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Sustainability of Urban Development with Population Decline in Different Policy Scenarios: A Case Study of Northeast China

Zhenshan Yang

Key Lab of Regional Sustainable Development and Modelling, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China; yangzs@igsnr.ac.cn

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Abstract: Urban shrinkage is becoming a major global challenge and causing a series of challenges to the sustainable urban development. In this study, a system dynamics-based model was proposed and used to dynamically evaluate the sustainability of the urban development under five different policy scenarios in response to population shrinkage. A model was applied to socioeconomic data from eight shrinking cities in Northeast China from 2002 to 2017 to investigate the past and future trends in their urban development sustainability from 2002 to 2035. The results show that the development sustainability indices of the eight cities increased overall up to 2017. However, some then peaked and are now declining. The model predicts that the cities would vary considerably in their development sustainability across the five different scenarios. For example, with smart shrinkage policies, cities are predicted to sustain their current levels of development sustainability; meanwhile, with anti-shrinkage policies, where growth-oriented development is pursued, some cities are also predicted to see improvements in sustainability. The present study provides a technical approach to simulating and investigating the circular feedback mechanism between components of a city system and effectively correlating population shrinkage with urban development sustainability across different policy responses to urban shrinkage.

Keywords: urban shrinkage; sustainable development; system dynamics; population decline; Northeast China

1. Introduction

For a long time, the sustainable urban development has been beset with a large number of people living in urban areas. However, many cities nowadays are faced with the challenge of population decline, and accordingly, urban shrinkage or shrinking cities have become an important issue for researchers and policy makers to carefully deal with [1], and cities are in a different situation from population growth, which they are familiar with. This paper contributes to exploring the sustainability of shrinking cities with introducing system dynamics (SD) models under the framework of shared socioeconomic pathways (SSPs) [2,3].

Compared with urban growth, urban shrinkage is a new issue for sustainable urban development. It is characterized by population decline, economic recession, financial deficits, increasing unemployment rates, vacant housing units and idled public facilities [4], and among these, population decline is usually regarded as the key factor. A typical example is Detroit, whose population peaked at more than 1.85 million in the mid-20th century, and later is the trap of economic stagnancy and environmental deterioration, a typical shrinking city [5]. Although there are still a lot of debates on definition and causes of urban shrinkage, it is quite clear that population decline is an indicator that cities may step on a track of urban shrinkage and there are many cities that may encounter the problem shrinkage due

to general demographic trend, i.e., ageing and low fertility, and fierce economic competition among cities and regions [6,7].

Facing population declines, some people claim to counteract this situation or revitalize cities [1,8]. On the other hand, some research calls for adaptation and optimization policies, rather than prevention, for example, policies to reasonably reduce city size, plan infrastructure in a green manner, and improve the quality of urban ecology and life [9,10], to pursue sustainable, controlled shrinkage or “smart” shrinkage with corresponding reduced land pressure [11–13]. Consequently, it is better that if we can assess sustainability of shrinking cities before proper measures are taken.

Therefore, studies on this issue can significantly contribute to literature of both sustainable urban development and shrinking cities. Existing sustainable literature is mostly centered on population growth, and has not yet been aware of the importance of population decline to sustainability. In addition, the current research on urban shrinkage either focuses on demographic changes or the interaction between many factors, which drive urban shrinkage [14–16]. As research has continued, it has become clear that there are many complex, interacting factors that contribute to urban shrinkage [17–19], which directly need an approach to assess the sustainability of shrinking cities.

Recognizing these gaps, the present study developed a dynamic system-based model for assessing the sustainability of shrinking cities in a typical region of Northeast China. Even though China continues to urbanize, approximately one fourth of its main cities encounter population decline. Among others, Northeast China is quite phenomenal, where cities have been suffering from stagnant or even negative GDP growth, serious population loss, and anemic growth in fiscal revenue [7,20,21]. Despite having strong policy support—population decline constrains options for sustainable urban development [22]. Using an SD-based model, this study explores the impact of population decline on the sustainability of their urban development for different policy response scenarios, enabling policy makers to better deal with urban shrinkage.

The paper is structured as follows: Section 2 analyzes the concept of urban shrinkage and the challenges on sustainability of urban development brought by population decline. Section 3 introduces the study area, data processing, and the model proposed in this study. Section 4 presents the findings and Section 5 discusses our findings by comparing other related studies in great details. Section 6 summarizes the paper.

2. Urban Shrinkage and Sustainable Development

Sustainable development was defined as that which “meets the needs of the present without compromising the ability of future generations to meet their own needs,” and has become a consensus of common future for mankind [23]. As a space carrier carrying 55% of the global population, whether the city can achieve sustainable development has always been the focus of attention of urban planning, urban geography and other interdisciplinary disciplines [24]. The research on sustainable urban development can be traced back to the early 1990s and can be characterized as the embodiment of the concept of sustainable development in the process of urban management [25]. Briefly, it refers to the urbanization process, which harmonizes with principles of sustainable development, so most of the research on sustainable urban development can be used to focus on the urban growth process [26,27]. However, as a natural phenomenon corresponding to urban growth, urban shrinkage is not contradictory to sustainable urban development, on the contrary, they are consistent in the process of urban development, with the similar characteristics of multi-dimension, dynamic, and uncertainty.

Compared with population growth, urban shrinkage emerges as a new issue for the sustainable urban development agenda. The term “urban shrinkage” was first used to describe the process of urban population decline and economic recession at the end of the 20th century [28]. It used to be regarded as an interim, reversible step in the urban social and industrial growth cycle, in which urban growth can be recovered and revitalized through appropriate measures [29,30]. However, due to globalization, the urban production system has been restructured, causing significant effects on population distribution. Loss of urban population and housing vacancies have become global

problems [31]. This has reduced the ability of the life cycle theory to accurately describe urban growth and recession [32]. Urban shrinkage is not considered to be a short-term divergence, but a natural, universal urban phenomenon [33]. Therefore, it has received wide attention in the scholarly communities of urban planning, human geography, and sociology.

Global research on urban shrinkage has increased rapidly. Within academia, there are two main descriptions of urban shrinkage. The first involves demographic change, including population size reduction and demographic structure deterioration. For example, Turok and Mykhnenko used population as their major indicator for the trajectory of city development because the data was readily available and it allowed for continuity with previous studies [14]. More importantly, population is usually the most straightforward and effective measure of changes in the urban development, and population loss incorporates many influencing factors such as urban environment deterioration, income decline, and loss of attractiveness. The second description refers to changes in a combination of multi-dimensional factors. This is because urban shrinkage is usually accompanied by problems such as population aging, economic recession, diminishing job opportunities, and increasing housing vacancies. The concept of urban shrinkage is much more than simple population decline. In a case study of Leipzig in Germany, Bontje proposed the rate of vacant housing units as a measure of urban shrinkage [15]. Schetke and Haase used many sustainable development-associated measures in their research on urban shrinkage, including the number of houses, the level of urban infrastructure development, job opportunities, social environment quality, and city attractiveness and vitality [16].

Urban shrinkage is a dynamic and continuous process. How and to what extent the population and economy decline depends on mutual effects of urban economy, society, resources, and environment sectors, which is the same as the change of urban sustainability. At present, the research on urban sustainability evaluation mostly emphasizes that there is a causal feedback mechanism of multiple factors in the urban development, rather than a linear causal relationship. Based on this dynamic non-linear relationship, many scholars around the world use system dynamics to establish models and evaluate the level of sustainable development in the process of urban growth [17]. Correspondingly, some research also pays attention to the dynamics of urban shrinkage. For example, Hartt used cross-correlation network analysis to examine the dynamic trends of two typical shrinking cities in Canada, trying to reveal a more complex and non-linear interpretation among the factors in the process of urban shrinkage [34]. Models used to simulate the change of single sector (land use, housing demand) during the process of urban shrinkage also made some progress, but it does not comprehensively consider the dynamic simulation of the sustainability in the process of urban shrinkage [35,36].

With the expansion of the concept of urban shrinkage, describing the trajectory of urban shrinkage and formulating a tailored response has become a subject of interest. Early researchers generally considered urban shrinkage to be caused by concrete factors such as political, demographic, and economic changes and treated the cause-and-effect mechanism as quasi-linear. However, urban shrinkage has been increasingly recognized as the dynamic process of low or even negative urban growth, in which population decline is the most obvious manifestation of various interacting factors [37]. The current mechanism proposed to describe urban shrinkage involves complex circular feedback loops between various components of the city, without clear cause and effect. Additionally, the process is accompanied by a series of socioeconomic, resource, and environmental problems which limit sustainable social development, such as vacant housing units, population loss, fiscal deficits, industrial recession, and land use changes [1].

Owing to the significant uncertainty in the process of urban shrinkage, it is necessary to make appropriate response policies for urban shrinkage as well as sustainable urban development path. The shrinkage mechanism of cities is related to their stages and geographical environments, which leads to strong heterogeneity in urban shrinkage [38]. Moreover, owing to different cultures, institutional backgrounds, and political environments, public intervention of shrinking cities varies considerably [19]. Shrinking cities not only require measures tailored to a comprehensive strategic approach, but also requires a coordinated approach under existing governance systems that enable

sustainable development [1]. Thus, scientifically modeling urban shrinkage across different scenarios to compare the sustainability of urban development along different paths contributes to an objective understanding of the urban shrinkage process and the formulation of appropriate, proactive policy responses [39].

Researchers also attempted to interpret the nonlinear, dynamic feedback mechanisms between various aspects of the city system through modeling. Some progress has been made using urban shrinkage modeling [35,36], which has revealed that local governments should abandon growth-oriented planning and attempt to fully utilize their reduced populations and corresponding reduced land pressure to improve local ecological and living quality and pursue sustainable, controlled shrinkage or “smart” shrinkage [11–13]. However, urban shrinkage is difficult to predict. The components of the urban system and their interactions are complex [17]. Changes in the external environment may create new factors that have not been previously incorporated into models. Additionally, because cities can be in different development stages and geographical environments, certain factors may affect cities to various extents. Moreover, public intervention varies considerably owing to different cultures, institutions, and political environments [18,19]. Thus, scientific modeling is necessary to aid in the formation of objective, appropriate, proactive policy responses to urban shrinkage, and this must be done for different scenarios to compare the sustainability of urban development along various paths [39].

In recent years, with the Chinese economy adjusting to a new normal, many cities in China have started to shrink. Preliminary research on this phenomenon has been performed. Most of the studies in Chinese literature use quantitative methods, define urban shrinkage using demographic measures, describe population distribution due to urban shrinkage, and investigate the causes of shrinkage on a macroscopic scale. Using demographic measures, Wu et al. analyzed shrinking cities in the Beijing-Tianjin-Hebei region and the Yangtze River delta, and discovered five significant factors, which cause urban shrinkage, namely, the demographics, environment, economics, political atmosphere, and population distribution [40]. Moreover, scholarly interest has increased in defining the multi-dimensional and multi-scale aspects, which cause cities to shrink in China. For example, Liu et al. defined shrinking cities in Northeast China using population and nighttime light data [41]. Yang and Yang defined urban shrinkage at the municipal district/county scale and analyzed its spatial patterns and characteristics using an urban development index with multi-dimensional, comprehensive criteria based on the concept of sustainable development [42].

However, existing studies are mainly focused on the definition of urban shrinkage and analysis of its underlying causes and mechanisms, with few studies reporting models or predictions based on policy responses to urban shrinkage. This is inadequate to form a comprehensive, objective understanding of the dynamic process of urban shrinkage. With the current economic structure transformation, the urban shrinkage phenomenon in China requires a multi-dimensional understanding and dynamic assessment from the perspective of sustainable development. Therefore, the present study investigates typical shrinking cities in Northeast China using population data.

3. Materials and Methods

3.1. Study Area and Data

Northeast China (Figure 1) is an old industrial base boasting rich resources. After several decades of rapid industrialization and urbanization during the 20th century, the region entered an era of transformation and economic development, but it is now experiencing urban shrinkage as a result of a complex interaction among ageing, outmigration, economic stagnancy, and fierce competition outside the region [20]. Since 2010, many cities in the region have experienced sustained low or even negative growth in major economic indices such as gross domestic product (GDP), fixed asset investment, and public fiscal revenue, indicating low economic growth, or a recession. Significant urban shrinkage has occurred, which has manifested as closed companies, vacant housing units, and net population loss.

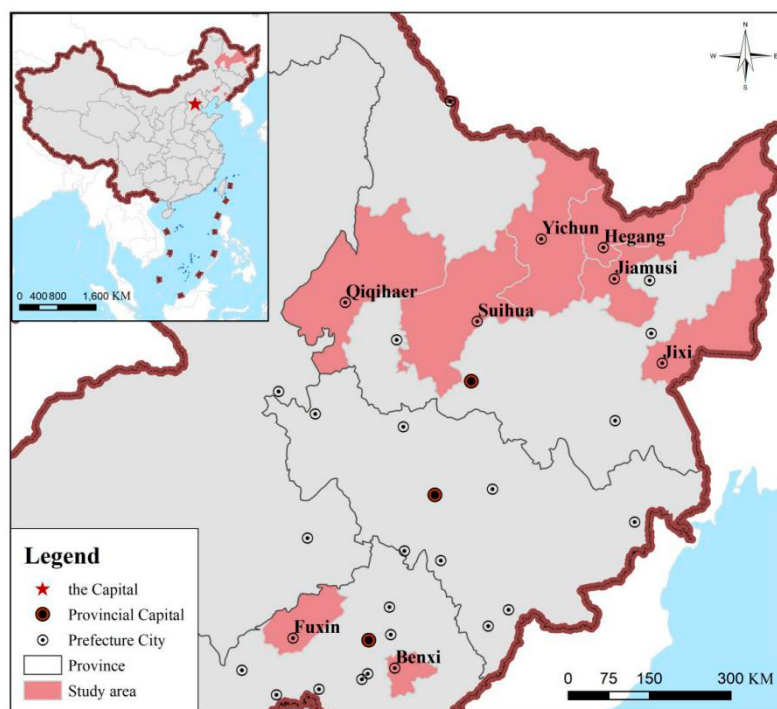


Figure 1. Location of study.

The socioeconomic data used in this study came from the statistics yearbooks and socioeconomic development statistics collected from official websites of each city of interest during the period from 2002 to 2017. Missing data were inferred by interpolation. The population data was then used to compute the average annual population decline rate in the urban district to identify typical shrinking cities in Northeast China. The average annual population decline rate can be calculated as follows:

$$r = \frac{1}{(t-1)} \sum_{i=2}^t \left(\frac{p_i - p_{i-1}}{p_{i-1}} \right) \quad (1)$$

where r is average annual population decline rate; t represents the total number of years in the study period; p_i denotes the total urban population at the end of year i .

Urban districts with a negative growth rate were defined as typical shrinking cities and were included in the scope of the present study. A total of eight cities satisfied this definition of shrinking city, as shown in Table 1.

Table 1. Typical shrinking cities in Northeastern China.

City	Population in 2017 (unit: Million People)	GDP in 2017 (unit: Billion Yuan)	Average Annual Population Growth Rate in Urban District during 2002 and 2017 (unit: %)
Benxi	1.50	76.7	−0.315
Fuxin	1.89	40.8	−0.179
Hegang	1.04	26.4	−0.528
Jixi	1.81	51.8	−0.663
Jiamusi	2.38	84.5	−0.324
Qiqihar	5.44	132.5	−0.337
Suihua	5.43	131.6	−0.151
Yichun	1.18	25.1	−0.769

3.2. A System Dynamics Based Model

System dynamics (SD), an important aspect of systems theory, has been widely used to study complex, dynamic systems. SD modeling can fully reveal the nonlinear structure and dynamic characteristics of interacting variables in a system and analyze the complex feedback and dependence relationships between the variables, thus offering a useful tool for simulating the sustainability of the urban development. SD modeling has been increasingly used to simulate the evolution of the various aspects of the urban development, such as economic and population growth, land use, ecology, and the environment [43–45].

Based on data availability and suited in the situation of the study area, this study established a sustainable development assessment system for Northeast China by building on the systems proposed in literature [46–48]. The assessment index system consisted of 20 indices organized into six subsystems, namely the economy, livelihood, environment, pollution governance, resource, and risk. An index may be positive or negative based on how its effects relate to the concept of sustainable development. A negative index harms sustainable urban development and includes per capita electricity, water, and gas consumption and the ratio of foreign investment in use to GDP. The remaining indices are positive and reflect practices which aid sustainability. The index weights were determined using a cross-entropy method [49], as shown in Table 2. The entropy method is one of the objective weighting methods commonly used in conventional index weighting and is mainly based on the numerical dispersion degree of each index, thereby avoiding information omission and human interference [50,51].

Table 2. Summary of the index system used in the model to evaluate the sustainability of shrinking cities.

Subsystems	Indices	Index Attribute/Weight
Economy (weight: 0.18)	Ratio of tertiary industry to GDP	Positive/0.22
	Gross domestic product per capita	Positive/0.40
	Total number of pupils	Positive/0.38
Livelihood (weight: 0.16)	Number of doctors per 10,000 people in the city	Positive/0.30
	Number of medical beds per 10,000 people in the city	Positive/0.20
	Number of public books per 100 people in the city	Positive/0.50
Environment (weight: 0.16)	Industrial sulfur dioxide emissions in the city (t)	Negative/0.48
	Green space area per capita in municipal districts (m ² /person)	Positive/0.32
	Green coverage ratio in constructed areas (%)	Positive/0.20
Pollution governance (weight: 0.12)	Comprehensive utilization rate of industrial solid waste in the city (%)	Positive/0.19
	Centralized sewage treatment rate in the city (%)	Positive/0.53
	Harmless treatment rate of domestic waste in the city (%)	Positive/0.28
Resource (weight: 0.2)	Electricity consumption per unit of economic output in municipal districts (kW·h/¥)	Negative/0.18
	Per capita electricity consumption in municipal districts (kW·h/person)	Negative/0.26
	Per capita water consumption in municipal districts (m ³ /person)	Negative/0.28
	Per capita gas consumption in municipal districts (m ³ /person)	Negative/0.28
Risk (weight: 0.18)	Ratio of foreign capital used to GDP (%)	Negative/0.27
	Registered urban unemployment rate (%)	Negative/0.26
	Government revenue-expenditure ratio	Negative/0.25
	Deposit-loan ratio of financial institutions	Negative/0.22

The feedback relationships in the model were represented using regression functions, which were selected and optimized using significance tests and the R² coefficient of determination. The proposed model consisted of more than 30 regression functions, with different parameter settings for each city. Figure 2 shows the cause-and-effect relationships dynamically assessed in the model to determine the development sustainability in each shrinking city.

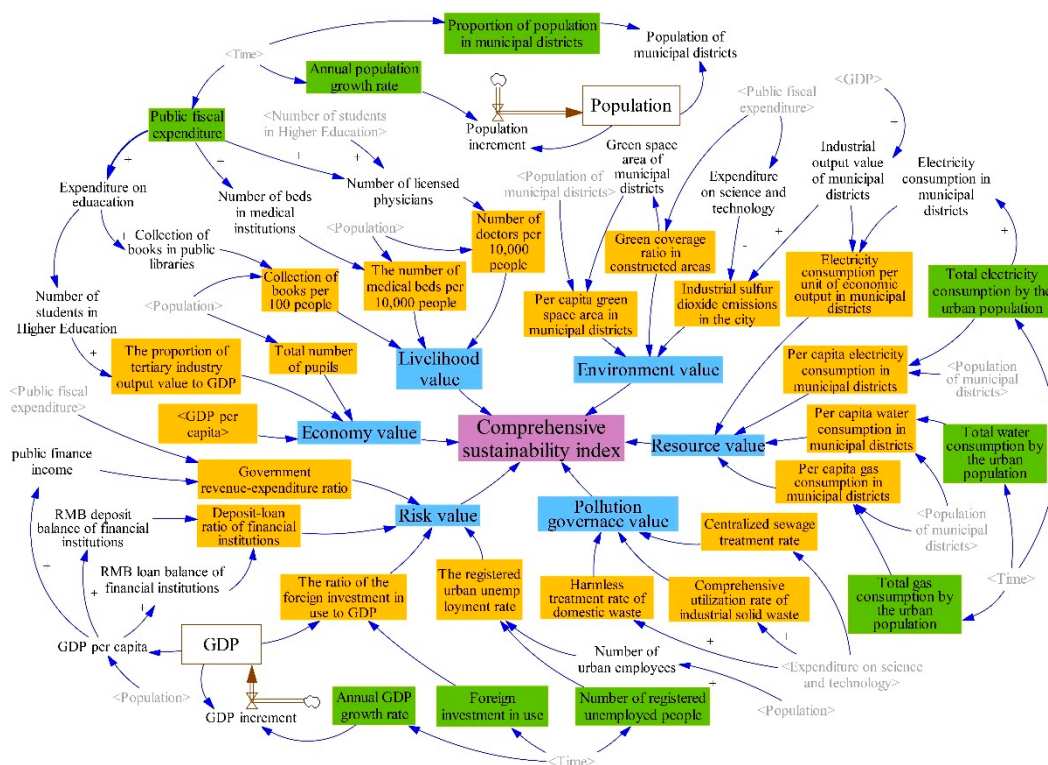


Figure 2. Diagram visualizing cause-and-effect relationships in the dynamic urban sustainability model used in this study.

Urban sustainability assessment is a huge, complex, and systematic issue. In this model, there are six subsystems (highlighted in blue in Figure 2), which contain the corresponding indices described in Table 2 (highlighted in yellow in Figure 2). Population and GDP are fundamental to the scale and type of city and were thus defined as stock variables in the model (boxed in maroon in Figure 2). Correspondingly, GDP and population changes were defined as flow variables. The remaining indices were defined as auxiliary variables (left in black in Figure 2). For clarity, the variables appearing more than once in the figure are highlighted in gray characters in brackets. Additionally, the model contained nine input variables (highlighted in green in Figure 2), namely, annual population growth rate (V1), annual GDP growth rate (V2), proportion of population in urban districts (V3), foreign investment in use (V4), number of registered unemployed people (V5), public fiscal expenditure (V6), and total electricity (V7), water (V8), and gas (V9) consumption by people in urban districts. These were the input variables of the model because city decision makers can control them by pursuing alternate urban development paths. They can fully describe several prominent features of urban shrinkage and sustainable urban development; their combination can reflect a guiding policy of urban decision makers in formulating specific urban management plans.

The plus or minus symbols near the arrows in Figure 2 indicate whether there is a positive or negative cause-and-effect feedback loop between the variables. For example, the economy subsystem consists of the following indices: GDP per capita to measure economic development, proportion of tertiary industry to measure the capacity for economic innovation, and total number of pupils to measure the potential for sustained economic growth. In a developing economy, as gross industrial output increases with GDP growth, industrial waste production also increases, thereby negatively impacting the environment. This impact is measured here using industrial sulfur dioxide emissions, a variable in the environment subsystem. This can be seen in Figure 2, from the positive relationship between GDP, industrial output, and sulfur dioxide emissions. Additionally, GDP affects the deposit-to-loan ratio of financial institutions and ratio of foreign investment in use to GDP, both critical variables in the risk subsystem, which can also be seen in Figure 2.

3.3. Scenario Analysis

To assess the sustainability of urban development in different scenarios, five scenarios (S1–5) are proposed to assist potential policy responses to urban shrinkage by referencing insightful work of Hospers’ [52] and under the framework of SSPs [3], and considering the situation of the social and economic development in Northeast China over the last decade. The differences between the scenarios were defined using nine input variables, which reflect sustainable urban development characteristics. Considering the national strategic goal of realizing socialist modernization by 2035, we extend the simulation range to 2035. According to the regional average level in 2017, and the relative level of each variable in the qualitative description of each policy scenario, the threshold value that the input variable will reach in 2035 is determined and the annual change rate of each variable needed to achieve the goal is calculated by the threshold. Table 3 displays the settings for these variables in each scenario.

Table 3. Annual change in rate for the nine input variables in each scenario from 2018 to 2035.

Scenarios	S1	S2	S3	S4	S5
	Ideal Growth	Smart Shrinkage	Historical Trend	Resisting Shrinkage	Deteriorating Shrinkage
V1	0.2%	−0.5%	−0.5%	0.2%	−1.2%
V2	3.0%	1.5%	1.5%	4.5%	−1.5%
V3	1.02%	−0.11%	−0.11%	1.02%	−1.23%
V4	6.29%	6.29%	*	9.35%	2.28%
V5	−1.23%	0.53%	*	0.53%	1.89%
V6	6.29%	5.22%	*	5.22%	3.93%
V7	1.02%	2.65%	*	5.89%	3.93%
V8	−1.23%	−0.23%	*	2.28%	1.02%
V9	1.02%	2.65%	*	5.89%	3.93%

* Note: The input variables for each city in the S3 scenario are extrapolated by a first order regression of its time series data.

S1 is the ideal development scenario, where population growth is sustained at a low level, economic growth is sustained at a medium-to-high level, dependence on fossil fuels is alleviated, energy consumption is reduced, significant attention is paid to infrastructure, social issues are addressed by increasing public financial expenditure, and resources are conserved by advocating the use of clean energy. S2 describes a “smart-shrinkage” scenario, where population growth continues at the current negative level, economic growth slows down, government fiscal expenditure increases markedly, and the focus of urbanization shifts from quantity to quality. This leads to efforts to utilize the opportunities from lower population pressure to improve the urban environment and quality of life. S3 is a differentiated-response scenario, where population and economic growth are sustained at their current level, government intervention in urban shrinkage is minimal, and urban development, in terms of urbanization, employment, and investment attraction, is consistent with their historical trajectory. S4 describes an extensive-growth scenario, where governments refuse to accept urban shrinkage, planning is mainly oriented toward rapid economic and population growth, family planning and immigration controls are relaxed, low-quality urbanization is pursued, and economic development depends on population increases and the traditional petrochemical industry, to recover and revitalize urban growth. In S5 aggravated shrinkage occurs, where the government fails to adopt proactive response measures, young and middle-aged labor is increasingly losing, social problems increase, economic growth is anemic, city vitality diminishes, risk gradually increases, and urban development enters a vicious cycle of shrinkage and recession.

4. Results

4.1. Accuracy Validation

Before the results of the SD simulation can be analyzed, their accuracy must first be verified. This was done by comparing the 2017 model outputs for the two stock variables (GDP and population) and auxiliary variables with historical data. Table 4 shows the relative error (RE) between the simulation (SD) and historical data (HD) for these variables. The relative error fell between -0.13 and 0.11 , consistent with errors in similar SD models in literature [53,54]. These results show that the model is accurate. Thus, it is capable of describing the cause-and-effect feedback relationships between system variables in a scientific and reasonable manner and quantifiably assessing the sustainability of shrinking cities.

Table 4. Relative errors between model results and historical data for 2017 to demonstrate the accuracy of the simulation.

City		GDP per Capita	Proportion of Tertiary Industry in GDP (%)	Unemployment Rate (%)	Fiscal Revenue-Expenditure Ratio	Medical Beds per 10,000 People	Green Coverage Rate (%)	Centralized Sewage Treatment Rate (%)	Electric Consumption per Capita
Benxi	SD	5.11	44.31	4.53	2.77	69.02	47.59	88.65	12,309.50
	HD	5.11	47.70	4.59	2.48	76.10	48.39	95.12	12,309.50
	RE	0.00	-0.07	-0.01	0.12	-0.09	-0.02	-0.07	0.00
Fuxin	SD	2.16	50.07	5.70	4.00	58.63	41.80	98.00	5132.99
	HD	2.16	49.19	5.69	3.85	60.38	43.34	88.50	5132.91
	RE	0.00	0.02	0.00	0.04	-0.03	-0.04	0.11	0.00
Hegang	SD	2.54	31.14	6.22	5.91	68.56	44.44	72.41	5740.14
	HD	2.54	35.81	6.06	5.63	76.52	42.57	75.55	5740.09
	RE	0.00	-0.13	0.03	0.05	-0.10	0.04	-0.04	0.00
Jixi	SD	2.86	40.04	4.83	4.26	71.45	37.20	50.99	4451.37
	HD	2.86	40.08	5.11	4.73	64.83	39.05	50.00	4451.38
	RE	0.00	0.00	-0.05	-0.10	0.10	-0.05	0.02	0.00
Jiamusi	SD	3.55	44.67	5.25	6.44	60.16	42.02	77.50	2832.20
	HD	3.55	47.28	5.01	6.25	62.78	41.61	85.00	2832.20
	RE	0.00	-0.06	0.05	0.03	-0.04	0.01	-0.09	0.00
Qiqihar	SD	2.44	48.48	5.24	8.38	53.21	39.94	66.82	2853.69
	HD	2.44	46.38	5.34	8.68	47.93	37.86	75.04	2853.69
	RE	0.00	0.05	-0.02	-0.04	0.11	0.05	-0.11	0.00
Suihua	SD	2.45	39.41	3.21	6.55	28.75	26.51	100.00	826.76
	HD	2.42	35.56	3.10	6.81	30.23	24.93	90.20	818.82
	RE	0.01	0.11	0.03	-0.04	-0.05	0.06	0.11	0.01
Yichun	SD	2.13	34.56	7.50	8.49	55.27	30.24	84.94	2455.33
	HD	2.13	38.03	7.91	9.04	54.68	30.54	87.90	2455.32
	RE	0.00	-0.09	-0.05	-0.06	0.01	-0.01	-0.03	0.00

4.2. Historical Trends in the Development of Sustainability in Shrinking Cities

The development sustainability model for shrinking cities simulated the variation in future results from 2005 to 2017 in eight cities in Northeast China from changes in the indices of six subsystems. Table 5 compares the historical values of the indices at the beginning and end of this period. The annual sustainability index and the index of each subsystem in each city are shown in Table S1.

As shown in Table 5, the economy subsystem index increased over the period for all eight shrinking cities. The greatest increase was in Qiqihar. Qiqihar is a sub-central city in Northeast China and with a large population base, diverse industries, and greater economic development compared to the other shrinking cities. The economic index increased by small margins for Fuxin, Hegang, Jixi, Suihua, and Yichun. These cities have typical resource-based economies, with homogeneous industrial structures and insufficient development momentum. It should be noted that these cities experienced negative GDP growth after 2015, having entered a stage of stagnant, slow economic development [20].

Table 5. Comparison of the index values of the model subsystems between 2002 and 2017 based on the historical data.

City	Year	Economic Subsystem	Risk Subsystem	Livelihood Subsystem	Environment Subsystem	Pollution Governance Subsystem	Resource Subsystem
Benxi	2002	28.53	54.57	35.07	37.31	43.93	39.25
	2017	37.74	53.20	44.90	48.15	54.64	45.23
Fuxin	2002	24.81	33.29	10.01	44.89	77.94	80.57
	2017	27.34	49.60	30.36	22.59	92.92	78.56
Hegang	2002	16.77	16.91	6.76	48.18	45.87	82.44
	2017	17.90	41.82	36.21	64.49	66.02	91.47
Jixi	2002	20.58	59.59	6.26	52.26	66.55	81.42
	2017	23.43	55.70	21.32	56.21	81.68	93.24
Jiamusi	2002	24.89	47.03	10.83	43.94	54.31	86.79
	2017	34.31	44.21	18.37	66.81	77.72	84.72
Qiqihar	2002	38.71	35.33	9.26	28.82	56.69	91.49
	2017	58.49	31.89	19.16	56.55	69.74	60.64
Suihua	2002	30.19	62.04	5.21	46.46	35.44	98.99
	2017	31.38	52.48	15.65	45.24	96.52	92.92
Yichun	2002	18.16	34.63	13.70	57.37	55.96	94.50
	2017	18.64	47.55	39.13	63.86	60.19	93.06

The risk index decreased for five cities (Benxi, Jixi, Jiamusi, Qiqihar, and Suihua), but only by small margins. Qiqihar faced the highest development risk owing to its high loan-to-deposit and revenue-to-expenditure ratios. Due to the effective control of unemployment rate and loan-deposit ratio, the risk scores of Hegang and Yichun cities increased significantly. The increase in the livelihood varied during the period. It increased the most in Hegang increased, becoming six times its original size, whereas in Benxi, it increased to only 1.6 times its original size. This shows that there was a huge difference in success of the cities in improving resident quality of life and there is a coupling relationship between the rise of people's livelihood index and the decrease of unemployment rate and social stability in Hegang City. The pollution governance index for all eight shrinking cities increased considerably during this period, indicating that local governments considered this to be important. Notably, in Suihua, this index increased rapidly from 35.44 in 2002 to 96.52 in 2017. However, the overall environment index of the city decreased slightly, demonstrating the effects of the complex feedback mechanisms within the city and that government investment in pollution governance does not necessarily result in short term improvements in the overall urban environment. The resource index for the majority of the shrinking cities was sustained at a stable, high level. However, Benxi had a much lower value for this index, 45.23 in 2017, much lower than the other cities indicating low resource utilization efficiency of this coal resources-based city. It is noted that the resource index in Qiqihar experienced a rapid decline because of rapid growth of per capita gas consumption.

Figure 3 shows line charts of the comprehensive development sustainability index for the eight shrinking cities plotted using the overall index values yielded by the model. Overall, the development sustainability of the cities increased slightly, despite fluctuations. The outliers were Hegang and Benxi, which showed rapid growth in the index from 2002 to 2005 and 2010 to 2012, respectively. Additionally, the eight cities experienced population decline during this period but exhibited significant differences in development sustainability. The first group of cities (Benxi, Qiqihar, Suihua, and Fuxin, shown with solid lines) experienced an overall increase in the sustainability index in the early years, but this eventually peaked and then decreased. Their peaks were in 2012, 2013, 2014, and 2015, respectively. However, the second group of shrinking cities (Jixi, Jiamusi, Yichun, Hegang, shown with dotted lines) exhibited an overall increasing trend in the index, without urban development sustainability decreasing as expected during urban shrinkage.

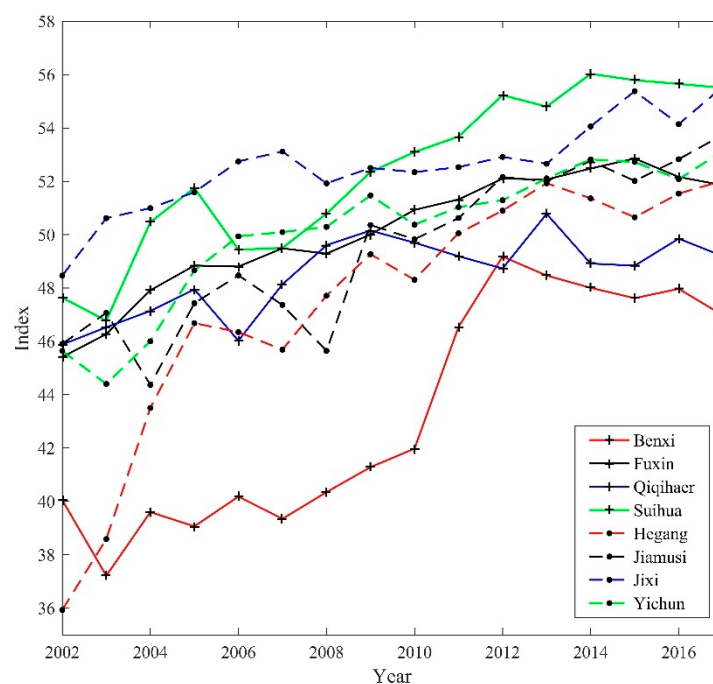


Figure 3. Variation in sustainability index for each city in the study from 2002 to 2017, based on historical data.

The eight shrinking cities were then further classified into five groups using the sustainability index thresholds of 40, 45, 50, and 55. Figure 4 shows how the cities fit into these groups geographically in 2003, 2010, and 2017. Overall, the cities exhibited low development sustainability in 2003. Jixi had the highest sustainability, whereas Benxi and Hegang were the least sustainable. By 2007, the sustainability of Benxi, Hegang, Suihua, and Yichun had improved markedly and by 2017, almost all of the eight cities had sustainability indices over 50. Qiqihar and Benxi were the exception, with Benxi at the lowest level of 46.98, while Jixi had the highest sustainability (55.54).

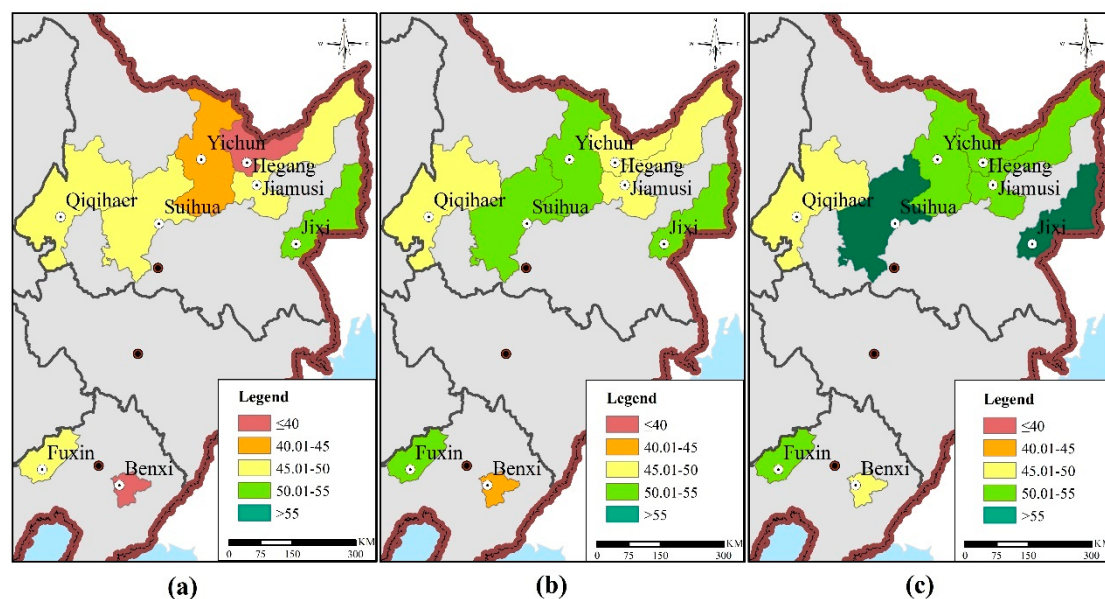


Figure 4. Spatial distribution of sustainability in selected Northeast China cities in: (a) 2003; (b) 2010; (c) 2017.

4.3. Analyzing the Trend of Shrinking Cities' Sustainability in Difference Scenarios

The future development paths of the cities due to five shrinkage policy responses were simulated using the development sustainability assessment model from 2017 to 2035. Figure 5 shows the predicted trends in the comprehensive development sustainability index. The annual sustainability index of each city in each scenario is shown in Table S2.

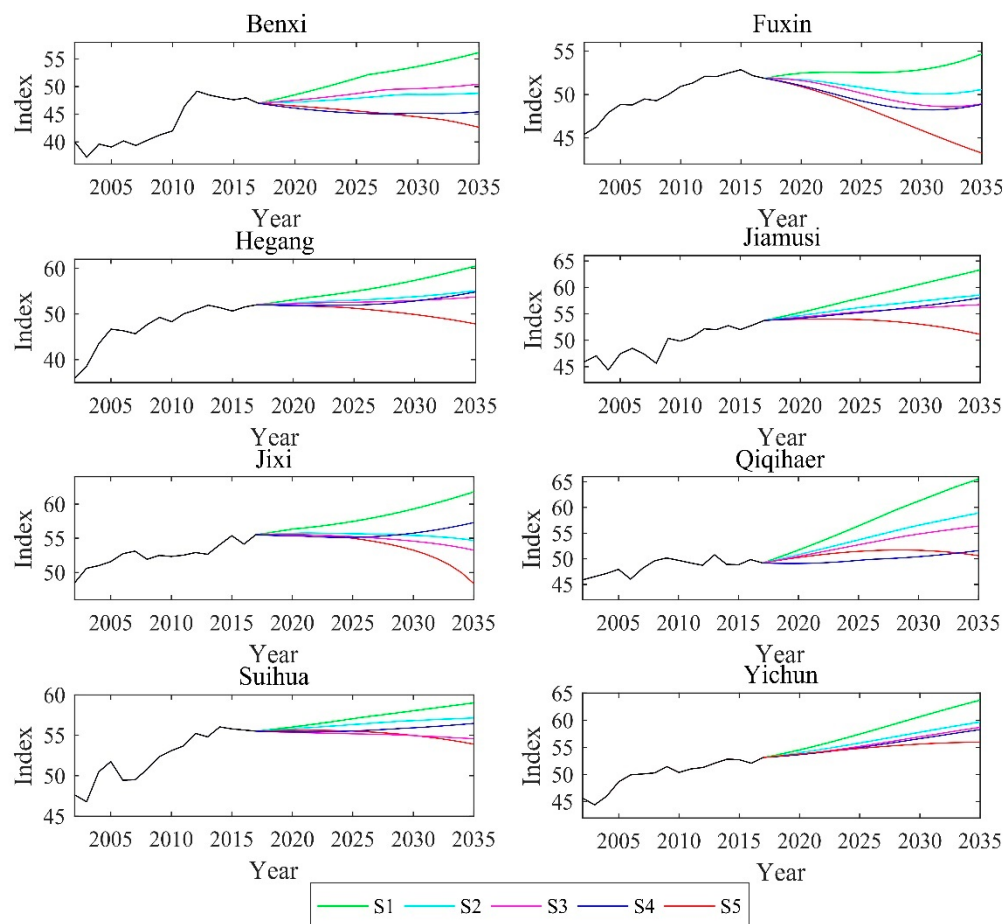


Figure 5. Values of sustainable development index of each city under different scenarios.

As shown in Figure 6, S1 is the ideal scenario for development, where urban population and economic growth are sustained at appropriate levels causing urban development sustainability to increase steadily, at a higher level than in the other scenarios. However, the shrinking cities have lost their comparative advantages in regional production, causing the fastest development stage to end. The chance of returning to a period of ideal growth is small.

S2 uses top-down policy responses to shrinkage. The urban development path is oriented to service a smaller population with fewer buildings and land spaces. This will cause the majority of the shrinking cities to sustain their development sustainability at current levels. However, Jiamusi, Qiqihar, and Yichun were predicted to experience improvements in development sustainability.

In S3, the government fails to adopt proactive response measures and lets the shrinkage process take place. Assuming the cities maintain their current shrinkage momentum, all the cities except for Benxi were predicted to experience similar development sustainability trends as in S2 but resulting in a lower overall sustainability level. Therefore, smart shrinkage is an appropriate policy choice for the majority of cities.

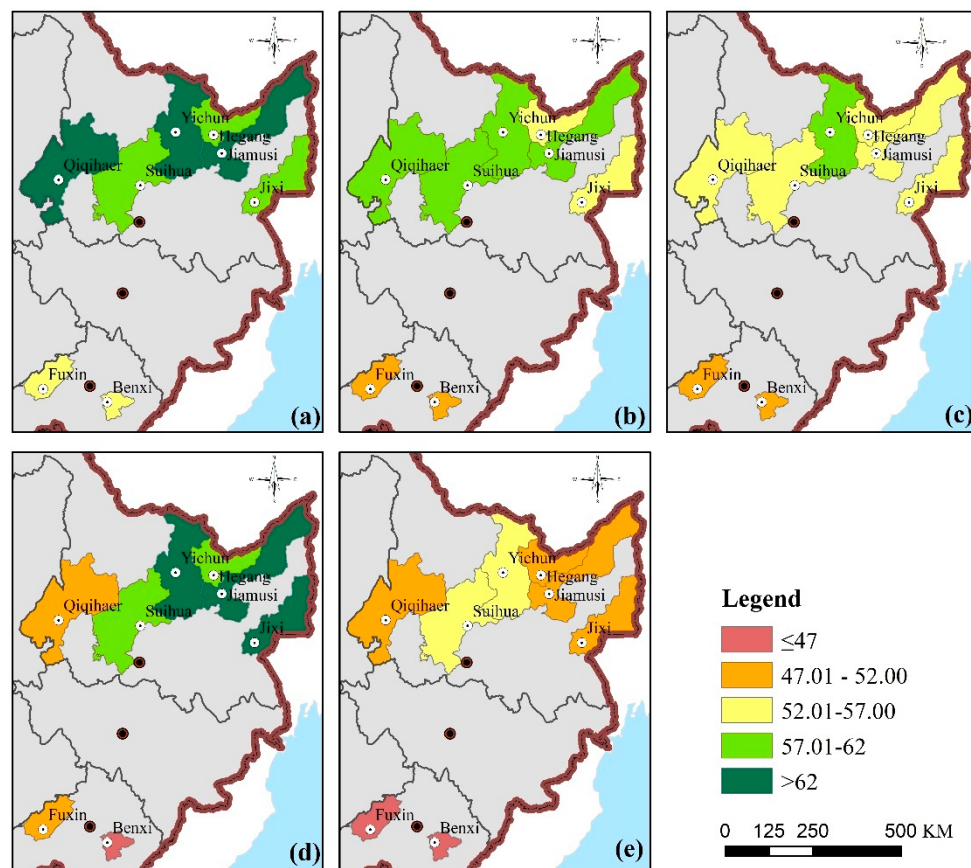


Figure 6. Sustainability scenarios of selected cities by 2035: (a) S1; (b) S2; (c) S3; (d) S4; (e) S5.

S4 is dominated by anti-shrinkage momentum, where the government focuses on growth as the ideal model of the urban development. Thus, it introduces policies to revitalize downtown districts, upgrade urban facilities, regain economic growth, and stop population loss. The simulation results show that only three cities (Jiamusi, Jixi, and Yichun) were predicted to achieve even small increases in development sustainability in this scenario. It should be noted, that Jixi was predicted to achieve a higher development sustainability in S4 than S2 by 2028. However, the development sustainability of other cities was lower in S4 than S2. In particular, Benxi, Fuxin, and Qiqihar were predicted to experience slow increases or even decreases in development sustainability in S4.

In S5, the government fails to adopt concrete counter measures, urban shrinkage increases owing to the positive feedback loop of the shrinking process, population and economy size decrease sharply, the government is faced with a fiscal revenue-expenditure imbalance, and the city system is on the verge of collapse. The development sustainability in this scenario is lower than in the first four scenarios. Benxi, Fuxin, Hegang, and Jixi were predicted to experience the biggest decrease in development sustainability and enter recession [55].

Figure 6 shows the analyzed shrinking cities (five groups with four threshold values of 47, 52, 57, and 62) across the five different policy scenarios in 2035. As shown in Figure 6, the shrinking cities are predicted to experience considerable changes in overall development sustainability by 2035, as compared to 2017.

In S1, the comprehensive development sustainability index predicted for the cities is higher than in S2, and significantly higher than in other scenarios. Smart shrinkage policies were predicted to improve the developmental sustainability of Qiqihar, Suihua, and Jixi, whereas the other cities sustain low development sustainability. In contrast, in S5, the region was predicted to experience a recession caused by the shrinking cities, and the sustainable development of the cities is at its lowest.

In S3, the cities can be thought of as three blocks in terms of development sustainability, with Yichun predicted to achieve the highest sustainability and Fuxin and Benxi predicted to suffer the lowest sustainability. In S4, where the cities attempt to revitalize economic growth, some of the cities (Jiamusi, Jixi, and Yichun) are shown to improve sustainability by pursuing a growth-oriented development path, whereas Qiqihar and Benxi were predicted to experience a marked decrease in sustainability, resulting in increased differentiation in the region's development sustainability.

5. Discussion

This paper demonstrates an approach to analysis sustainability scenarios of urban shrinkage. Compared with the completely negative and pessimistic concept of "urban decay", urban shrinkage is more neutral and can objectively describe the situation faced by cities in a weak position for global competition [56]. The negative effects of urban shrinkage are obvious, including population loss, urban poverty, rising unemployment and crime rate, and a shrinking housing market. These indirect negative effects have reduced the possibilities for sustainable development. Due to the lack of external forces to reverse the process, shrinking cities further decline due to cyclic and self-reinforcing mechanisms [57]. However, urban shrinkage also provides opportunities because of lessening pressure on ecological, environmental, housing, and transportation aspects of the city. The decrease in urban population density and increase in available land space create conditions for the potential improvement of the urban living environment, alleviation of traffic congestion, creation of urban green space, and allocation of public resources [58]. Therefore, the results of sustainability scenarios as references during the policy making process take a proper strategy facing population shrinkage.

In this paper, the results show that four of the eight typical shrinking cities in Northeast China selected showed a decline in sustainable development level from 2002 to 2017, while others exhibited an overall increase during the period. The policy of the latter group is consistent with sustainable development, or smart population shrinkage, revealing that there is no need to be pessimistic about urban shrinkage. Previous studies have shown that urban shrinkage does not lead to a decline in happiness and quality of life for urban residents. By comparing shrinking cities and growth cities in Germany, Delken found that the satisfaction of shrinking city residents to the quality of life is even higher than that of some growth cities in some aspects [59]. Through a survey of residents in 38 cities in the United States, Hollander found that whether a city shrinks (measured by population reduction) is not significantly related to the quality of the block that residents feel [12]. The government can fully use the opportunity of urban shrinkage to promote the development of the city towards environmental protection, harmony, and sustainability.

The policy ideas of urban decision makers and managers are facing great changes. They urgently need to realize clearly that the urban management mode guided by the doctrine of urban growth will become the past. Some cities in Europe and America actively responded to the current decline of the urban population, for instance, the Magdeburg government has put forward the "new state" strategy, taking shrinkage as the premise of long-term development [60]. International experience shows that the transformation of planning paradigm from growth to shrinkage is the driving force to promote the transformation of urban planning from material form and economic development to people-oriented and quality of life, advocating that local governments should abandon growth-oriented planning and attempt to fully utilize the reduced population and land pressure to improve local ecological and living quality and pursue sustainable, controlled shrinkage or "smart" shrinkage [13].

To enable an in-depth investigation into the uncertainty of the sustainability of urban development with population decline, five scenarios for coping with population decline were defined. The results show that, for most cities, urban sustainability under the ideal growth scenario (S1) is optimistic, while ignoring the problem of urban shrinkage and taking no additional measures (S5) will lead to the decay of the city, with urban sustainability declining concurrently. In addition, the effects of responding with smart shrinkage (S2) or resisting shrinkage (S4) can have the opposite result. In fact, there is no single governance model for urban shrinkage which can be copied between cities [61,62]. It is also found

that the landscape reconstruction and public space opening policies based on the concept of accepting shrinking in some shrinking cities, have not been carried out to the end, and policies on population and social issues are not fully effective, which eventually leads to the aggravation of urban problems [58].

6. Conclusions

Urban shrinkage has emerged as a new but important issue for sustainable research. Drawing upon literature of urban shrinkage, to the best of my knowledge, this paper is the first attempt to explore sustainability of urban shrinkage. Inspired by system dynamics, this paper provides a stylized approach to consider complex relations and interactions of urban shrinkage and derives five future policy scenarios under SSPs framework, which equips policy makers to better deal with this issue. Empirically, this study uses Northeast China as a case, showing the differences of the cities if they take different scenarios and possible policy reactions. The results enrich literature and practice on both urban shrinkage and sustainable urban development, and the approach can be applied to other cities and regions.

The present study suffers from some limitations. Urban shrinkage is a long, developing process. This study uses a dataset covering 16 years, which revealed the urban development process to a certain degree, considering the rapid growth in China. However, a more extensive dataset would improve the reliability of the model. In addition, owing to data availability, the paper only selects some key indicators to perform analysis. It would be great if future studies and models can include more indicators, especially on social and environmental dimensions. Despite this, the present study provides a new perspective on urban shrinkage and its development sustainability.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2071-1050/11/22/6442/s1>, Table S1: The annual sustainability index and the index of each subsystem in each city from 2002 to 2017, Table S2: The annual sustainability index of each city under different scenarios from 2018 to 2035.

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