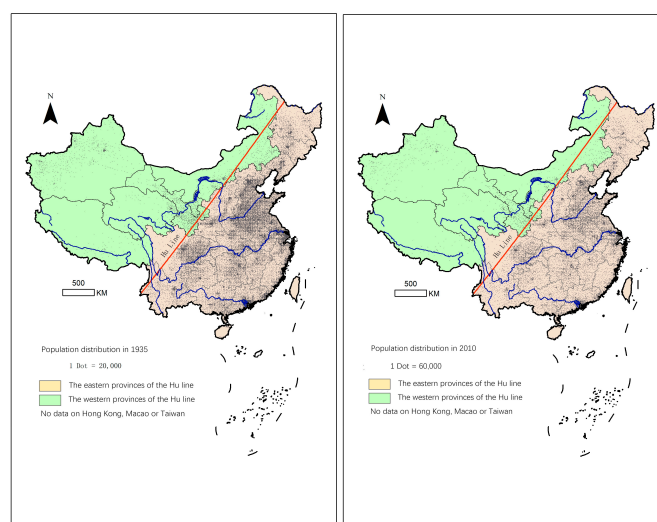


Figure 2. China's population distribution in 1935 (left) and 2010 (right).

A closer comparison of the eastern side in 1935 and 2010 revealed that the population became far more concentrated by 2010. Clusters formed in the Beijing–Tianjin area, the Yangtze River Delta, the Pearl River Delta, and several inland provincial capitals, while stark disparities emerged between urban and rural population densities. In contrast, the 1935 distribution was more dispersed, reflecting the predominantly agrarian nature of society at the time. The northeast, which was highlighted by Hu Huanyong as a potential destination for migration, also became more densely populated by 2010. Although Hu Huanyong held a reserved attitude about large-scale westward migration [1], population growth west of the Hu Line between 1935 and 2010 was concentrated in areas with relatively favorable water resources, such as the northern and southern Tianshan regions in Xinjiang, the Hetao area of Inner Mongolia, the Yellow River basin in Ningxia, and south-eastern Gansu. Overall, while the east–west population ratio shifted only slightly between 1935 and 2010, significant internal redistribution occurred either side of the Hu Line.

Traditionally, research on the Hu Line used county-level data. However, because county-level statistics disaggregated by age and education are lacking, this study relied on provincial-level data (see Figure 2 for provincial division). We classified Inner Mongolia, Xinjiang, Gansu, Ningxia, Qinghai, and Tibet as western provinces, and all others as eastern provinces.

The discovery of China’s population boundary line (the Hu Line) was based on county-level data [1]. For mesoscale research on China’s population distribution, in 1983, Hu Huanyong further proposed the concept of “one boundary line, three tiers, and eight population zones,” where the eight population zones were studied at the provincial level [29]. Yin Wenya et al. proposed a “quasi-Hu Huanyong Line” which divided China into northwest and southeast halves by separating the six provinces west of the Hu Line from the twenty-five provinces east of it [30]. This division facilitates the statistical analysis of multidimensional population data at the provincial level.

The land area on both sides of the Hu Line (straight line) and the quasi-Hu Huanyong Line (provincial boundary line) (see Figure 2) changed. The southeastern side of the quasi-Hu Huanyong Line covers 4.2962 million square kilometers, accounting for 44.7% of the 31 provincial-level administrative regions, while the northwestern side covers 5.3141 million square kilometers, accounting for 55.3% of the 31 provincial-level administrative regions. Compared to the distribution where the area east of the Hu Line accounted for 42.9% and the area west of it accounted for 57.1% [2], the difference is only 1.8 percentage points [30]. The population proportion on both sides of the quasi-Hu Huanyong Line in this paper was calculated at the provincial scale. In 2010, the population ratio between the east and west sides of the line was 93.73:6.27, while at the county scale (the Hu Line), the ratio was 93.68:6.32 [4].

3.2. Population Structure on Both Sides of the Hu Line

Population pyramids provide valuable insights into demographic structure and quality. Using data from the Fifth and Sixth National Censuses, we constructed population pyramids for 2000 (Figure 3a) and 2010 (Figure 3d). In these diagrams, the left side of the horizontal axis represents females, and the right side is males; the vertical axis indicates age groups. Red, yellow, blue and dark blue denote no education (NoEdu), primary education (PriEdu), secondary education (SecEdu), and tertiary education (TerEdu). Males slightly outnumber females across all age groups, especially among younger cohorts. In terms of age, the 2000 pyramid shows a conical structure for those aged 40 and above, and a bell shape for those under 40, reflecting the differing growth rates before and after the family planning policy. A notable concern was the shrinking share of children under 14. Already contracting by 2000, it declined further by 2010, signaling a continuous drop

in births. Although the working-age population (15–64) still dominated, the aging trend was becoming increasingly pronounced. Educationally, by 2010, the share of people with no schooling or only primary education had fallen sharply, while secondary and tertiary education levels had risen significantly.



Figure 3. Population pyramids for China and for the eastern and western sides of the Hu Line.

Figure 3b,c,e,f compare east–west differences. Because the 2010 ratio of east to west population was 93.73% to 6.27%, we used “relative population pyramids” that normalize age, gender, and education shares within each region. In 2000, the west had a higher relative share of children aged 0–14 (Figure 3b vs. Figure 3c), indicating higher fertility, though this advantage diminished by 2010 (Figure 3e). Educational disparities were striking in 2000: the west had a much higher share of uneducated people, especially women, and a larger proportion of working-age adults with only primary education or less. This underscored the lag in basic education and gender inequality in the west. By 2010, however, the east–west gap in education had narrowed, and gender disparities in education had also declined. Interestingly, the west did not significantly lag in tertiary education attainment in either 2000 or 2010. Yet, a comparison of cohorts revealed a possible migration effect. In 2000, children aged 10–14 made up 10.3% of the western population, but by 2010 the corresponding 20–24 age group accounted for only 8.4%. This drop could not be explained by mortality alone; it likely reflected net out-migration of young adults, particularly those with tertiary education, from west to east.

3.3. Multidimensional Variations in Population Proportions on Both Sides of the Hu Line

Extending the analysis of both age and education (Table 1), we found that in 2000, the west area accounted for 6.07% of China’s total population, compared with 93.93% in the east. By age group, the western shares were 6.92% for children (0–14), 5.98% for working-age adults (15–64), and 4.29% for the elderly (65+), indicating a lighter aging burden. Between 2000 and 2010, the west’s total population share rose slightly by 0.2 percent, but the

share of the elderly increased by 0.73 percent, suggesting that aging was accelerating in the west.

Table 1. Changes in population proportions by age group and educational attainment east and west of the Hu Line.

Type		2010				2000				West Side of Hu Line Specific Gravity Change (%)
		Population (in Millions)		Population Proportion (%)		Population (in Millions)		Population Proportion (%)		
		West of the Hu Line	East of the Hu Line	West of the Hu Line	East of the Hu Line	West of the Hu Line	East of the Hu Line	West of the Hu Line	East of the Hu Line	
Total population		85	1277	6.27	93.73	77	1196	6.07	93.93	0.2
Age	0–14 years old	16	210	7.02	92.98	20	270	6.92	93.08	0.1
	15–64 years old	63	950	6.26	93.74	53	838	5.98	94.02	0.28
	Aged 65 and above	6	116	5.02	94.98	4	87	4.29	95.71	0.73
Education	Uneducated	13	139	8.45	91.55	19	178	9.53	90.47	−1.08
	Primary education	26	336	7.23	92.77	27	419	6.04	93.96	1.19
	Secondary education	39	681	5.36	94.64	29	547	5	95	0.36
	Tertiary education	8	121	6.12	93.88	3	52	5.18	94.82	0.94

Educationally, uneducated people in the west were disproportionately high in 2000 (9.53% vs. its 6.07% population share). The proportion of primary-educated people roughly matched the population proportion, while secondary (5%) and tertiary education (5.18%) shares lagged behind. From 2000 to 2010, the proportion of uneducated people declined by 1.08 percentage points, while primary, secondary, and tertiary education proportions rose by 1.19, 0.36, and 0.94 percent, respectively. These trends showed significant progress in reducing illiteracy and improving primary education, slower progress in secondary education, and a relatively strong foundation for tertiary education in the west of China.

Overall, the west's population share grew only slightly between 2000 and 2010, but its demographic profile remained younger and less educated than the east. The areas of the west also experienced faster aging, marked gains in literacy and primary schooling, moderate improvement in tertiary education, but persistently slow progress in secondary education.

4. Future Trends in Multidimensional Demographic Characteristics on Both Sides of the Hu Line

4.1. The Approach of the Multidimensional Demographic Model

The multidimensional demographic model can be summarized as follows: starting with $t = 2000$ as the jump-off year for the back projection for which we have a full distribution of population by age (five-year age groups), sex and level of education (four categories), when there are no transitions between education levels, we go back in time in five-year intervals to calculate the same full distribution for year $t - 5$ according to:

$$N(\text{age} - 5, \text{educ}, t - 5, \text{sex}) = \frac{N(\text{age}, \text{educ}, t, \text{sex})}{\text{Survival Ration}(\text{age} - 5, \text{educ}, t - 5, \text{sex})} \quad (1)$$

where

$N(\cdot)$ refers to the number of people in the group defined by $(\cdot)$;

age refers to the five-year age group starting with age α (e.g., $\alpha = 20$ refers to the age group 20–24);

educ refers to the educational attainment category;

t refers to calendar year t and $t - 5$ to five years earlier;

sex refers to the gender of individuals;

Survival Ration($\cdot$), refers to the proportion of people surviving for five years in the country (i.e., combining mortality and migration) in each age-, sex- and education-specific group over the period $t - 5$ to t .

The four educational attainment states are defined as:

- No education: those who have never been to school and have received no formal education (no education);
- Primary: those with uncompleted primary to uncompleted lower secondary education (completed primary);
- Secondary: those with completed lower secondary to uncompleted first level of tertiary education (completed lower secondary, completed upper secondary or completed post-secondary, non-tertiary);
- Tertiary: those who at least completed the first level of tertiary (tertiary completed).

The key steps taken in producing reconstruction results:

Step 1: Find reliable empirical information on the proportions of population by levels of educational attainment for men and women for five-year age groups for the base year (around 2000).

Step 2: Adjust the educational categories.

Step 3: Apply the empirical proportions to the age structure for the year 2000.

Step 4: Obtain the period life expectancy at age 15 for all men and women from the general model life table as used for the corresponding country for the period 1995–2000.

Step 5: Calculate the corresponding education-specific period life expectancy at age 15 by using education differentials in life expectancy as described in Section 4.3.

Step 6: Obtain survival ratios for all five-year age groups above age 15 corresponding to each education–sex-specific period life expectancy at age 15.

Step 7: Calculate the number of people $N(\text{age}, \text{educ}, \text{sex}, 1995)$ by age (age going from 15–19 to 80–85), sex and education living five years earlier (in 1995) by using Equation (1) above.

Step 8: Adjust for the transitions to secondary and tertiary education that happen after the age of 15.

Step 9: Convert the number of people by age and education calculated for 1995 ($t - 5$) into age and sex-specific proportions and apply to the estimates of population structure for this year in order to assure full consistency (including adjustments for migration).

4.2. The Prediction of China's Total Population in the Future

As the most populous country in the world, China's demographic outlook has long attracted both domestic and international attention. Assuming fertility remained between 1.5 and 1.6 under continued family planning policies, organizations such as the United Nations Development Programme (UNDP) and China's National Population and Family Planning Commission (NPFPC) projected that China's population would peak at about 1.41 billion between 2025 and 2030 before declining to 1.25–1.3 billion by 2050, with aging becoming increasingly severe [17,31]. Under alternative policy scenarios—including partial or full relaxation of the one-child policy—population peaks would be delayed by 5–30 years, with totals reaching 1.4–1.5 billion by 2050 [17]. Consequently, scholarly concern shifted from overall population size to issues such as aging, education, and the urban–rural divide [32].

Against the backdrop of sustainable development and global climate change, Lutz and Striessnig argued that research on population size, distribution, quality, and structure must move beyond traditional demographic frameworks [25]. This led to the proposal of Shared Socioeconomic Pathways (SSPs) for future development [33]. Together with Representative Concentration Pathways (RCPs), which describe greenhouse gas emissions, the SSPs form a critical framework linking socioeconomic development with environmental change in climate research [25].

The International Institute for Applied Systems Analysis (IIASA) and partners developed global SSPs, providing projections for population, urbanization, and economic development across different scenarios [33]. The SSPs outline five baseline development pathways [34]. Among them, SSP2 represents a “middle of the road” trajectory, where social, economic, and technological trends continue broadly along historical patterns. Fertility, mortality, and migration remain at moderate levels, while educational attainment rises steadily. SSP1 and SSP5 envision rapid economic growth, strong institutions, and substantial investment in health and education. Tertiary education—especially among women—lowers fertility, reduces mortality, and extends life expectancy [18]. Migration is moderate under SSP1 but higher under SSP5, which emphasizes economic efficiency. SSP5 is characterized as fossil fuel-intensive growth, while SSP1 represents a shift toward sustainability. SSP3 focuses on regional competition, prioritizing food and energy security at the cost of broader development. It features relatively high fertility and mortality, coupled with lower migration due to weak economic growth. SSP4 envisions a world of stark inequality, where high-fertility countries experience high birth and death rates while wealthier nations maintain low fertility, moderate mortality, and moderate migration [31,33].

4.3. Comparative Analysis of Population Scenarios Across Three Versions of China's SSPs

4.3.1. IIASA Version of China's SSPs Population Scenarios

Samir and Lutz classified China as a low-fertility country in their SSP framework [31], setting its future total fertility rate (TFR) at 1.5—consistent with the UNDP and related estimates [17]. Under SSP1 and SSP5, both fertility and mortality are low, so natural population growth is slower than under SSP2. By contrast, SSP3 assumes higher fertility and mortality, producing faster growth than SSP2. SSP4 represents a pessimistic scenario with low fertility and medium mortality, leading to the fastest population decline. The IIASA global SSPs considered only international migration. Jones et al. used a population potential model combined with SSP-based urbanization assumptions to project future global population distribution at a 10 km resolution [35,36].

Figure 4a,b illustrates population trends east and west of the Hu Line based on these projections. Since the IIASA version does not account for regional variation in natural growth rates or policy changes, the results have limitations [37]. Under SSP2, China's population peaks around 2025, then declines. By 2050, the east is projected to have 1.18 billion people, and the west 79 million. Under SSP1, the peak occurs in 2030, followed by a faster decline than SSP2; SSP4 shows the steepest decline. Only SSP3 results in a slight increase in the west's share, while SSP1/5 and SSP4 reduce it. A key takeaway from the IIASA version is that—absent regional variation—China's western population share may stagnate or even decline by 2050. This outcome reflects three factors: the overall national decline in population, rising urbanization, and the concentration of major urban centers in the east. With limited urban growth capacity in the west, more migrants move eastward, reducing the west's population share. Only under SSP3, with slower urbanization and migration, does the west's share rise modestly.

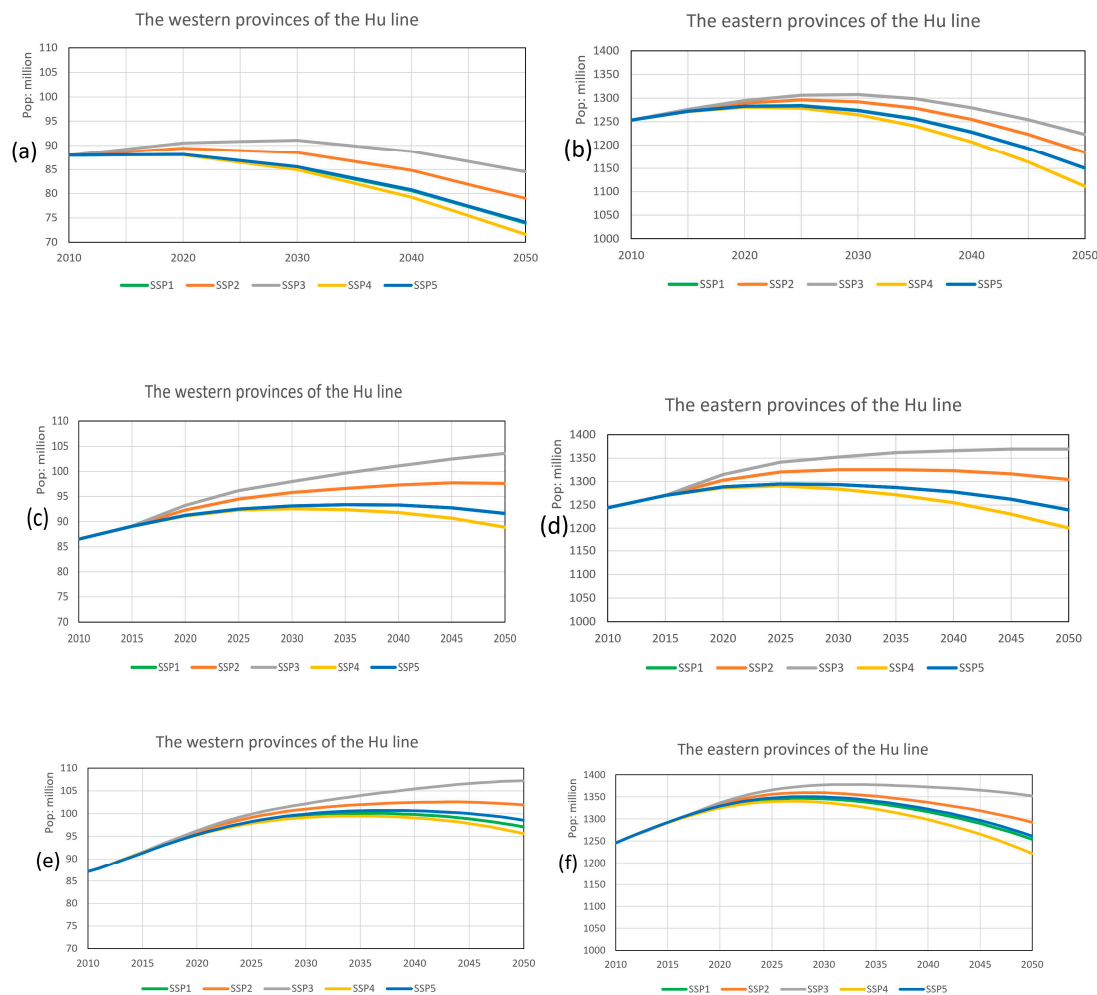


Figure 4. Population trends from 2010 to 2050 on the eastern and western sides of the Hu Line under SSPs. (a,b) IIASA version; (c,d) NUIST version; (e,f) Tsinghua version.

4.3.2. NUIST Version of China's SSP Population Scenarios

Recognizing the IIASA version's shortcomings—particularly its neglect of China's regional fertility differences and family planning reforms—Jiang et al. at Nanjing University of Information Science and Technology (NUIST) developed provincial-level SSP projections using a multidimensional demographic model [31,38]. A major revision concerned fertility assumptions. After China fully relaxed the two-child policy in 2015, Jiang et al. modeled a temporary fertility rebound. In the SSP2 medium-fertility pathway, TFR rises from 1.18 in 2010 to 1.85 in 2020 before stabilizing at 1.8 after 2025. Under SSP3, TFR climbs to 2.25 by 2050. In contrast, in SSP1/4/5, TFR peaks at 1.67 in 2020 before falling to 1.35 by 2050. Mortality and life expectancy assumptions follow SSP conventions, with provincial convergence toward high-longevity benchmarks. Migration is modeled using historical provincial patterns: medium assumptions (SSP1/2/4) maintain current rates, SSP3 lowers them, and SSP5 raises them. Since the 1980s, inland provinces east of the Hu Line have experienced net out-migration, while coastal provinces have seen net immigration. West of the Hu Line, however, net migration has remained negligible.

Figure 4d presents the projected population changes for the provinces east of the Hu Line based on the NUIST model. Under the SSP2 “middle-of-the-road” pathway, the population is projected to peak at approximately 1.33 billion in 2035, followed by a gradual decline to about 1.30 billion by 2050. Under SSP3, the population continues to grow slowly, reaching around 1.37 billion by 2050. In contrast, under the SSP1/5 pathway, the popula-

tion peaks earlier, at roughly 1.30 billion in 2025, and then gradually declines to 1.24 billion by 2050. The SSP4 pathway shows the sharpest decline, with the population decreasing to about 1.20 billion by 2050. Figure 4c shows the projected population changes for the provinces west of the Hu Line based on the NUIST model. Owing to relatively high fertility rates, the population is expected to continue modest growth under the SSP2 pathway, reaching approximately 98 million by 2050. Under SSP3, the population is projected to increase further to about 104 million by 2050. In the SSP1/5 pathway, the population peaks at roughly 94 million in 2040 and then gradually declines, while under SSP5 it peaks earlier, at 93 million in 2035, before beginning to fall. By 2050, the share of the population in the western provinces relative to 2010 is projected to rise by 0.76 percentage points under SSP3, 0.61 percentage points under SSP1/5 and SSP4, and 0.69 percentage points under SSP2 (Table 2). This increase in the population share of the western provinces is primarily driven by their relatively high fertility rates and gradual improvements in life expectancy, while low levels of net migration have only a limited effect on the population balance between the eastern and western sides of the Hu Line.

Table 2. Population proportions and their changes on the eastern and western sides of the Hu Line across the IIASA, NUIST, and Tsinghua versions.

Type		2010		2030		2050		2010–2030	2010–2050
		Population Ratio (%)		Population Ratio (%)		Population Ratio (%)		Change in Population Proportion	Change in Population Proportion
		West of the Hu Line	East of the Hu Line	West of the Hu Line	East of the Hu Line	West of the Hu Line	East of the Hu Line	on the West Side of the Hu Line (%)	on the West Side of the Hu Line (%)
IIASA	SSP1	6.27	93.73	6.28	93.72	6.04	93.96	0.01	−0.23
	SSP2	6.27	93.73	6.41	93.59	6.26	93.74	0.14	−0.01
	SSP3	6.27	93.73	6.51	93.49	6.47	93.53	0.24	0.2
	SSP4	6.27	93.73	6.29	93.71	6.05	93.95	0.02	−0.22
	SSP5	6.27	93.73	6.28	93.71	6.04	93.96	0.01	−0.23
NUIST	SSP1	6.27	93.73	6.72	93.28	6.88	93.12	0.45	0.61
	SSP2	6.27	93.73	6.74	93.26	6.96	93.04	0.47	0.69
	SSP3	6.27	93.73	6.75	93.25	7.03	92.97	0.48	0.76
	SSP4	6.27	93.73	6.72	93.28	6.89	93.12	0.45	0.61
	SSP5	6.27	93.73	6.72	93.28	6.88	93.12	0.45	0.61
Tsinghua	SSP1	6.27	93.73	6.89	93.11	7.18	92.82	0.62	0.91
	SSP2	6.27	93.73	6.92	93.08	7.32	92.68	0.65	1.05
	SSP3	6.27	93.73	6.9	93.1	7.35	92.65	0.63	1.08
	SSP4	6.27	93.73	6.91	93.09	7.28	92.72	0.64	1.01
	SSP5	6.27	93.73	6.89	93.11	7.27	92.73	0.62	1

4.3.3. Tsinghua Version of China's SSP Population Scenarios

Building on the recognition of limitations in the IIASA version of China's SSP population pathways, Chen Yidan, Cai Wenjia, and colleagues at Tsinghua University [37] developed an alternative set of projections. While the Tsinghua version follows the general modeling framework and scenario design by Samir and Lutz [31], it incorporates distinct assumptions regarding parameter settings and policy interventions. Similar to the NUIST version [36], it emphasizes the importance of accounting for China's internal regional heterogeneity. Accordingly, the Tsinghua scenarios adopt province-level population projections and explicitly incorporate shifts in family planning policies. For fertility, three scenarios are considered: an effective two-child policy (medium fertility), a fully liberalized policy (high fertility), and an ineffective policy (low fertility). Drawing on the findings of Zhai et al. [39] and Wang [40], which suggest that the 2010 census substantially underestimated China's total fertility rate (TFR), the Tsinghua SSP2 baseline adjusts the 2010 TFR upward from 1.18 to 1.6. Under this pathway, the TFR rises from 1.6 in 2010 to 1.8 in 2020, before stabilizing at 1.65. In the high-fertility scenario (SSP3), TFR reaches 2.0 in 2020 and remains about 25% above the SSP2 level by 2050. By contrast, in the low-fertility scenar-

ios (SSP1/4/5), TFR increases modestly between 2010 and 2020 before declining, ending 25% below the SSP2 level by 2050. The fertility gap between SSP3 and SSP1/4/5 relative to SSP2 is broadly symmetric. At the provincial level, fertility is modeled using matrices that cross-tabulate women of childbearing age (15–49) by education level and province, derived from the 2010 census, extending the country-level approach of the IIASA version. Life expectancy assumptions also differ across pathways. In the medium scenario (SSP2), life expectancy increases by one year per decade, with provincial figures adjusted using 2010 census mortality ratios, converging to the UN medium projection for China (87 years) by 2100. In the low-expectancy scenarios (SSP1, SSP5), life expectancy rises by 0.5 years per decade, converging to 82 years by 2100, while the high scenario (SSP3) assumes an increase of 1.5 years per decade, converging to 91 years. Provincial life expectancy and mortality rates are initialized using age- and sex-specific data from the 2010 census. For inter-provincial migration, the Tsinghua version introduces the concept of development stages, categorizing provinces into high-, medium-, and low-economic-level groups. High-level provinces (mostly coastal, with the exception of Inner Mongolia) are assumed to impose population caps to limit over-concentration, leading their net migration to approach zero. Low-level provinces (mainly inland provinces east of the Hu Line, excluding Tibet and Gansu) are characterized by negative net migration due to outflows of labor. Medium-level provinces (including Qinghai, Ningxia, and Xinjiang west of the Hu Line) are projected to adopt more talent-attraction policies, resulting in positive migration. These assumptions effectively embed household registration policies into migration dynamics. Because the six provinces west of the Hu Line are modeled with mixed assumptions of net inflow, net outflow, and zero migration, overall net migration in this region remains low. International migration is also incorporated. The baseline net international migration rate in 2010 is set at -0.3015% (net outflow), applied uniformly across provinces. In the medium scenario (SSP1/2/4), this rate remains constant through 2050. In the high (SSP5) and low (SSP3) scenarios, the rate is increased or decreased by 50%, respectively.

Turning to regional projections, provinces east of the Hu Line (Figure 4f) are projected to peak at 1.36 billion in 2030 under SSP2 before declining to about 1.295 billion by 2050. Under SSP3, the peak occurs around 2035 at 1.38 billion, followed by a gradual decline to 1.35 billion by 2050. Both SSP1 and SSP5 reach a peak of about 1.35 billion around 2030, but due to stronger net outflows in SSP5, the 2050 populations are 1.255 billion and 1.25 billion, respectively. The SSP4 pathway peaks earlier, at 1.34 billion in 2025, before declining more rapidly to 1.22 billion by 2050. Provinces west of the Hu Line (Figure 4e) display a different trajectory. Under SSP2, the population peaks at 125 million in 2045 before declining gradually, while SSP3 projects steady growth to 107 million by 2050. SSP1 and SSP5 both peak in 2040 and decline to 98 million and 97 million, respectively, by 2050. The SSP4 pathway peaks earlier, in 2035, before falling to 95 million in 2050. Compared with 2010, the western population share in 2050 increases the most under SSP3 (by 1.08 percentage points), followed by SSP2 (1.04 percentage points), with the smallest gain observed under SSP1 (0.91 percentage points) (Table 2).

4.3.4. Summary Across Three Versions of China's SSPs

All three versions are grounded in the design framework of the Shared Socioeconomic Pathways (SSPs) [33]. This framework conceptualizes socioeconomic development along the dual dimensions of climate change mitigation and adaptation—for example, contrasting pathways reliant on fossil fuels with those emphasizing low-carbon sustainable development. It further incorporates variations in investments in education, healthcare, and technology. Taken together, these factors yield differentiated projections for fertility, mortality, migration, and urbanization [33].

In terms of fertility scenarios, the IIASA version [31] assumes that China's total fertility rate (TFR) will stabilize at 1.5 under the medium pathway (SSP2), without incorporating the potential effects of adjustments to family planning policy. By contrast, the revisions introduced in the Nanjing University of Information Science and Technology (NUIST) version [38] and the Tsinghua University version [37] place greater emphasis on capturing these policy changes. Both models consider the cumulative effects of the earlier one-child policy, projecting a period of rising fertility followed by stabilization. In the NUIST version, the TFR peaks at 1.85 in 2020, while the Tsinghua version places this peak slightly lower, at 1.8. The two versions also differ markedly in their assumptions about the 2010 baseline: the NUIST model adopts 1.18 based on the Sixth National Population Census, whereas the Tsinghua version adjusts this value upward to 1.6. Looking ahead, the NUIST version assumes a higher stable TFR of 1.8 after 2025, compared with a more conservative 1.65 in the Tsinghua model. For the high-fertility scenario (SSP3), the IIASA version projects an increase in TFR but keeps it below 2. In contrast, both the NUIST and Tsinghua versions anticipate sustained increases, with TFRs exceeding 2 between 2025 and 2030. Under the low-fertility scenarios (SSP1/4/5), both models incorporate fertility compensation effects following the relaxation of family planning policies, resulting in stable TFRs after 2025 that are lower than the SSP2 baseline. The IIASA model, however, does not account for such effects. A more fundamental distinction lies in scale: the global SSPs framework developed by IIASA and its partners is constructed at the national level, which precludes capturing China's substantial regional heterogeneity. Both the NUIST and Tsinghua versions address this limitation by adopting provincial-level TFRs from the 2010 census as their baseline, and then adjusting them in line with national fertility trajectories. This approach explicitly reflects the relatively higher fertility rates characteristic of provinces west of the Hu Line in future demographic projections.

With respect to mortality and life expectancy scenarios, the IIASA, Nanjing University of Information Science and Technology (NUIST), and Tsinghua University versions exhibit broad similarities. Under the medium pathway (SSP2/4), life expectancy is projected to rise by two years per decade in the IIASA model, compared with one year per decade in both the NUIST and Tsinghua versions. In the high- and low-life-expectancy scenarios (SSP1/5 and SSP3), values are adjusted upward or downward relative to the medium-scenario baseline. A key distinction lies in the treatment of regional variation. The IIASA version does not incorporate subnational heterogeneity within China, whereas the NUIST and Tsinghua versions derive initial estimates from 2010 provincial census data and then adjust them according to national-level life expectancy trajectories. Overall, provincial life expectancy is projected to converge gradually toward that of higher-expectancy provinces or the benchmark values set by the United Nations for China. Provinces that currently have lower life expectancy are expected to experience more rapid gains in the future.

In terms of migration rate scenarios, the IIASA version built by Jones [35] integrates SSP population projections [31] and urbanization scenarios [36]. This approach considers the urban–rural spatial distribution and applies distinct migration radii and damping coefficients to urban and rural populations to simulate future population redistribution. By contrast, the Nanjing University of Information Science and Technology (NUIST) and Tsinghua University versions primarily focus on interprovincial migration. The NUIST version adopts provincial net migration rates from 2005 to 2010 as initial values, maintaining them under the medium-migration scenario, while the high- and low-migration scenarios are derived by proportionally increasing or decreasing these baseline rates. The Tsinghua version classifies provinces into three migration patterns based on their level of economic development and establishes high-, medium-, and low-migration scenarios accordingly. It then incorporates SSP urbanization rate scenarios at the provincial level to estimate in-

traprovincial urban–rural population redistribution. As a result, both the NUIST and Tsinghua versions constrain spatial redistribution to within provincial boundaries. In the IIASA framework, interprovincial and intraprovincial migration are conceptually analogous to international and domestic migration. In practice, however, the boundary between inter- and intraprovincial migration is often indistinct. By transcending these boundaries, Jones modeled nationwide urban–rural migration, producing results of considerable reference value [35]. In the Tsinghua framework, migration rates in economically developed provinces are assumed to converge gradually toward zero under different speeds (high, medium, low). In contemporary China, restrictions on population mobility are mainly imposed at the urban scale through the household registration (hukou) system to mitigate the adverse impacts of megacities [41]. Applying similar constraints at the provincial scale, however, remains debatable.

4.4. Future Population Size and Proportion Changes on Both Sides of the Hu Line

Figure 4 illustrates the projected population trends on both sides of the Hu Line in China from 2010 to 2050, simulated using three versions of the SSP population scenarios. Under the IIASA version of China's SSPs, the overall future population trends for provinces west of the Hu Line (Figure 4a) and east of the Hu Line (Figure 4b) are similar. Nearly all SSPs indicate that China's future population will continue to decline. Even under the SSP3 pathway, China's population will peak in 2025 and gradually decrease thereafter. This stems from the IIASA SSPs setting different birth rates, death rates, and urbanization rates without accounting for regional variations within China. They fail to capture regional differences in China's natural population growth rate and do not respond to changes in China's family planning policies. While the authenticity of the IIASA simulation results warrants discussion, it yields a significant conclusion: assuming no regional variations in natural population growth rates, the population share west of the Hu Line in China may decline rather than increase by 2050 (Table 2). This occurs because, under projections of declining total population and increasing urbanization rates, coupled with China's spatial pattern where urban areas predominantly cluster east of the Hu Line, the limited scale and number of cities west of the Hu Line will drive greater migration of urban populations eastward, thereby reducing the population proportion west of the Hu Line. Only under the SSP3 pathway (low population decline, low migration rates, and slow urbanization) does the population proportion west of the Hu Line show a slight increase (Table 2).

The future population trends on both sides of the Hu Line under the SSPs in the NUIST version (Figure 4c,d) and the Tsinghua version (Figure 4e,f) differ significantly from the results of the IIASA version. Specifically, provinces west of the Hu Line exhibit peak populations between 2035 and 2040 followed by stabilization under SSP2 (medium development), sustained growth under SSP1, and gradual decline after peaking in 2040 under other SSPs. The population of provinces east of the Hu Line in the Tsinghua version exhibit trends of initial increases followed by a decline across all SSPs. Conversely, populations of the NUIST version show a continuing rise under SSP3, while other SSPs result in initial increases followed by declines. This discrepancy stems from differing projections for China's total fertility rate—its initial level, peak, and stabilization phase—following the implementation of the new family planning policy.

The future population growth rates projected for provinces west of the Hu Line in both NUIST and Tsinghua versions exceed those of eastern provinces primarily due to relatively higher birth rates and faster increases in life expectancy in western provinces. However, regarding changes in the population share, the Tsinghua version projects a greater increase in the population share of provinces west of the Hu Line compared to the NUIST

version (Table 2). Beyond differing projections for the total fertility rate following fertility policy changes, the Tsinghua version's SSPs set migration rates that gradually approach zero in the future from economically developed provinces which are located east of the Hu Line, which constrains population migration from provinces west of the Hu Line (relatively economically underdeveloped) to economically developed provinces. Consequently, the upward trend in population share driven by higher birth rates in provinces west of the Hu Line is sustained. In summary, due to provincial-level simulation analysis and considerations such as changes in China's family planning policy, both the UNIST version and the Tsinghua version indicate that the population share of provinces west of the Hu Line in China will experience steady growth in the future (Table 2).

4.5. Future Multidimensional Changes in Population Proportions on the Eastern and Western Sides of the Hu Line

Compared to shifts in population size proportions, changes in the share of the population characterized by specific age groups and educational attainment levels warrant greater attention. Figure 5 presents the proportion of the population aged 0–14 and 15–64 with specific educational attainment levels west of the Hu Line in 2030 (Figure 5 top) and 2050 (Figure 5 bottom) under the Tsinghua version of the SSPs. This proportion is shown as a bar chart representing the share of the national population with corresponding characteristics and as a scatter plot illustrating the change relative to 2010. To validate the reliability of the simulated data, a regression analysis was conducted comparing the 2015 provincial-level simulated population by age and education level under the SSPs with the national 1% population sample survey data (2015) (Figure 6). The linear regression correlation coefficients R^2 for different age groups were all above 0.99, while those for different education levels were above 0.97. This indicates that the Tsinghua version of the SSP population scenario simulation data possesses high credibility.

By age group, the population of youth aged 0–14 west of the Hu Line in 2030 and 2050 is characterized by a large base and a high proportion, though its growth rate is relatively slow compared with overall changes in the western population proportion. The working-age population (15–64) west of the Hu Line exhibits slightly higher base numbers and proportions, with moderately faster growth relative to the total population proportion. The elderly population (65+) shows a low base and proportion but experiences a comparatively rapid increase. Overall, compared to the eastern side, the areas west of the Hu Line will retain a relatively younger population structure and enjoy a significant demographic dividend in the near future. However, this advantage is projected to gradually diminish, and by 2050, the western area will also face challenges related to population aging. Moreover, across different SSPs, the differences in age-specific population shares west of the Hu Line remain small, indicating that regardless of the SSP scenario, the trend of the western side aging faster than the eastern side is expected to persist.

In terms of educational attainment, the uneducated population west of the Hu Line in 2030 and 2050 is characterized by a large base, high proportion, and differing growth rates across SSPs. Specifically, under the SSP3 and SSP4 scenarios, the proportion of uneducated individuals is projected to increase relatively rapidly. In contrast, under SSP1, SSP2, and SSP5, the growth rate of the uneducated population's share by 2050 is lower than the overall population growth rate, indicating that although the absolute number of uneducated individuals may rise, their relative share will decline. The population with primary education west of the Hu Line in 2030 and 2050 shows a large base, high proportion, and substantial growth relative to the overall population proportion. Comparing 2030 and 2050, while the overall population proportion continues to rise and the uneducated population proportion remains largely stable (except under SSP4), the increasing share of the population with primary education suggests that a significant portion of the previously

uneducated population have acquired basic education, effectively reducing illiteracy in the area west of the Hu Line. For secondary education, the growth rate of the population proportion slightly lags behind overall population growth in 2030 but exceeds it by 2050. Despite this progress, the overall foundation for secondary education in the area west of the Hu Line remains relatively weak. The population with tertiary education exhibits a relatively stable proportion, with growth consistently outpacing that of the overall population in the area west of the Hu Line.

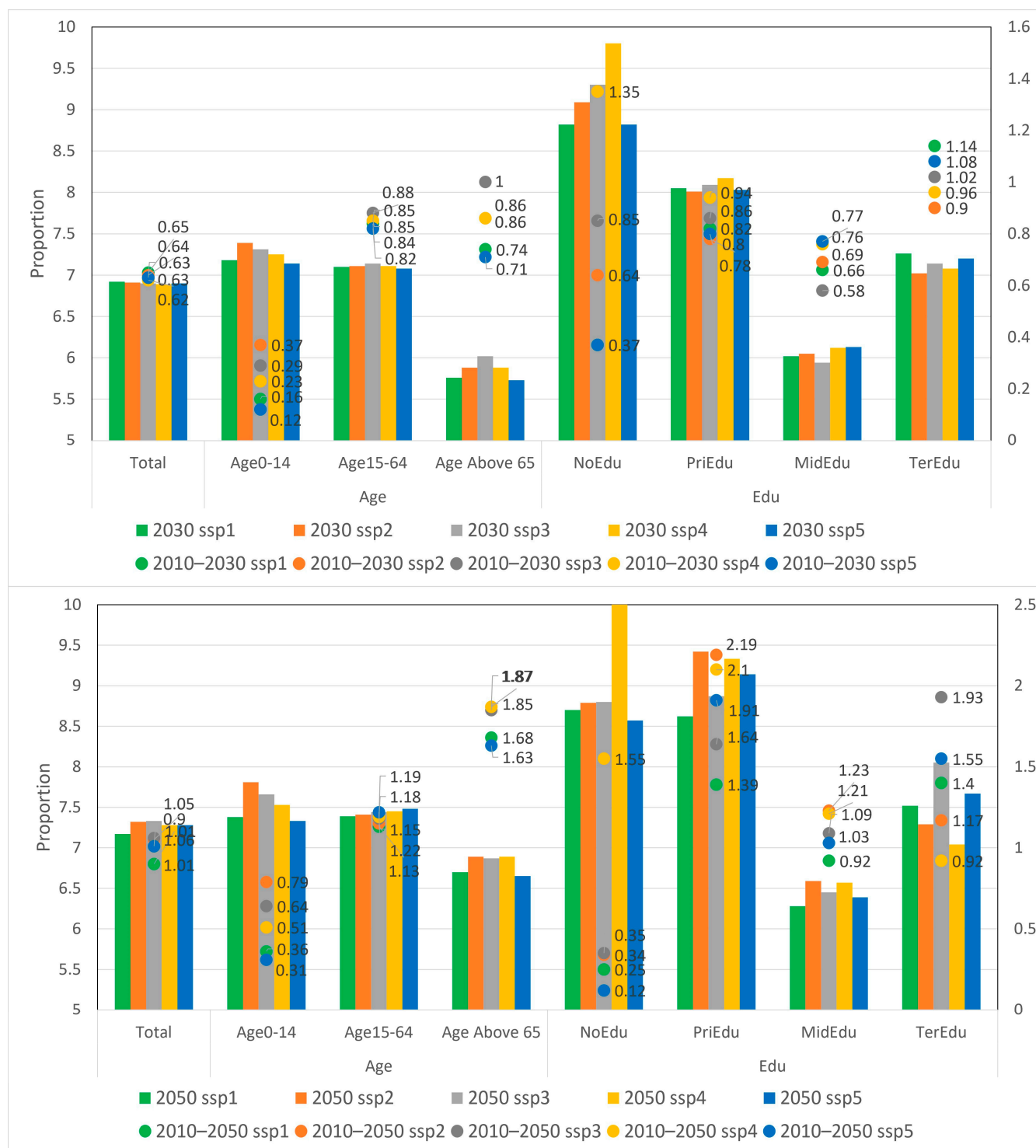


Figure 5. Proportion and changes in population by different demographics west of the Hu Line under SSPs in 2030 (**top**) and 2050 (**bottom**).

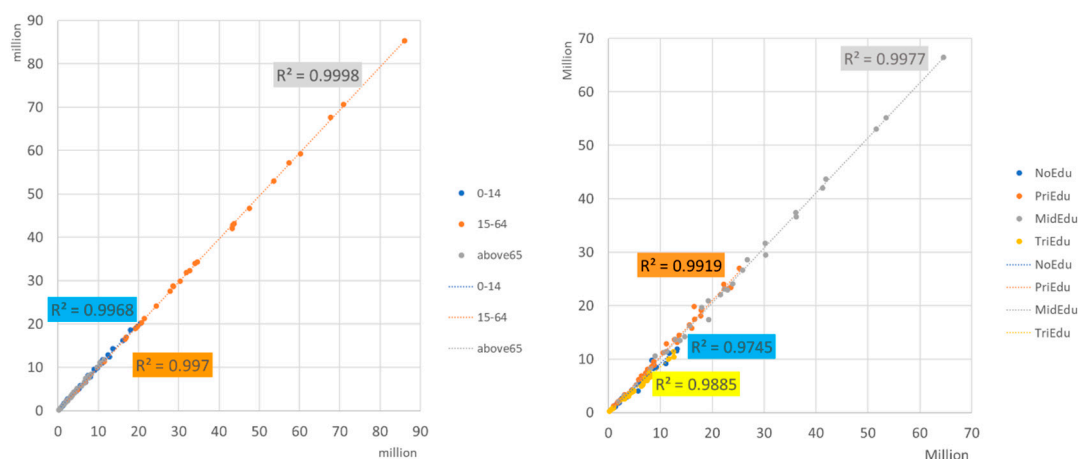


Figure 6. Regression analysis of population by age (**left**) and education level (**right**) (the horizontal axis represents the simulated population number in 2015 under SSPs scenario, and the vertical axis represents 1% national sample census in 2015).

5. Summary

5.1. Breakthrough Mechanisms of the Hu Line Under Population–Socioeconomic–Natural Environment Coupling

Dynamic changes in population size, distribution, quality, and structure have become a critical interface connecting socioeconomic systems with natural environmental systems in research on sustainable development and climate change. Population size, quality, and structure together constitute the first driving force of population dynamics, influencing spatial changes in population distribution—including attributes such as gender, age, and education. These population dynamics affect socioeconomic development—covering production, consumption, technological progress, culture, and trade—while socioeconomic development, in turn, feeds back by shaping population dynamics and spatial distribution through impacts on births, deaths, and migration, forming the second layer linking population and socioeconomic development. Regional differences and future changes in population size, distribution, and structure will face varying challenges arising from both climate change mitigation and adaptation, which together form the third layer encompassing the interaction between socioeconomic development and the natural environment. Collectively, these three layers constitute the driving mechanisms behind the potential breakthrough of the Hu Line, forming an integrated and dynamic system.

5.2. Changes in Population Proportions on Both Sides of the Hu Line Under Shared Socioeconomic Pathways (SSPs)

Within the context of climate change and sustainable development, Shared Socioeconomic Pathways (SSPs) provide a practical framework for exploring the potential for future shifts on both sides of the Hu Line. A comparative analysis of three Chinese SSP population scenarios—from IIASA, NUIST, and Tsinghua—reveals that, despite differences in population dynamics parameters, responses to family planning policy changes, and provincial-level initial values and scenario settings, a consistent pattern emerges. Under the SSP3 scenario, the population proportion west of the Hu Line is projected to increase the most by 2050, followed by the intermediate SSP2 scenario, while the smallest increases are observed under SSP1, SSP2, and SSP5. In the NUIST version, the 2050 increase ranges from 0.61 to 0.76 percentage points across SSPs; in the Tsinghua version, it ranges from 0.91 to 1.08 percentage point; whereas the IIASA version shows a 0.2 percentage point increase under SSP3, with other SSPs predicting a decline relative to 2010. Simulations from the NUIST and Tsinghua versions suggest that the future rise in the population propor-

tion west of the Hu Line primarily depends on maintaining relatively high fertility rates and relatively rapid gains in life expectancy. Conversely, IIASA simulations indicate that, without accounting for regional differences in natural population growth rates, China's urban–rural spatial distribution patterns and rapid urbanization could lead to a decrease in the population share west of the Hu Line. Ultimately, differences in natural population growth and urbanization rates across scenarios and regions govern shifts in population distribution on either side of the Hu Line.

5.3. Shared Socioeconomic Pathway (SSP) Selection and Its Influence on Multidimensional Population Characteristics Across the Hu Line

Under the SSPs, variations in age-specific population proportions west of the Hu Line are relatively small. In contrast, differences in population proportions by educational attainment are more pronounced. For instance, the 2050 projections under SSP4 indicate exacerbated regional disparities, with a rapid decline in China's total population and accelerated aging—particularly in provinces west of the Hu Line, where the population's educational structure deteriorates more severely. Although SSP1, labeled as a sustainable development pathway, predicts substantial improvements in education, the scenario also depicts a sustained rapid decline in total population and intensified aging, which does not reflect truly sustainable population development for China. SSP5 follows similar socioeconomic trends as SSP1 but is associated with extremely high greenhouse gas emissions under RCP8.5, posing severe potential impacts on the natural environment [33,34]. SSP3, implementing a fully open fertility policy, results in a high natural population growth rate, making continuous population increase more likely. However, slow economic development and limited investment in education and healthcare mean that, despite the fastest population growth west of the Hu Line, China faces dual challenges in climate change mitigation and adaptation. Even though tertiary education enrollment grows rapidly west of the Hu Line, overall population educational quality declines. Overall, the intermediate SSP2 pathway appears most appropriate for China's future, projecting a stable-to-decreasing total population. West of the Hu Line, the population proportion will rise relatively quickly, driven by faster increases in primary and secondary education enrollment, while the proportion of uneducated individuals grows more slowly (below overall population growth, indicating a relative reduction in illiteracy). Meanwhile, the proportion of tertiary education enrollment largely keeps pace with total population growth.

5.4. Increasing Investment in Basic Education in Provinces West of the Hu Line

The educational structure in the provinces west of the Hu Line is characterized by weak basic education. Although some improvements are expected in the future, simultaneously stabilizing and increasing the population proportion in these areas while raising overall educational attainment is highly challenging given the current level of economic development. Beyond selecting appropriate socioeconomic development pathways, the government needs to increase both policy and financial support for primary and secondary education in these western provinces. Special attention should be given to developing technical and vocational schools that align with the region's environmental characteristics and industrial strengths, such as modern agriculture, animal husbandry, and energy sectors. Measures like tuition waivers and enhanced subsidies should be implemented to address gaps in basic education.

5.5. Rational Layout and Development of New-Type Towns in Provinces West of the Hu Line

The population proportion with tertiary education on the western side of the Hu Line approaches the national average level. This is likely due to the government's consideration of population distribution when allocating universities across regions, as well as the

substantial portion of tertiary education funding provided by state finances. However, a comparative analysis of population pyramids from 2000 and 2010 shows a net migration trend of highly educated individuals from the western to the eastern side of the Hu Line. Moreover, IIASA model simulations indicate that varying urbanization rates and China's urban–rural distribution patterns could further drive net population inflows into eastern provinces. The provinces west of the Hu Line should seize opportunities from national strategies such as the Belt and Road Initiative [42,43] and New-Type Urbanization [6,7]. By strategically planning and promoting urbanization in areas with relatively abundant water resources, these provinces can create more employment opportunities and establish hubs for talent concentration, helping retain highly educated populations.

6. Future Work

Regarding population dynamics under SSP scenarios for China's provinces, the versions from NUIST and Tsinghua largely follow the IIASA model methodology at the national scale. Their improvements primarily involve further consideration of future birth rates, death rates, and migration rates under different SSP scenarios across China's provinces. Therefore, compared to the IIASA version, which conducts downscaled simulations at the national level, the NUIST and Tsinghua versions better align with China's actual conditions. However, they still have shortcomings, namely that migration rates between Chinese provinces are more complex than international migration between countries. Furthermore, due to changes in family planning policies and China's overall trend toward low fertility and aging, fertility and mortality rates vary across regions. Consequently, when analyzing and utilizing actual SSP simulation data, greater emphasis should be placed on comparing relative changes across different eras and scenarios. Regarding population dynamics under future SSP scenarios, greater emphasis should be placed on statistically significant changes in both the mean and variance.

In future work, we should conduct further integrated analyses combining climate change RCP scenarios to develop assessments under various combined scenarios. This will enable deeper analysis and discussion on how population dynamics can adapt to and mitigate climate change.

Author Contributions: Conceptualization: H.X.; methodology: H.X., Q.L.; formal analysis: H.X.; investigation: Q.L., X.X.; resources: H.X., Q.L.; data curation: H.X., J.Y.; writing—original draft preparation: H.X.; writing—review and editing: H.X., J.Y.; visualization: F.S.; supervision: H.X., J.Y.; project administration: H.X.; funding acquisition: H.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Social Science Fund of China, grant No. 20BRK022; and the Natural Science Foundation of Shanghai, grant No. 23ZR1419700.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments: The authors would like to thank Gaoxiang Gu and Xi Tang for their technical support.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Hu, H. The Distribution of Population in China, With Statistics and Maps. *Acta Geogr. Sin.* **1935**, *2*, 33–74.
2. Hu, H. The Distribution, Regionalization and Regionalization and Prospect of China's Population. *Acta Geo-Graph. Sin.* **1990**, *57*, 139–145.
3. Ge, M.; Feng, Z. A Study of population distribution pattern in China in 2000 based on GIS—And a comparison with Hu Huanyong's 1935 study. *Popul. Res.* **2008**, *32*, 51–57.
4. Qi, W.; Liu, S.; Zhao, M. Study on the stability of Hu Line and different spatial patterns of population growth on its both sides. *Acta Geogr. Sin.* **2015**, *70*, 551–566.
5. Bai, Z.; Wang, J.; Yang, Y.; Sun, J. Characterizing spatial patterns of population distribution at township level across the 25 provinces in China. *Acta Geogr. Sin.* **2015**, *70*, 1229–1242.
6. Chen, M.; Li, Y.; Gong, Y.; Lu, D.; Zhang, H. The population distribution and trend of urbanization pattern on two sides of Hu Huanyong population line: A tentative response to Premier Li Keqiang. *Acta Geogr. Sin.* **2016**, *71*, 179–193.
7. Wang, K.; Deng, Y. Can new urbanization break through the Hu Huanyong Line? Further discussion on the geo-graphical connotations of the Hu Huanyong Line. *Geogr. Res.* **2016**, *35*, 825–835.
8. Wang, Z.; Xia, H.; Tian, Y.; Wang, K.; Hua, H.; Geng, W.; Tian, L.; Zheng, B.; Zhao, J. Big-data analysis of HU Line existence in the ecology view and new economic geographical understanding based on population distribution. *Acta Ecol. Sin.* **2019**, *39*, 5166–5177. [[CrossRef](#)]
9. Ding, J.; Cheng, C.; Zhang, W.; Tian, Y. The ideological origins and geographical demarcation significance of Hu Huanyong Line. *Acta Geogr. Sin.* **2021**, *76*, 1317–1333.
10. Wang, L.; Yany, Y.; Feng, Z.; You, Z. Prediction of China's population in 2020 and 2030 on county scale. *Geo-Graph. Res.* **2014**, *33*, 310–322.
11. Wang, Z.; Yue, Q.; Xia, H.; Sun, Y.; Zhong, Z.; Xu, C.; Wang, Y.F. China 2050: Climate scenarios and stability of Hu-line. *Sci. Sin. Terra* **2016**, *46*, 1505–1514.
12. Nüchel, J.; Bøcher, P.K.; Svenning, J.-C. Topographic slope steepness and anthropogenic pressure interact to shape the distribution of tree cover in China. *Appl. Geogr.* **2019**, *103*, 40–55. [[CrossRef](#)]
13. Liu, C.; Wang, F.; Xu, Y. Habitation environment suitability and population density patterns in China: A regionalization approach. *Growth Change* **2019**, *50*, 184–200.
14. Chen, D.; Zhang, Y.; Yao, Y.; Hong, Y.; Guan, Q.; Tu, W. Exploring the spatial differentiation of urbanization on two sides of the Hu Huanyong Line—Based on nighttime light data and cellular automata. *Appl. Geogr.* **2019**, *112*, 102081. [[CrossRef](#)]
15. Lu, D.; Wang, Z.; Feng, Z.; Zeng, G.; Fang, C.; Dong, X.; Liu, S.; Jia, S.; Fang, Y.; Meng, G.; et al. Academic debates on Hu Huanyong population line. *Geogr. Res.* **2016**, *35*, 805–824.
16. Mara, H. China's Population Growing Slowly, Changing Fast. *Science* **2011**, *332*, 650–651. [[CrossRef](#)] [[PubMed](#)]
17. Peng, X. China's Demographic History and Future Challenges. *Science* **2011**, *333*, 581–587. [[CrossRef](#)] [[PubMed](#)]
18. Lutz, W.; Kc, S. Global Human Capital: Integrating Education and Population. *Science* **2011**, *333*, 587–592. [[CrossRef](#)] [[PubMed](#)]
19. Lee, R. The Outlook for Population Growth. *Science* **2011**, *333*, 569–573. [[CrossRef](#)] [[PubMed](#)]
20. Blumenstock, J.E. Fighting poverty with data. *Science* **2016**, *353*, 753–754. [[CrossRef](#)] [[PubMed](#)]
21. Lutz, W.; Cuarema, J.C.; Kebede, E.; Prskawetz, A.; Sanderson, W.C.; Striessnig, E. Education rather than age structure brings demographic dividend. *Proc. Natl. Acad. Sci. USA* **2019**, *116*, 12798–12803. [[CrossRef](#)] [[PubMed](#)]
22. van Vuuren, D.P.; Riahi, K.; Calvin, K.V.; Dellink, R.B.; Emmerling, J.; Fujimori, S.; Kc, S.; Kriegler, E.; O'Neill, B. The Shared Socio-economic Pathways: Trajectories for human development and global environmental change. *Glob. Environ. Change-Hum. Policy Dimens.* **2017**, *42*, 148–152. [[CrossRef](#)]
23. O'Neill, B.C.; Dalton, M.; Fuchs, R.; Jiang, L.; Pachauri, S.; Zigova, K. Global demographic trends and future carbon emissions. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 17521–17526. [[CrossRef](#)] [[PubMed](#)]
24. Shayegh, S. Outward migration may alter population dynamics and income inequality. *Nat. Clim. Change* **2017**, *7*, 828–833. [[CrossRef](#)]
25. Lutz, W.; Striessnig, E. Demographic aspects of climate change mitigation and adaptation. *Popul. Stud. A J. Demogr.* **2015**, *69*, 69–76. [[CrossRef](#)] [[PubMed](#)]
26. O'Neill, B.C.; Jiang, L.; Kc, S.; Fuchs, R.; Pachauri, S.; Laidlaw, E.K.; Zhang, T.; Zhou, W.; Ren, X. The effect of education on determinants of climate change risks. *Nat. Sustain.* **2020**, *3*, 520–528. [[CrossRef](#)]
27. McLeman, R.A.; Hunter, L.M. Migration in the context of vulnerability and adaptation to climate change: Insights from analogues. *Wiley Interdiscip. Rev.-Clim. Change* **2010**, *1*, 450–461. [[CrossRef](#)] [[PubMed](#)]
28. Cattaneo, C.; Beine, M.; Fröhlich, C.J.; Kniveton, D.; Martinez-Zarzoso, I.; Mastroiello, M.; Millock, K.; Piguet, E.; Schraven, B. Human Migration in the Era of Climate Change. *Rev. Environ. Econ. Policy* **2019**, *13*, 189–206. [[CrossRef](#)]
29. Hu, H. *Population Density and Population Policy in China's Eight Major Regions*; Shanghai Foreign Language Education Press: Shanghai, China, 1983.

30. Yin, W.; Yin, X.; Yan, H. The Hu Huanyong Line: A 65-Year Development Perspective. *Chin. J. Popul. Sci.* **2016**, *12*, 25–40.
31. Kc, S.; Lutz, W. Demographic scenarios by age, sex and education corresponding to the SSP narratives. *Popul. Environ.* **2014**, *35*, 243–260. [[CrossRef](#)]
32. Hvistendahl, M. Has China Outgrown the One-Child Policy? *Science* **2010**, *329*, 1458–1461. [[CrossRef](#)] [[PubMed](#)]
33. O'Neill, B.C.; Tebaldi, C.; van Vuuren, D.P.; Eyring, V.; Friedlingstein, P.; Hurtt, G.; Knutti, R.; Kriegler, E.; Lamarque, J.-F.; Lowe, J.; et al. The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geosci. Model Dev.* **2016**, *9*, 3461–3482. [[CrossRef](#)]
34. Riahi, K.; Van Vuuren, D.P.; Kriegler, E.; Edmonds, J.; O'Neill, B.C.; Fujimori, S.; Bauer, N.; Calvin, K.; Dellink, R.; Fricko, O.; et al. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Glob. Environ. Change-Hum. Policy Dimens.* **2017**, *42*, 153–168. [[CrossRef](#)]
35. Jones, B.; O'Neill, B.C. Spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways. *Environ. Res. Lett.* **2016**, *11*, 084003. [[CrossRef](#)]
36. Jiang, L.; O'Neill, B.C. Global urbanization projections for the Shared Socioeconomic Pathways. *Glob. Environ. Change-Hum. Policy Dimens.* **2017**, *42*, 193–199. [[CrossRef](#)]
37. Chen, Y.; Guo, F.; Wang, J.; Cai, W.; Wang, C.; Wang, K. Provincial and gridded population projection for China under shared socio-economic pathways from 2010 to 2100. *Sci. Data* **2020**, *7*, 83. [[CrossRef](#)] [[PubMed](#)]
38. Jiang, T.; Zhao, J.; Jing, C.; Cao, L.; Wang, Y.; Sun, H.; Wang, A.; Haung, J.; Su, B.; Wang, R. National and Provincial Population Projected to 2100 Under the Shared Socioeconomic Pathways in China. *Clim. Change Res.* **2017**, *13*, 128–137.
39. Zhai, Z.; Chen, J.; Li, L. What is the total fertility rate of China at the present stage?—New evidence from household registration data. *Popul. Res.* **2015**, *39*, 22–34.
40. Wang, J.; Ge, Y. China's Population Development Trend under the implementation of the comprehensive two-child Policy. *Popul. Res.* **2016**, *40*, 3–21.
41. Zhang, J.; Wang, R.; Lu, C. A quantitative analysis of Hukou reform in Chinese cities: 2000–2016. *Growth Change* **2019**, *50*, 201–221. [[CrossRef](#)]
42. Lin, S.; Sidaway, J.D.; Woon, C.Y. Reordering China, Respacing the World: Belt and Road Initiative (一帶一路) as an Emergent Geopolitical Culture. *Prof. Geogr.* **2019**, *71*, 507–522. [[CrossRef](#)]
43. Brakman, S.; Frankopan, P.; Garretsen, H.; Van Marrewijk, C. The New Silk Roads: An introduction to China's Belt and Road Initiative. *Camb. J. Reg. Econ. Soc.* **2019**, *12*, 3–16. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.