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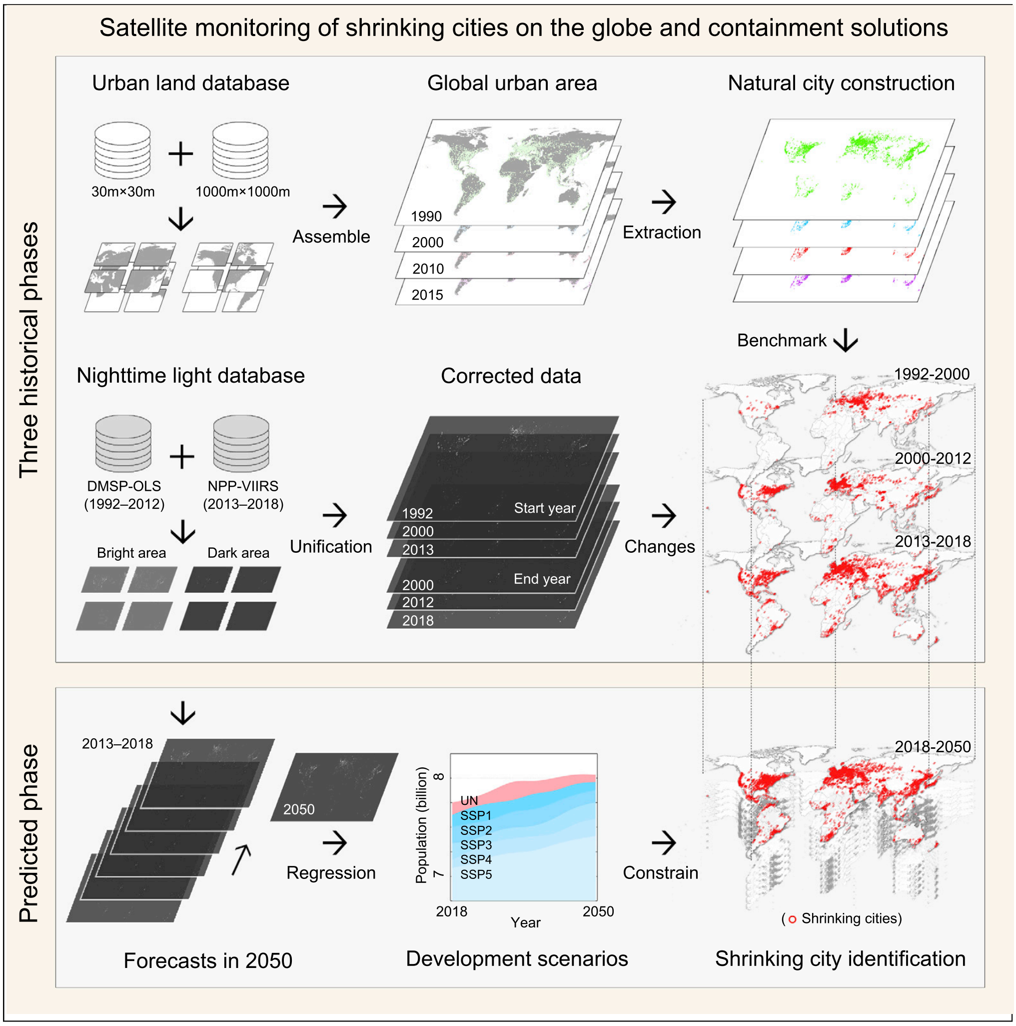

Weixin Zhai,
Zhidian Jiang,
Xiangfeng Meng,
Xiaoling Zhang,
Mengxue Zhao,
Ying Long

xiaoling.zhang@cityu.edu.hk
(X.Z.)
ylong@tsinghua.edu.cn (Y.L.)

Highlights

Nighttime light images perform well in identifying shrinking cities in the world

Natural cities can be used as a benchmark for comparison of shrinking cities

Shrinking cities in 2050 are predicted to account for 37% of all cities

Synergistic efforts aiming at shrinking cities will help achieve SDG 11

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Satellite monitoring of shrinking cities on the globe and containment solutions

Weixin Zhai,[1] Zhidian Jiang,[2,3] Xiangfeng Meng,[3] Xiaoling Zhang,[4,5,*] Mengxue Zhao,[6] and Ying Long[3,7,*]

SUMMARY

Shrinking cities are often neglected in the context of global urbanization, the tip of the iceberg that was driven by underlying complex sets of causes. Therefore, it is urgent and crucial to investigate the invisible aspects of global urbanization propelling specific challenges to attain Sustainable Development Goal 11 (SDG 11) related to sustainable cities and communities. Here, we identify shrinking cities in 1992–2000, 2000–2012, and 2013–2018 and predict them in 2018–2050, using nighttime light images and redefined natural city boundaries. The proportion of shrinking cities increased from 9% to 16 and 25%. Looking ahead, there will be 7,166 predicted shrinking cities in 2050, accounting for 37% of all cities. In this context, synergistic efforts like regreening vacant lands and constructing compact cities would help achieve SDG 11 in consideration of the new urban shrinking landscape with multisource data like CO_2 emissions and points of interests (POIs).

INTRODUCTION

A number of studies focus on the global urban growth in the past (Liu et al., 2020; Sun et al., 2020) and to the future (Chen et al., 2020; Gao and O'Neill, 2020); however, urban shrinkage, as the other side of urban growth, is often neglected. Urban shrinkage is not a new phenomenon; though the driving factors for shrinking cities are complex and variegated; the deceleration of urban growth across the globe is heterogeneous but is becoming a new reality. Shrinking cities are usually characterized by significant population loss (Güneralp et al., 2017), economic decline (Hudson, 2005), and physical disorder, including spatial decay (Lee and Newman, 2017), and have become a common phenomenon throughout the world. The existing SDG 11 was designed in the context of rapid urbanization; however, shrinking is a nonnegligible part of the urban future, which has not received enough attention. To sustain global economic prosperity in the face of plateauing urbanization and global urban shrinking, city authorities are urged to implement coping strategies to address population loss challenges (Lu et al., 2015). For city administrators, this means policy responses that shift the focus from curbing urban sprawl to governing residents within shrunk city boundaries. However, our understanding of how much the spatiotemporal changes of shrinking cities encompass the whole picture is limited. Therefore, it is necessary to identify these shrinking cities around the world accurately enough to provide empirical support for the effective government responses needed to form a healthier urban development mode. This analysis at a global scale would also help urban decision-makers make informed decisions regarding the dialectical view of the impacts of population loss and urban shrinkage.

The current understanding of shrinking cities is largely based on population data and the official administrative boundaries for one or several countries rather than global data, and the spatial characteristics of shrinking cities are not examined. For instance, Martinez et al. used population data to identify shrinking cities in Australia, Japan, Germany, the United Kingdom, France, and the United States and proposed corresponding political strategies for city development (Martinez-Fernandez et al., 2016). Long et al. identified 180 shrinking administrative cities in China alone, each accompanied by rapid urban expansion (Long, 2016). However, previous studies of the spatial distribution of shrinking cities at the global scale have their limitations. The only study on this topic was based on 1950–2000 statistics and did not cover every urbanized area or consider any temporal changes (Oswalt and Rieniets, 2006). The Shrinking Cities Project of Germany's Federal Cultural Foundation revealed the polarization tendency of cities around the world in 2005–2015 (Project, 2015). However, the statistical data fell short in accurately describing the evolution of every city in the world and objectively evaluating shrinking cities between countries with different statistical

[1] College of Information and Electrical Engineering, China Agricultural University, Beijing 100083, China

[2] College of Architecture and Urban Planning, Tongji University, Shanghai 200092, China

[3] School of Architecture and Hang Lung Center for Real Estate, Key Laboratory of Ecological Planning & Green Building, Ministry of Education, Tsinghua University, Beijing 100084, China

[4] The State Key Laboratory of Marine Pollution (SKLMP) and Department of Public Policy, City University of Hong Kong, Hong Kong, PR China

[5] Shenzhen Research Institute, City University of Hong Kong, Shenzhen 518057, China

[6] Department of Public Policy, City University of Hong Kong, Hong Kong, PR China

[7] Lead contact

*Correspondence:
xiaoling.zhang@cityu.edu.hk (X.Z.),
ylong@tsinghua.edu.cn (Y.L.)

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standards (Long, 2016). In addition, there is a lack of quantitative research on how shrinking cities developed in the past decades and will evolve in the future.

Compared with demographic data and statistical data, nighttime light remote sensing data are more objective and can more quickly reflect human activities and habitation (Chen and Nordhaus, 2011; Li et al., 2017; Yeh et al., 2020). To investigate the global spatiotemporal evolution of shrinking cities, therefore, we seek to understand the concurrent urbanization era and demographic transformation using nighttime light remote sensing data on a worldwide scale. Instead of administrative boundaries, we utilize natural cities as a benchmark to depict the precise distribution of such spatial cities at a global scale. Natural city is a product of the bottom-up thinking in terms of data collection and geographic units or boundaries proposed by Bin Jiang (Jiang and Jia, 2011; Jiang and Miao, 2015). To accomplish this, we first evaluated historical urban shrinkage to establish that the proportion of identified global shrinking cities increased from 9% to 16 and 25% during 1992–2000, 2000–2012, and 2013–2018, respectively. There were 183,451,413, 547,940,208, and 2,061,743,186 inhabitants in shrinking cities in 2000, 2012, and 2018, according to the distribution of nighttime light pixels. Shrinking cities spread from relatively developed areas to underdeveloped areas and from relatively small-sized cities to medium- and large-sized cities. It is predicted that a total of 7,166 shrinking cities would come into existence, accounting for 37% of all cities, covering 29% of the total natural city area with 2,921,647,019 inhabitants by the year 2050.

To reveal where people from shrinking cities migrate to, we take China, a country with the most shrinking cities in 2013–2018, as an example for further examination. Baidu Huiyan migration statistics from Nov. 2017 to Nov. 2019 were acquired to analyze the migration among 3,022 natural cities in China. The movements demonstrated that the out-migration from shrinking cities contributes to the emergence of large cities, leading to other small and medium-sized cities' loss of workplaces and waves of population out-migration. We further predicted that the number of natural cities with a population of less than 10,000 will decrease by approximately 32% in the world by 2050. By using large-scale urban data with geotags, the dual existence of mega and shrinking cities emerges which has coincidently contributed to concentrating environmental impacts spatially, enhancing the public resources' equity and efficiency (e.g., education and medical). This could help mobilize the achievement of sustainable cities and communities of SDG 11.

In consideration of a new urban shrinking landscape, we therefore proposed two innovative solutions with quantitative simulation experiments toward enriching SDG 11: 1) Regreening vacant lands in shrinking cities. It will benefit in preserving green space, increasing the flexibility of energy system design, rendering stormwater management services, improving the urban thermal environment, expanding terrestrial carbon sinks, adapting to climate change, and finally accomplishing the sustainable development goals of shrinking cities. 2) Constructing compact cities. It has potential to improve the living environment, maintain subject well-being and reduce the expenditure on public services.

RESULTS

Spatial distribution characteristics of global shrinking cities in the past (1992–2018): Global and local scales.

To identify the spatial evolution of global shrinking cities at the city level, we analyzed the first three phases, 1992–2000, 2000–2012, and 2013–2018, based on nighttime light remote sensing data at the global level (Figures S1 and S2). Figure 1A–1C shows there are increasingly more shrinking cities with lower initial nighttime light intensity, which indicates that the cities in underdeveloped areas have been shrinking. In the three phases, 18%, 32%, and 62% of the total cities with an initial nighttime light intensity of less than ten were shrinking. Figure 1D–1F indicate that natural cities with larger areas have been experiencing shrinking. For the cities smaller than 10 km^2, the mean shrinking ratios are 56%, 51, and 43%; in contrast, for the cities larger than 50 km^2, the ratios are 5%, 7, and 12% of all the cities globally. In addition, we did not find a causal relationship between urbanization rates and proportions of shrinking cities in different countries. Shrinking cities emerge in countries with different levels of urbanization as indicated in Figure 2. Belgium and Japan have the highest urbanization rates, while the proportions of shrinking cities in these two countries do not exceed 25%. Countries with a high urbanization rate like Sweden, Denmark, and the United Kingdom and countries with a low urbanization rate like Egypt, Uzbekistan, and Syria suffer from a high proportion of shrinking cities.

Figure 3 shows the overall changes in the shrinking cities of different countries in the first three phases. In general, shrinking cities spread from Eastern Europe and Central Asia to the developed countries in Europe

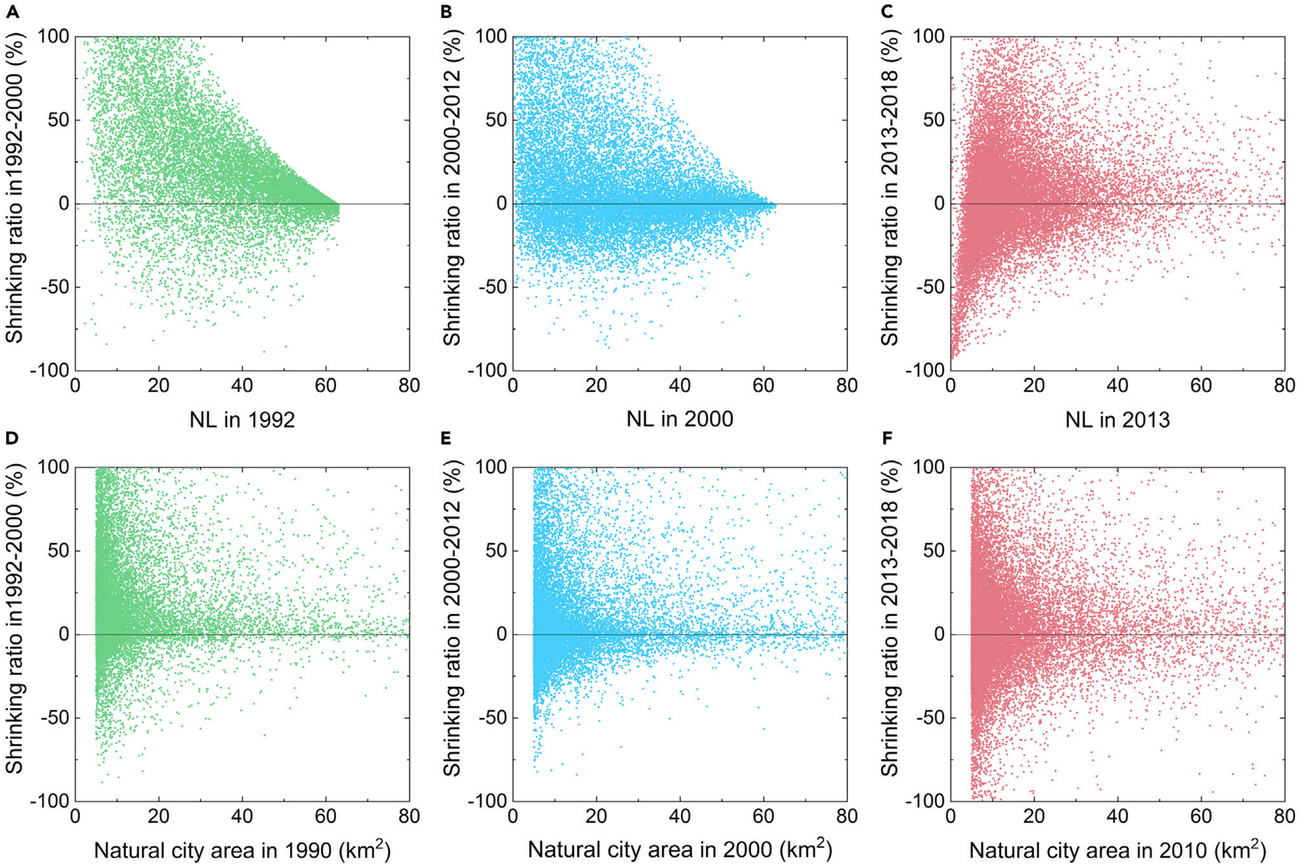


Figure 1. Relationship between the shrinking ratio and the initial nighttime light intensity
(A), 2000 (B), and 2013 (C) or the natural city area in 1992–2000 (D), 2000–2012 (E), and 2013–2018 (F). The initial nighttime light intensity represents the development level of the natural city.

and the United States and then worldwide. Moreover, we present cartograms to reveal the spatial distribution of global natural cities and their proportions of shrinking cities in the three stages From 1992 to 2000, shrinking cities were relatively uncommon at only 1,295 (9%) of all cities worldwide — and they were mainly concentrated in Eastern Europe and Central Asia. Ukraine was the country with the highest proportion with nearly 60% of its natural cities shrinking. Others were sparsely distributed in Western Europe, the United States, the Middle East, and North Africa. From 2000 to 2012, we identified 2,821 shrinking cities (accounting for 16% of all cities) that were increasing and stretched globally, especially in developed countries. In the United States, which ranked first among the nations, there were 612 cities extending from the northeast to the east and west coasts. Many cities were shrinking in Western Europe, including cities in Germany (305), France (224), and the United Kingdom (185). From 2013 to 2018, the number further accelerated at a global scale, with nearly a quarter of all cities shrinking and around 27% of people living in shrinking cities in the world (Figure 4). A substantial number of shrinking cities appeared in Africa, Latin America, and East Asia. They were no longer restricted to developed countries but spread to developing countries such as BRICS (Brazil, Russia, India, China, and South Africa). For instance, the number of cities in China reached 754, which was almost seven times higher than in the previous phase, outnumbering that of the United States, and China became the country with the most shrinking cities. There were 167 in India, which was eight times that in 2000–2012.

Four primary driving factors of shrinking cities

By summarizing the reasons affecting urban shrinkage, we drew a schematic diagram as indicated in Figure 5 through reviewing 100 studies (Table S1). The driving factors can be categorized into five types. First, cities that are faced with population decline because of such economic factors as globalization, industrial transformation, high housing costs, and resource depletion. Second, cities that are suffering from a

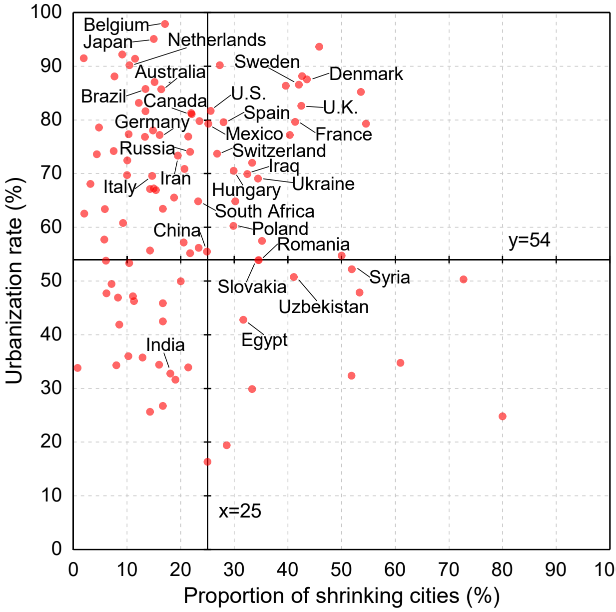


Figure 2. Relationship between urbanization and urban shrinkage

We plotted the urbanization rate in 2015 and the proportion of shrinkage from 2013 to 2018 of 102 countries in the world with more than 10 natural cities and at least one shrinking city. The urbanization rates in different countries were achieved from the United Nations. Thirty countries with the largest number of shrinking cities are labeled. The world average urbanization rate and proportion of shrinking cities are 54 and 25%.

demographic decline, which is the result of low fertility rates, high life expectancies, and aging. There are many factors that may affect the global urban shrinkage which include the wide gap between the number of births and deaths and the declining labor force. Third, several social factors lead to urban shrinkage in many small and medium-sized cities; for example, the social services and urban infrastructure are lacking, which has caused the population's out-migration. Moreover, the development of transportation and formation of suburbanization accelerate this trend. Fourth, institutional factors such as the transformation of the social system, adjustment of national policy, and even wars will have a lasting impact upon the development of cities. The main functions, industries, and labor forces of some cities are affected or damaged by the aforementioned transformation, which has led to the emergence of shrinking cities. Finally, some shrinking cities are exacerbated by environmental factors such as natural disasters, low temperature, climate change, and air pollution.

To illustrate the driving factors and mechanism of shrinking involved, we selected a few typical shrinking cities from four representative countries in the aforementioned literature review as shown in Figure 6. First, such cities as Detroit, Cleveland, and Chicago in the Rust Belt of the United States are an example of shrinking cities caused by unequal regional development. The recession of the manufacturing industry has led to a reduction in labor demand, whereas healthcare, education, working environment, and other supporting services are not comparable to those in other cities. Consequently, the population in the Rust Belt has declined dramatically. Second, Dresden and Leipzig in Eastern Germany suffered from great social and economic transformations after the reunification of East and West Germany in 1990. Many problems have appeared since then, including plant closures and bankruptcies, population out-migration, and increasing unemployment rate. Third, Hegang, Anshan, and other cities in Northeast China have gradually lost their vitality, which has led to population loss, economic decline, and spatial decay. Fourth, in Japan, small and medium-sized cities in Hokkaido (Sapporo) experienced shrinking because of severe population aging. The declining demographics are also partly exacerbated by the insufficient supply of labor in these single-industry cities, which further lead to their economic decline.

Out-migration from shrinking cities mainly move to large cities

Because there are so many shrinking cities on the globe, where do their populations mainly flow? Few studies have investigated the out-migration from shrinking cities because of the missing big data as well

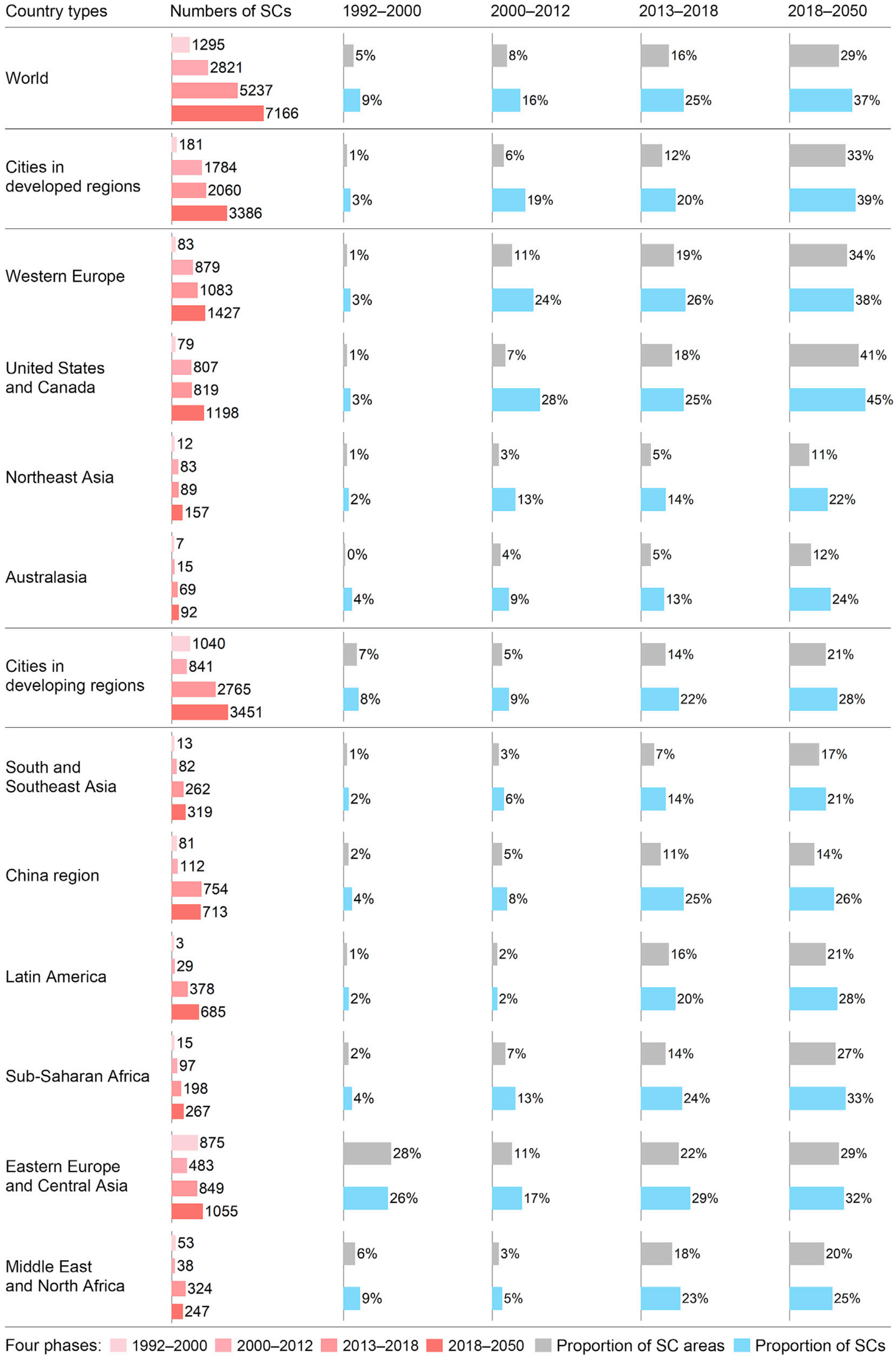

Country types
Numbers of SCs
1992–2000
2000–2012
2013–2018
2018–2050
World
1295
2821
5237
7166
5%
9%
8%
16%
16%
25%
29%
37%
Cities in developed regions
181
1784
2060
3386
1%
3%
6%
19%
12%
20%
33%
39%
Western Europe
83
879
1083
1427
1%
3%
11%
24%
19%
26%
34%
38%
United States and Canada
79
807
819
1198
1%
3%
7%
28%
18%
25%
41%
45%
Northeast Asia
12
83
89
157
1%
2%
3%
13%
5%
14%
11%
22%
Australasia
7
15
69
92
0%
4%
4%
9%
5%
13%
12%
24%
Cities in developing regions
1040
841
2765
3451
7%
8%
5%
9%
14%
22%
21%
28%
South and Southeast Asia
13
82
262
319
1%
2%
3%
6%
7%
14%
17%
21%
China region
81
112
754
713
2%
4%
5%
8%
11%
25%
14%
26%
Latin America
3
29
378
685
1%
2%
2%
2%
16%
20%
21%
28%
Sub-Saharan Africa
15
97
198
267
2%
4%
7%
13%
14%
24%
27%
33%
Eastern Europe and Central Asia
875
483
849
1055
28%
26%
11%
17%
22%
29%
29%
32%
Middle East and North Africa
53
38
324
247
6%
9%
3%
5%
18%
23%
20%
25%
Four phases:
1992–2000
2000–2012
2013–2018
2018–2050
Proportion of SC areas
Proportion of SCs

Figure 3. Overall changes of global shrinking cities in four phases

The numbers and total areas of shrinking cities and natural cities are presented. Defense Meteorological Satellite Program-Operational Linescan System (DMSP-OLS) images with a 1 × 1 km^2 spatial resolution are used for the first two phases, and Suomi National Polar-Orbiting Partnership-Visible Infrared Imaging Radiometer Suite (NPP-VIIRS) images with a 500 × 500 m^2 spatial resolution are used for the last two phases. Natural city boundaries were converted from Liu et al.'s global land use distribution data from the years 1990, 2000, 2010, and 2015 (Liu et al., 2018). Note: SC refers to a shrinking city. The division of global countries is based on World Urbanization Prospects (2014 revision, UN Population Division). A natural city is recognized as a shrinking city if its average nighttime light intensity decreases by more than 10% in 10 years.

as quantification difficulties. As the country with the most shrinking cities in 2013–2018, China is further investigated as an example to quantify the out-migration from shrinking cities employing the Baidu Huiyan migration statistics. To the best of knowledge, it is the first research to investigate where the residents are from shrinking cities moving to, with high-resolution user location information. As a typical representative, China's population flows reflect the general law of population flow out of shrinking cities. The results indicate that 65% of them migrate to cities at the top 12% in size (Figure 7). Approximately 78% of the distances between destinations and shrinking cities from which residents migrate out are less than 1,000 km; 19% of them are in 1,000–2,000 km; only 3% of the distances are over 2,000 km.

This could be explained by Myrdal's theory (Myrdal and Sitohang, 1957) of circular and cumulative causation. In Myrdal's framework, large cities attract population from less developed neighboring areas, leading to the 'backwash effects' on the neighbors, whereas the urban agglomeration may increase demand for agricultural products and raw materials and thus create employment opportunities in the peripheral areas, thereby exerting 'spreading effects'. This model holds that in no circumstances do spread effects exceed backwash effects. In this context, the cities with increasing out-migration were to face a 'vicious circle' of cumulative population decline. Urban shrinkage was thus conceptualized as a self-reinforcing process propelled by labor-oriented out-migration.

The negative effects of shrinking cities

A persistent loss of population usually has a negative impact on shrinking cities (Table S2), including economic hardship (García-Ayllón, 2016; Pagano and Bowman, 2004), social disruption (Frazier et al., 2013; Hudson, 2005; Rybczynski and Linneman, 1999), abandonment of built environments (Blanco et al., 2009; Greenberg and Schneider, 1996; Lee and Newman, 2017), and urban planning problems (Pallagst, 2009; Ryan and Gao, 2019). According to the inflow-outflow migration statistics from Baidu Huiyan in China, 43% of labor productivity in urban areas decreased 22% because of urban shrinkage (Yang et al., 2020). Further, 15% of labor productivity in the world decreased with the same scale from 2013 to 2018. Furthermore, the adverse effects of urban shrinkage may lead to causal relationships and form a cyclical chain (Kim, 2019). For instance, a declining population leads to a shortage of labor resources that may cause factories and companies to cease operations, economic crises, unemployment, and more population immigrating into other prospering regions (Haase, 2013). This, as a kind of a vicious cycle, results in further demographic decline (Nuissl and Rink, 2005), which occurs in many such cities (Couch et al., 2005).

The coincidental positive shrinking effects on carbon emission mitigation, healthcare, and education enhancement

Our quantitative experiments in China proved that accompanying the increasing number of shrinking cities, there is an out-migration trend from nonurban areas or small cities to large cities, which is also verified by traditional census data (Mu et al., 2021) and emerging Internet data (Egidi et al., 2020; Keuschnigg et al., 2019; Zhang et al., 2020). This is echoed with our predictions that the number of natural cities with a population of less than 10,000 will decrease by approximately 32% (Figures S4 and S5).

Based on data provided by a global dataset of CO_2 emissions, we examined the relationships between annual CO_2 emissions per capita (t/year) and city area/population size in 343 administrative cities in 2015. The results indicate that with an increase in city size, the emissions of CO_2 in cities gradually decreased (Figure S6). The annual amount of CO_2 emissions per capita in administrative cities with an area over 2,000 km^2 is 35% of that with an area less than 50 km^2. The annual CO_2 emissions per capita of administrative cities with a population of over 20 million are 40% of those with a population of less than 500,000.

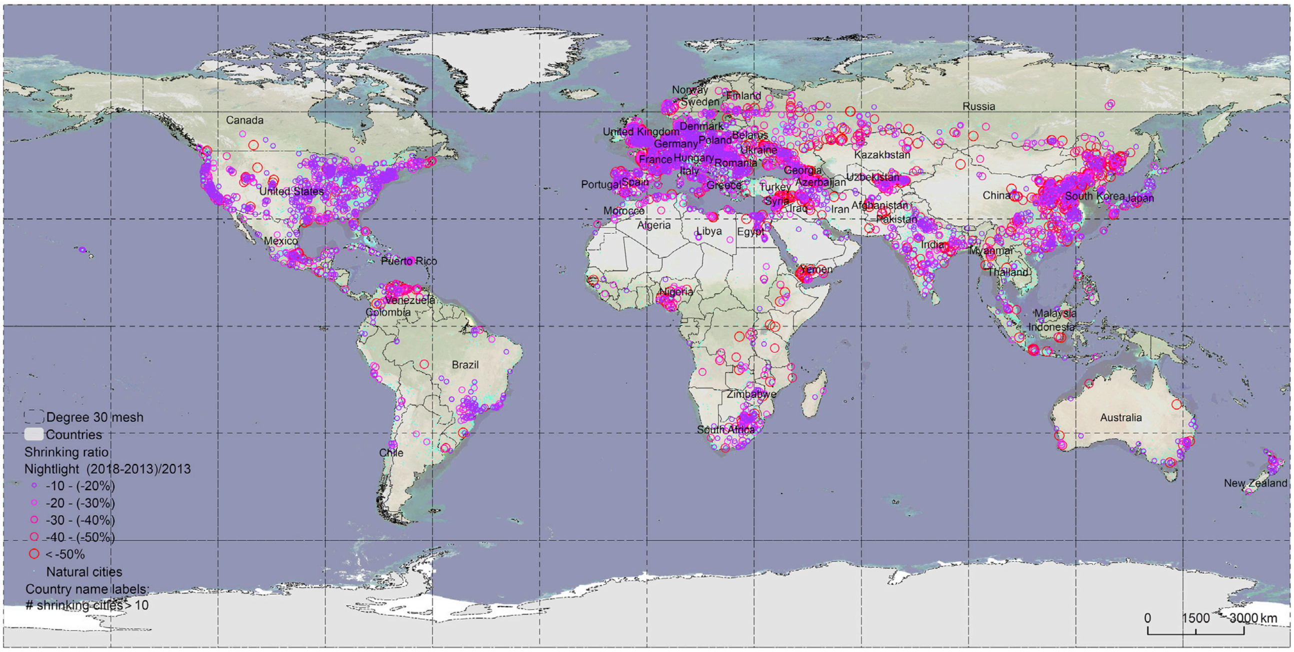


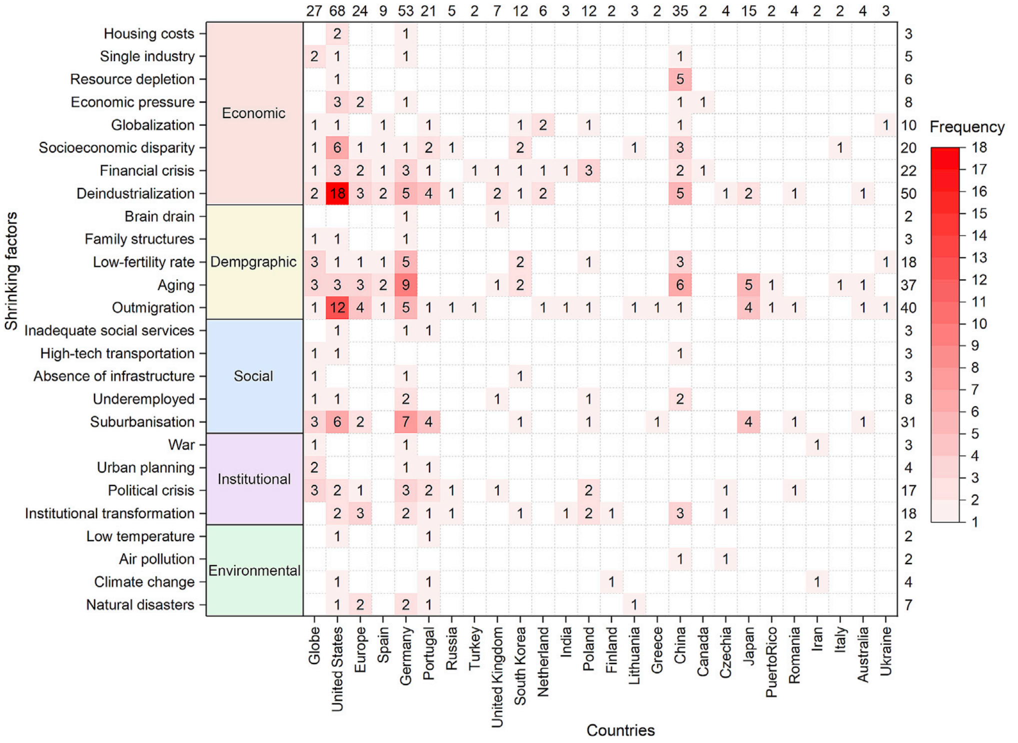
Figure 4. Satellite map of the distribution of global natural cities and the shrinking ratio at the city level by NPP-VIIRS (2013–2018)

We redefined 21,058 natural cities of over 5 km^2 for the year 2010 to estimate and compare their areas by using the NPP-VIIRS nighttime light data for 2013 and 2018. The total area was 715,638 km^2. A total of 5,237 of the 21,058 natural cities had shrunk during 2013–2018, among which there were 531 natural cities with the shrinking ratios exceeding 50%. The total shrinkage area was 114,158 km^2, which covered more than 16% of the total area of natural cities with 2,061,743,186 inhabitants. The shrinking cities were mainly located in Eastern Asia, Western Europe, and the eastern United States.

Then, we explored the healthcare-related and education-related points of interest (POIs) from OpenStreetMap (OSM) to evaluate the densities of the POIs in natural cities with different areas (Figures S7 and S8). Cities with a higher density of healthcare-related or education-related POIs are regarded as cities with better healthcare facilities or educational resources. The result shows that the density of healthcare resources in natural cities with an area over 2,000 km^2 is twice that of cities with an area less than 50 km^2. Similar studies show that the density of educational resources in natural cities with an area over 2,000 km^2 is 2.5 times that in natural cities with an area less than 50 km^2 (Figures S7 and S8). To sum up, as some megacities grow, they pull in ever more people, leading to other small-sized and medium-sized cities' proportionate urban shrinkage, it is coincidentally beneficial to reducing environmental problems, enhancing public resources' efficiency, establishing good health and well-being, and thus mobilizing the achievement of sustainable cities and communities of SDG 11 (Table S3).

National urbanization strategies across the world: Does policy matter?

Most of the existing studies on shrinking cities have focused on the negative effects of urban shrinkage and called on the government to carry out planning interventions. Urbanization strategies in different countries across the world have been adjusted to manage shrinking cities. We thus attempted to investigate whether these policies are effective as containment policies (Table S4). We divided national urbanization strategies into three types according to the purpose of the urbanization strategies formulated by the governments: proactive, negative, and balanced (Mingione, 1982; Renaud, 1979; Richardson, 1981). A proactive strategy promotes the development of metropolises, a negative strategy slows down the urbanization process, and a balanced strategy promotes the development of both urban and rural areas (Pfeffermann, 1982). Owing to the difficulty of data acquisition, we only obtained twelve relevant policy indicators (six positive policy indicators and six negative policy indicators) published by the UN in 2015 to identify different countries' urbanization strategies in 2013–2018. We classify a country's urbanization strategy by comparing the numbers of proactive and negative indicators. If the proportions of the two types of policy indicators are equal, the urbanization strategy of the country is balanced. The results show that 89, 48, and 55 countries adopted proactive, negative, and balanced urbanization strategies in 2013–2018, respectively (Figure 8).



		Globe	United States	Europe	Spain	Germany	Portugal	Russia	Turkey	United Kingdom	South Korea	Netherland	India	Poland	Finland	Lithuania	Greece	China	Canada	Czechia	Japan	PuertoRico	Romania	Iran	Italy	Australia	Ukraine	
		27	68	24	9	53	21	5	2	7	12	6	3	12	2	3	2	35	2	4	15	2	4	2	2	4	3	
Economic	Housing costs		2			1																						3
	Single industry	2	1			1												1										5
	Resource depletion		1															5										6
	Economic pressure		3	2		1												1	1									8
	Globalization	1	1		1		1				1	2		1				1									1	10
	Socioeconomic disparity	1	6	1	1	1	2	1			2					1		3							1			20
	Financial crisis	1	3	2	1	3	1		1	1	1	1	1	3				2	1									22
	Deindustrialization	2	18	3	2	5	4	1		2	1	2						5		1	2		1			1		50
Dempgraphic	Brain drain					1				1																		2
	Family structures	1	1			1																						3
	Low-fertility rate	3	1	1	1	5					2			1				3									1	18
	Aging	3	3	3	2	9				1	2							6			5	1			1	1		37
	Outmigration	1	12	4	1	5	1	1	1			1	1	1		1	1	1			4	1	1			1	1	40
Social	Inadequate social services		1			1	1																					3
	High-tech transportation	1	1															1										3
	Absence of infrastructure	1				1					1																	3
	Underemployed	1	1			2				1				1				2										8
	Suburbanisation	3	6	2		7	4				1			1			1				4		1			1		31
Institutional	War	1				1																		1				3
	Urban planning	2				1	1																					4
	Political crisis	3	2	1		3	2	1		1				2						1			1					17
	Institutional transformation		2	3		2	1	1			1		1	2	1			3		1								18
Environmental	Low temperature		1				1																					2
	Air pollution																	1		1								2
	Climate change		1				1								1									1				4
	Natural disasters		1	2		2	1									1												7

Figure 5. A literature review of the driving factors for shrinking cities

Each digit in the diagram represents the number of shrinking city cases resulting from a specific reason in one country. Driving factors contributing to shrinking cities in the literature involve five groups: economic factors, demographic factors, social factors, institutional factors, and environmental factors. The number of cases mentioned for the five groups are 124, 100, 48, 42, and 15. The top four studied countries in the world are the United States, Germany, China, and Japan.

To reveal whether the national urbanization strategy has an impact on urban shrinkage, we applied two hypothesis testing approaches (Tables S5 and S6), including the *t*-test (two-sample equal variance) (Díaz–Pachón et al., 2020; Schnuerch et al., 2020) and the Friedman test (two-way ANOVA by rank) (Beasley and Zumbo, 2003; DeJuan and Seater, 2007). We set the null hypothesis that national urbanization strategies have no effect on shrinking cities and analyzed the significance of the shrinkage rate at the national level under the three types of urbanization strategies in 2013–2018 to test the authenticity of the null hypothesis. The results show that the null hypothesis is true; that is, each of the nations' urbanization strategies has no significant effect upon the shrinking ratios across these countries. It could be inferred that the national urbanization strategy has little impact on the migration and spatial distribution of population (Banerjee and Schenk, 1984). This result agrees well with the outcome of the urbanization strategies implemented in historical periods in some countries.

Global urban shrinkage: Prospecting urban futures

A quantitative prediction of shrinking cities can reveal the development tendency of shrinking cities in the world; however, such projections are limited at present. We used night light data to analyze the distribution of global shrinking cities over a long-time span from 2000 to 2018; however, grasping the distribution of shrinking cities in the future is essential for effectively guiding the healthy development of cities. We made future predictions of urban shrinkage from 2018 to 2050 based on the past developmental trend identified by historical nighttime light images, which were also constrained by global country-level population prediction data. The technological details for the future predictions can be found in the STAR Methods section. According to our forecast, the decline of cities will continue from 2018 to 2050 worldwide. There are expected to be 7,166 shrinking cities in 2018–2050, accounting for 37% of all cities and covering 29% of the total natural city area. Shrinking cities in 2050 involve 2,921,647,019 inhabitants. The increase of inhabitant quantity in shrinking cities decelerates. Their quantity and intensity will keep increasing in both developed and developing countries. Approximately 32% of cities in the world will shrink to more than 50% of their original area. For cities with an area smaller than 10 km^2, the

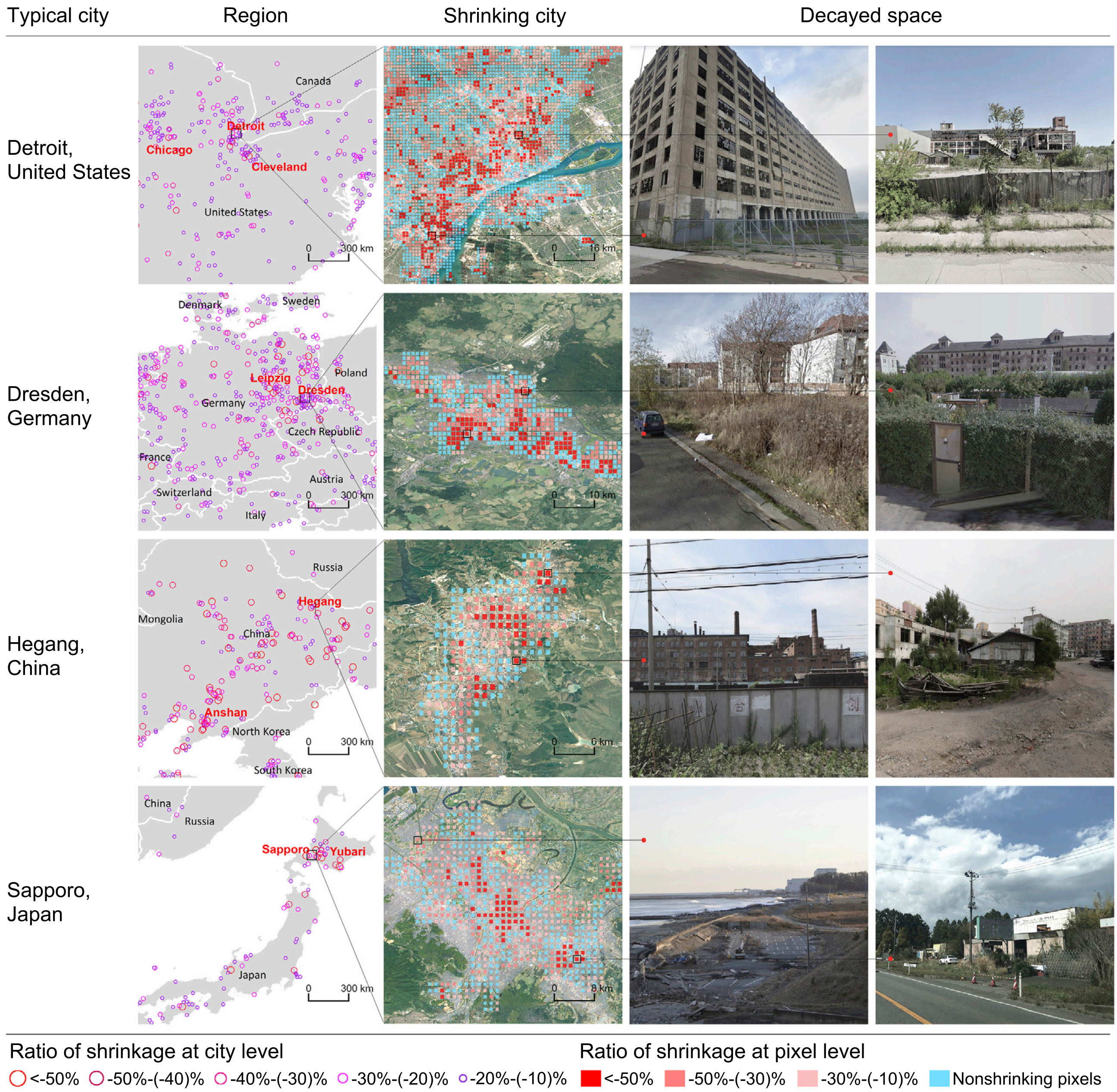


Figure 6. Four typical shrinking cities (Hegang in China, Detroit in the United States, Dresden in Germany, and Sapporo in Japan) are specifically examined at the regional, city, and block levels

The locations of the four cities are given in the regional level column. The spatial distributions of the intensity of the shrinking in the four cities are shown in the city level column. Two street view pictures in each city are given in the block level columns. Hegang and Detroit are described for the 2013–2018 phase, and Dresden and Sapporo are described for the 2000–2012 phase. The remote sensing images and street view photos are from Google Maps.

mean shrinking ratio will be approximately 39%. In contrast, the ratio is 13% of all the cities larger than 50 km^2 globally. During this phase, significant increases in shrinking cities will appear in regions such as Australasia and Northeast Asia. Figure 9 displays their predicted distribution and proportion of shrinking cities at the country level from 2018 to 2050. The United States, China, Russia, Brazil, Germany, and India are the top six countries with the highest numbers worldwide. We compared the urban shrinking forecast developed by the United Nations, Department of Economic and Social Affairs, Population Division with the forecasts developed by the five scenarios of shared socioeconomic pathways (SSPs); the six results are consistent (Table S7).

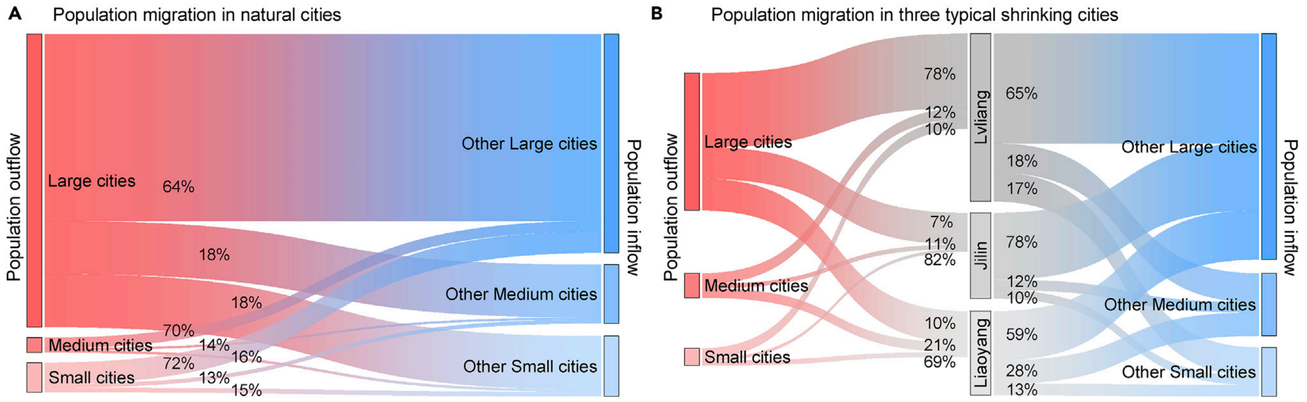


Figure 7. Migration flow in natural cities and shrinking cities

(A and B) There are 64%, 18%, and 18% of migration from large cities flowing to large, medium, and small cities in China (A). As for migration from medium shrinking cities, 70%, 14, and 16% of them migrate to large, medium, and small cities. What is more, as for migration from small shrinking cities, 72%, 13, and 15% of them migrate to large, medium, and small cities. Large, medium and small in this figure refer to 12%, 15, and 73% of natural cities in China according to city size, referring to the five-level urban hierarchy classification standards (Figure S3). The inflow-outflow migration statistics of three typical shrinking cities Lvliang, Jilin, and Liaoyang are presented in inset (B). The outflow outnumbers the inflow of shrinking cities and a majority of outflow move to large cities.

Shrinking cities have existed for decades and will continue to spread in the future. At present, it seems that the policies in different countries have limited influence and that this trend is irreversible. Their presence may not be conducive to the development of specific cities. Nevertheless, our experimental results from Baidu Huiyan migration statistics demonstrated that shrinking cities have also contributed to the emergence of additional large cities, which can be beneficial in various respects. We tested the trend of shrinking cities around the world with different population situations, as indicated in Figure 10. In addition to the number of shrinking cities calculated based on the population distribution under the UN normal scenario, we calculated the situations under high fertility, low fertility based on estimates from the Global Burden of Diseases, Injuries, and Risk Factors Study (GBD) 2017 (Murray et al., 2018; Vollset et al., 2020) and the situation under zero migration based on the UN forecast data. Next, we calculate the number of cities in the world in 2050 under the SSP1 scenario with global aging population (Samir and Lutz, 2017). Moreover, we assume that China's relaxation of the *Hukou* and the migration from small cities to large cities will lead to a 10% increase in the population of the top seven natural cities. Finally, it is assumed that cities will shrink when affected by an epidemic situation, such as because of COVID-19 deaths, in an unmitigated scenario in different regions. The results indicate that the relaxation of the *Hukou* in China, a low fertility policy, a zero migration, and the influences of pandemic diseases (e.g., COVID-19) will accelerate the shrinking of cities around the world, whereas a high fertility will have a mitigating effect.

Synergistic efforts toward SDG 11 in consideration of the new urban shrinking landscape

The Sustainable Development Goals (SDGs) were adopted by the United Nations in 2015, providing a shared blueprint for peace and prosperity for people and the planet now and into the future. The previous SDG 11 was designed and defined in the context of rapid urban growth, although shrinking is a nonnegligible part of the urban future. There is an urgent need for a planning paradigm shift toward 'planning for shrinking' besides 'planning for growth'. In this research, we propose two solutions to shrinking cities for the enrichment of SDG 11.

Regreening vacant lands in shrinking cities

The outflow of population and capital from a shrinking city result in massive vacant lands. Shrinking spaces are converted from nighttime light image pixels whose intensities decrease over 10% within shrinking city boundaries (Figure S9). Existing studies suggest that vacant land constitutes over 15% of the total land area in cities throughout the United States (Bowman, 2004; Nickerson et al., 2011). According to the previous studies, vacant land can be converted into green infrastructures (GI) such as temporary or permanent community gardens, urban farmland, and community forests (Hummel, 2015). The regreening of shrinking cities will benefit in preserving green space (Choi et al., 2021), increasing the flexibility of energy system design (Jing et al., 2020), rendering stormwater management services (Kelleher et al., 2020; Lovell and Taylor,

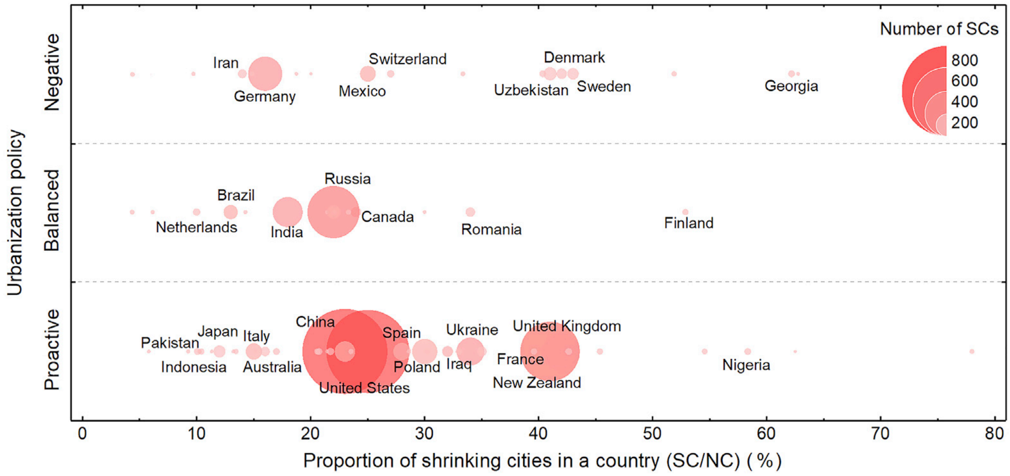


Figure 8. Correlation between national urbanization policy and proportion of shrinking cities in 2013–2018

Note: NC and SC refer to a natural city and a shrinking city.

2013), improving the urban thermal environment (Bosch et al., 2021), increasing terrestrial carbon sinks (Anderson and Gough, 2020), adapting to climate change (Gaffin et al., 2012), and finally achieving the sustainable development goals of shrinking cities.

For instance, green infrastructure has been introduced across many urban areas as a decentralized, economical approach to reducing sewer system overflows and to supply urban ecosystem services (Lovell and Taylor, 2013). If all vacant land in shrinking cities were converted into GI, we applied a simple model to estimate the rainfall detention capacity (Kelleher et al., 2020) with the average precipitation in depth in different countries. In this model, we take average parcel infiltration as the maximum rate that water can be infiltrated over the percentage of previous area, and we assume unvegetated surfaces (impervious surface, bare ground) cannot contribute to rainfall detention capacity and will contribute to the volume of overland flow (Kelleher et al., 2020). The results suggested that rainfall of 1.26×10^8 m^3 for a representative 1 h storm event will be absorbed and thereby diminish stormwater runoff (Table S8). The elimination is approximately two times of the average discharge of the Mississippi river per hour.

In addition, the newly built green infrastructures in shrinking cities form ‘cooling islands’ to improve the urban thermal environment. Recent work demonstrated a linear correlation between cooling intensity and green infrastructure patch area and another linear correlation between cooling range and green infrastructure patch area (Tan et al., 2021). We referred to the quantitative relationships to estimate the effects generated from the newly built green infrastructures in shrinking cities. The results revealed that if all vacant lands of shrinking space in the world are converted into green infrastructures, the total area of green infrastructures over 50 ha reaches 7,334 km^2, leading to an air temperature reduction of 1.83–2.17°C with a 256–291 m range. The total area of green infrastructures between 10 and 50 ha reaches 3,621 km^2, reducing air temperature by 1.37–1.59°C with a 202–226 m range. As for the green infrastructures smaller than 10 ha, the total area reaches 2,832 km^2, and the cooling intensity is 1.05–1.29°C with a 162–178 m range.

Moreover, the newly built green infrastructures function as terrestrial carbon sinks. We referred to the relationship from an intensive field campaign involving 14,371 field plots (Tang et al., 2018) and applied a linear estimation on the increase of the total carbon pool in the world. It is estimated that 1.51 ± 0.08, 0.83 ± 0.04, 0.83 ± 0.05, or 0.88 ± 0.02 Pg C will be supplemented to the terrestrial carbon pool if the vacant lands are converted into forests, shrublands, grasslands, or croplands, respectively (Table S9).

Constructing compact cities

There are also other alternative solutions to remake a shrinking city into a compact city, such as solutions to improve the living environment (Lee and Erickson, 2017), maintain the subject well-being (Mouratidis,

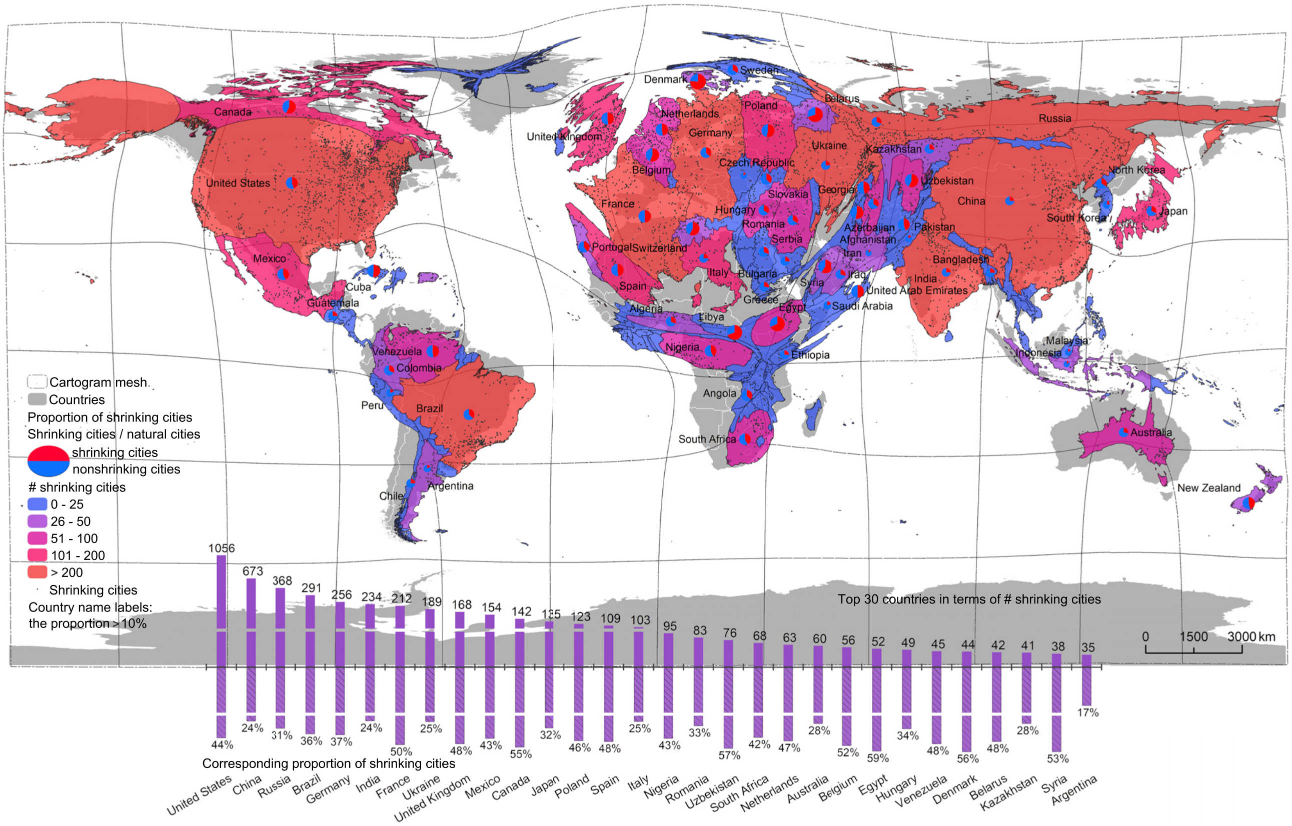


Figure 9. Cartogram of the distribution of global number of shrinking cities and the proportion of shrinking cities at the country level by NPP-VIIRS (2018–2050)

Of the 30 countries with the largest numbers of shrinking cities, the proportions of shrinking cities in France, Canada, Uzbekistan, Belgium, Egypt, Denmark, and Syria exceed 50%, whereas those in China, India, Ukraine, Italy, Australia, Kazakhstan, and Argentina are below 30%. At the city level, the numbers of shrinking cities and the shrinking ratios will accelerate around the world.

2019), and reduce the expenditure on public services (van Vliet, 2019). Compact development has to be implemented to go against other dimensions of sustainable urbanization to preserve the livability of cities for their inhabitants. Owing to the outflow of population and capital, it is costly and redundant to keep the original urban size and infrastructure intensity (Schilling and Logan, 2008). If the residence, working place and public services are shrinking to concentration, the efficiency will be promoted in a shrinking city for different aspects. Several shrinking cities such as Detroit in the United States, Toyama in Japan have attempted to downsize their shrinking space by means of consolidating schools as well as their public transport routes.

We conducted several simulation experiments to evaluate the potential cut in expenditures in different aspects of public infrastructures for local governments. Education and healthcare-related POIs and road networks on the globe from OSM were acquired, representing the spatial information of three typical public infrastructures. We assumed that the city size and the number of public infrastructures in each shrinking city should be compressed proportionally to the reduction of nighttime light intensity. The results indicate that the urban land of 91,926 km^2 in shrinking cities can be converted into nonurban areas to adapt to the outflow of population. In addition, the financial burden on 20% of both educational infrastructures and healthcare infrastructures in shrinking cities can be eliminated. Detailed effects from constructing compact cities within the 30 countries that have the largest number of shrinking cities in 2013–2018 are presented (Table S10). The eliminated proportions on educational infrastructures and healthcare infrastructures are above average in France (24%, 24%), China (23%, 21%), and Russia (23%, 24%). Moreover, the financial burden on 19% of road networks with a total length of 207,245 km in shrinking cities can be reduced, among which the roads and traffic occupy 49.3 and 50.7% (Table S11). In particular, the reductions of the financial

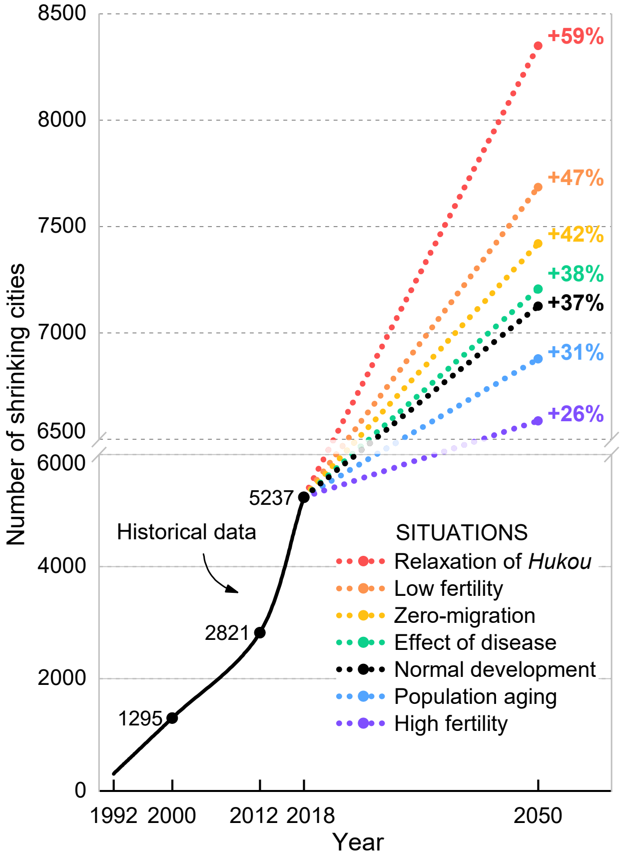


Figure 10. Numbers of shrinking cities under different situations

Under normal developmental situations (black line), there will be 7,166 shrinking cities in the world in 2050 and the increasing rate will reach 37%. Low fertility (orange line) and high fertility (purple line) lead to slow and fast increases of the population, respectively, resulting in increasing rates of 47 and 26%, respectively. In the zero-migration situation (yellow line), there are more shrinking cities given comparatively smaller populations in West Europe and North America. Population aging (blue line) will be aggravated in SSP1, and there will be an additional 42% shrinking cities in 2050 in this trajectory. If China relaxes the Hukou restriction (red line), migration to large natural cities will lead to the depletion of small cities. Infectious diseases (green line) such as COVID-19 have caused a population decline over the world, which will contribute to an increase in the number of shrinking cities.

burden on pathways in Africa, Asia, Australia, North America, South America, and Europe are 23%, 26%, 17%, 14%, 22%, and 20%, respectively.

Limitations of the study

Few limitations remain. First, the division in four phases is phenomenological, which is restricted by the continuity of remote sensing images.

Although the division of four phases can be utilized to investigate the trend of shrinking cities in the world, the time lags for different countries still remain. In this regard, global shrinking cities evolve differently and face variegated challenges.

Second, it is perhaps not effective to use a linear regression for nighttime light data prediction as the nighttime light image may serve as a type of manifestation of human distribution only and the linear regression model may fail to include important information in time series analysis. Hence, the driving factors contributing to shrinking cities should be further analyzed in future studies with a more detailed analytical framework.

Third, the lagging effect of policies should be considered when analyzing the relationship between urbanization strategies and shrinking cities.

Finally, the list of shrinking cities is narrowed in this study, which is because of the complexity of the formation of shrinking cities. Each shrinking city may have specific evolutionary trajectories, which were affected by different policies; therefore, it is difficult to draw a generalized law/rule from a global perspective. In fact, we do not attempt to explain the causal effect of national policy on the formation of shrinking cities in a country, though it is still important to do so in the future studies.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- RESOURCE AVAILABILITY
  - Lead contact
  - Materials availability
  - Data and code availability
- METHOD DETAILS
  - Division of the four phases
  - Natural city construction from nighttime images
  - Shrinking city identification
  - Literature review of the driving factors of shrinking cities
  - Outmigration from shrinking cities in China
  - Global nighttime light forecast
- QUANTIFICATION AND STATISTICAL ANALYSIS

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2022.104411.

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AUTHOR CONTRIBUTIONS

W.Z. and Z.J. contributed equally to this work. Y.L. conceived the original idea and X.Z. developed the research idea further. Y.L. and X.Z. co-funded the research. W.Z., Z.J., and X.M. designed and conducted the experiments. Z.J., X.M., and X.Z. analyzed the results. Y.L. and X.Z. supervised and led the research. W.Z., Y.L., and X.Z. wrote the manuscript, with substantial input from Z.J., X.M., and M.Z.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
DMSP-OLS nighttime light data (1992, 2000 and 2012)	NOAA	https://www.ngdc.noaa.gov/eog/dmsp/downloadV4composites.html
NPP-VIIRS nighttime light data (2013 and 2018)	NOAA	https://www.ngdc.noaa.gov/eog/viirs/download_dnb_composites.html
High-resolution global urban land (1990, 2000, 2010 and 2015)	GlobalUrbanLand	http://www.geosimulation.cn/GlobalUrbanLand.html
The world population prospects (2020–2100)	Department of Economic and Social Affairs (US)	https://population.un.org/wpp/Download/Standard/Population
The urbanization rate in 2015	UN	https://population.un.org/wup/Download/
SSP database	Climate change research community	https://tntcat.iiasa.ac.at/SspDb/
World POIs data	Open Street Map	http://download.geofabrik.de/index.html
China's POIs (2018)	AMap	https://lbs.amap.com/
The GDP per capita, total population data (1992–2018) and average precipitation (2014)	Worldbank	https://data.worldbank.org/indicator
The global dataset of CO_2 emissions and ancillary data (for 343 administrative cities)	GlobalCarbonCities	https://katirg.github.io/GlobalCarbonCities/
Migration statistics in China (2017–2019)	BaiduMap	https://huiyan.baidu.com/
Software and algorithms		
ArcGIS 10.5	ESRI	https://www.arcgis.com/
Origin 12	OriginLab	https://www.originlab.com/
SPSS 22	IBM	https://www.ibm.com/
Matlab 2020	Mathworks	https://www.mathworks.com/

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Ying Long (ylong@tsinghua.edu.cn).

Materials availability

This study did not generate new unique materials.

Data and code availability

The data used in this study are all available from public data resources that have been appropriately cited in the manuscript. Code and any other additional information required to reanalyse the data reported in this paper is available from the lead contact upon request.

METHOD DETAILS

Division of the four phases

We investigated the global shrinkage of cities in four phases by using night-time light remote sensing images. Compared with the ordinary demographic and statistical data, night-time light remote sensing data are considered more objective which could quickly reflect human activities and nature habitation (Shi et al., 2014; Wardrop et al., 2018; Wei et al., 2014) and widely applied to urban sciences in recent times.

DMSP-OLS nighttime light data with a 1 × 1 km^2 spatial resolution are available from 1992 to 2012, and they were used to study the shrinking cities from 1992 to 2012. The year 2000, as the turn of the century, was used as the division between the first two phases. NPP-VIIRS nighttime image data with a 500 × 500 m^2 spatial resolution are available since 2013, and they were applied to evaluate the global shrinking cities in the past few years (phase 3) and forecast the future ones (phase 4).

Natural city construction from nighttime images

This study proposed an alternative approach to identify shrinking cities based on the transformation of urban nighttime light data at the global level in three phases and further predict the future forecasts of shrinking cities. Every pixel in the nighttime light image for 2050 was predicted by a linear regression model for each corresponding pixel in 2013–2018. In particular, we identify urban shrinkage by utilizing natural cities as a benchmark to make it comparable for shrinking cities in different countries. The phenomenon of shrinking cities has been ignored by urban planners and policymakers, especially in developing countries. According to our prediction, more than one-third of the world's cities will shrink to varying degrees by 2050.

Shrinking city identification

We collected monthly NPP-VIIRS nighttime remote sensing images captured in Jan.–Mar. and Oct.–Dec. from 2013 to 2018 spanning from 75 °N to 65 °S latitude to avoid the effects of missing data over the high-latitude regions of the Northern Hemisphere in summer months and computed the average intensity of each year pixel by pixel. To make the nighttime light data in different years comparable, we used the brightest areas and the darkest areas as pseudo-invariant features to correct the images (Wei et al., 2014). The identification of the shrinking cities in four phases was based on natural cities, and this was achieved by delineating the global urban land distribution images in 1990, 2000, 2010, and 2015, reserving only those with an area greater than 5 km^2, following previous studies (Long et al., 2018). Next, we computed the ratio of change of the mean pixel values within each natural city in the four phases. The shrinking ratio at the city level is defined by the decreased percentage of nighttime light intensity from the start year to the end year in one phase. Following previous studies (Table S12), a natural city with a shrinking ratio lower than -10% over ten years is defined as a shrinking city. The proportion of shrinking cities at the country level is defined by the ratio of the number of shrinking cities among all natural cities within one country. In the actual experiments, although the time spans in each phase are not exactly ten years, they do not affect the robustness of their results according to our additional experiments (Table S13).

Literature review of the driving factors of shrinking cities

We conducted a literature review of the driving factors of shrinking cities on the *Web of Science*, and the searching query is *(AK=(shrinking cities) OR AK=(urban shrinkage)) AND (TS=(reasons) OR TS=(causes) OR TS=(factors) OR TS=(resources) OR TS=(population) OR TS=(regional development) OR TS=(transformation) OR TS=(policy) OR TS=(war) OR TS=(demographics decline) OR TS=(low fertility rates) OR TS=(lack of labor))*. A total of 284 research papers were retrieved, of which 100 were empirical papers related to shrinking cities after manual review and excluding papers unrelated.

Outmigration from shrinking cities in China

We acquired 4,538,201 migration trajectories in China in Nov. 2017–Nov. 2019 from Baidu Huiyan. First, approximately 170 million personal residence information were gathered from software and services of Baidu on different terminals with privacy information removed. Second, a movement of personal residence over 6 months from one city to another is regarded as a migration. Based on the natural cities in 2018 (Song et al., 2018) with a minimum size of 2 km^2, we finally identified the migration of residents in China among 5,950 natural cities.

Global nighttime light forecast

We acquired NPP-VIIRS global nighttime light images from 2013 to 2018. A linear regression was applied to each corresponding pixel of the six global annual nighttime images to obtain an estimated global annual nighttime image in 2050, which had a size identical to those of the images from 2013 to 2018. The brightest areas and the darkest areas were selected as pseudo-invariant features to correct the nighttime light images in 2050. We scaled the values of the nighttime light data in 2050 constrained by the population data of each country from the United Nations and five SSPs so that the distribution of the sum of the nighttime light intensity was equal to the population distribution in each country. In this way, a global nighttime light map for 2050 with a 500 × 500 m^2 resolution was achieved. A sensitivity analysis of natural cities and the constraint selection strategy for the forecasted shrinking cities was conducted for the validation (Table S14).

QUANTIFICATION AND STATISTICAL ANALYSIS

In this research, we analyzed the data using MATLAB R2018a and ArcGIS 10.5. The pixel-based average calculation for the DMSP-OLS nighttime light data was processed by the MATLAB R2018a mapping toolbox. The global natural city areas were generated with the assistance of the ''raster to polygon'' tool from the ArcGIS Toolboxes. The mean nighttime light pixel value of each natural city area was computed with the ''zonal statistics as table'' tool, which is also generated from the ArcGIS 10.5 system toolboxes. The cartogram figures in this study were created with the ''cartogram geoprocessing tool'' (http://arcscripts.esri.com/details.asp?dbid=15638).

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Supplemental information

Satellite monitoring of shrinking cities on the globe and containment solutions

Weixin Zhai, Zhidian Jiang, Xiangfeng Meng, Xiaoling Zhang, Mengxue Zhao, and Ying Long

Supplementary Information

Satellite monitoring of shrinking cities on the globe and containment solutions

Weixin Zhai, Zhidian Jiang, Xiangfeng Meng, Xiaoling Zhang*, Mengxue Zhao, Ying Long*

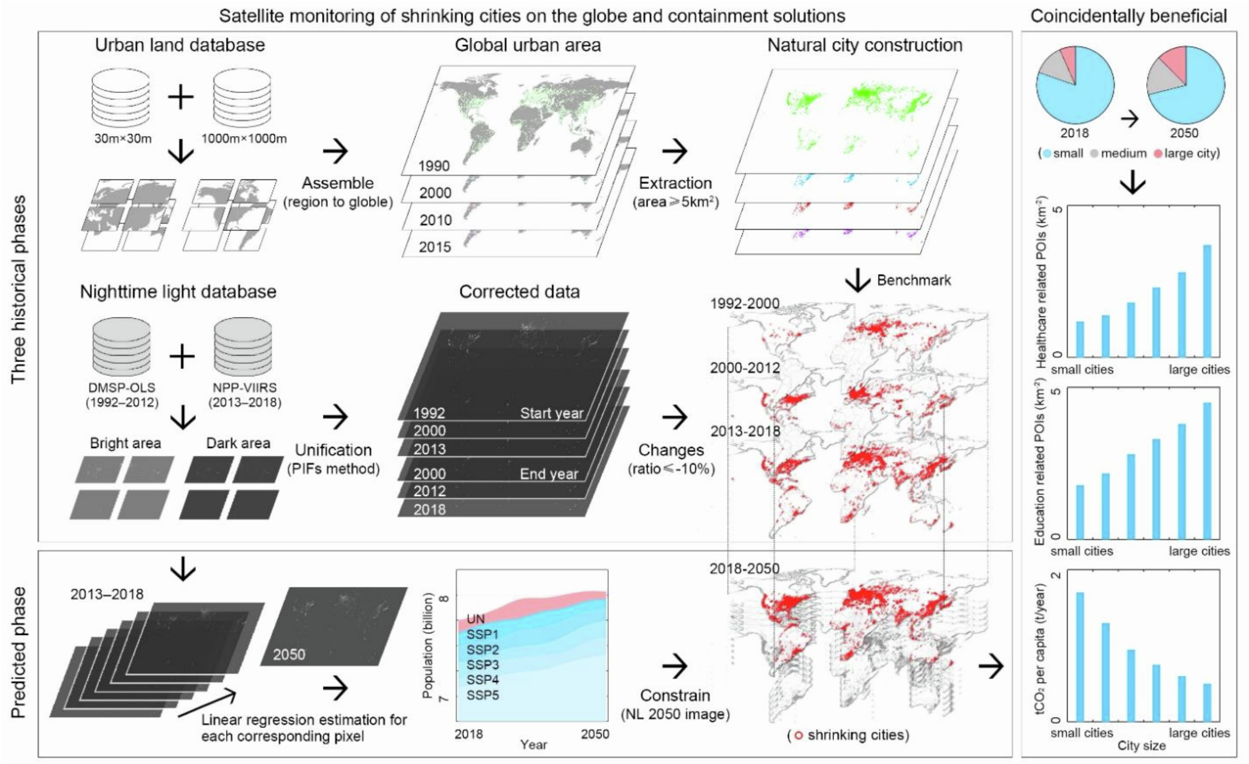

Figure S1. Experimental flow chart of the study, related to Figure 3, Figure 4 and Figure 9. PIFs, Pseudo-invariant-features; UN, the predicted country-level population from the United Nations; SSPs, the predicted country-level population based on the five scenarios in the shared socioeconomic pathways (SSPs); NL, nighttime light data. First, we extracted global natural cities with an area greater than 5km^2 based on previous research on global land use data (30×30 m^2 for phases 1992–2000, 2000–2012 and 2013–2018 (Liu *et al.*, 2018); 1000×1000 m^2 for phase 2018–2050 (Chen et al., 2020b)). Defense Meteorological Satellite Program-Operational Linescan System (DMSP-OLS) data were collected to study the first two phases, and Suomi National Polar-orbiting Partnership-Visible Infrared Imaging Radiometer Suite (NPP-VIIRS) data were collected to study the third and the predicted phases. The shrinking cities in the first three phases were identified by comparing nighttime light data within the corresponding regions. For each group of comparisons, we selected the matching brightest 1% and the darkest 1% of the pixel intensities in two years as pseudo-invariant features (Wei *et al.*, 2014) and corrected the pixel intensities of the later year. The threshold for identification was set to -10% over ten years. Next, a linear regression was applied to each corresponding pixel in the global annual nighttime images from 2013 to 2018 to obtain an estimated global annual nighttime image for 2050. The forecast of nighttime light data in 2050 was used to identify shrinking cities in phase 2018–2050. The projected data were processed in the same way for the prediction of the nighttime light distribution in 2050, and the predicted data were further constrained by the predicted country-level population data acquired from the UN data and based on the five SSPs.

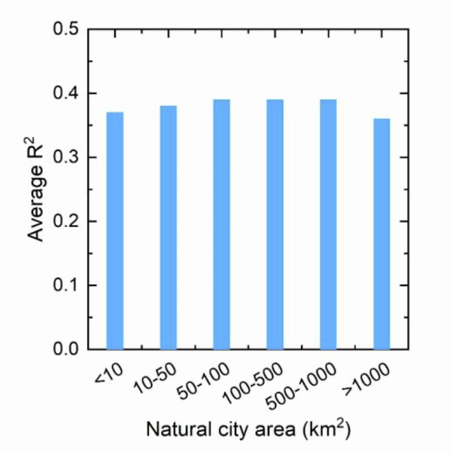

Figure S2. The histogram of R^2 values of regressions for the pixels within the natural cities with values over 0 in the years 2013–2018, related to Figure 4. The average R^2 values of the natural cities with different areas are similar. The mean R^2 value is 0.375.

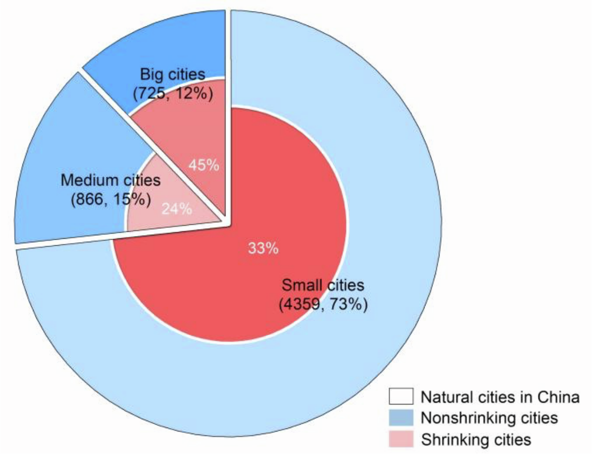

Figure S3. The proportion of shrinking cities at different levels in China, related to Figure 7. Taking The Notice on Adjusting the Standard of City Size Division issued by China's State Council in October 2014and Statistical yearbook of urban construction in China in 2018 issued by Ministry of Housing and Urban-Rural Development of People's Republic of China (MOHURD) in 2020 as references, we classify natural cities in 2018 into three categorizations, i.e. large, medium, and small cities. The proportion of shrinking cities is 33% in China; as for large, medium, and small cities, the proportions are 45%, 24% and 33%.

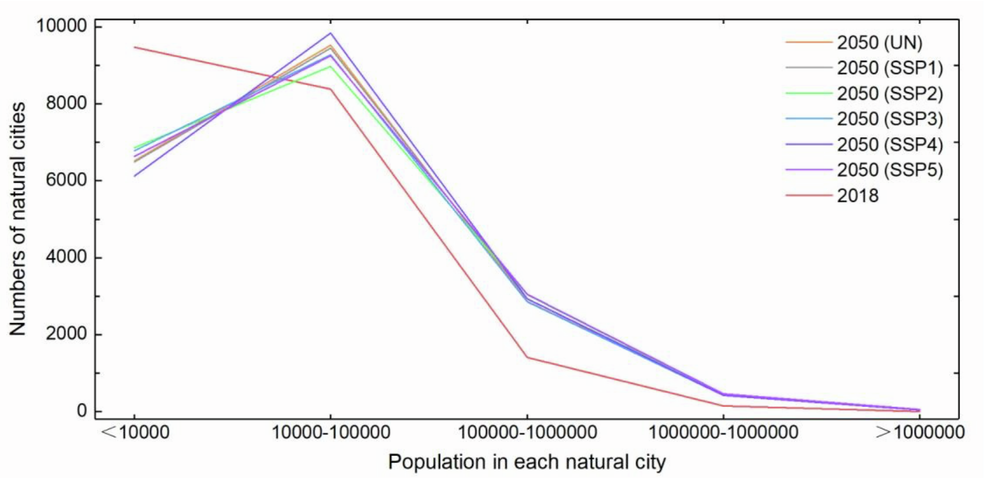

Figure S4. Number of natural cities within different predicted population ranges in 2050, related to Figure 9. We estimated the population of each natural city based on the nighttime light data. All natural cities were categorized into five groups according to their estimated population. The trend of population aggregation in large cities is obvious, which leads to a reduction in many small cities' internal populations. The estimated population in 2050 shows a similar distribution regardless of the population prediction method used. There were 9,477 natural cities with a population of less than 10,000, while this number decreased to approximately 6,500 in the six scenarios for 2050. People in small cities flow into large cities, which results in growing polarization. Similar population distribution predictions can be found in “The World's Cities in 2018: Data Booklet” from the United Nations (Nations, 2018).

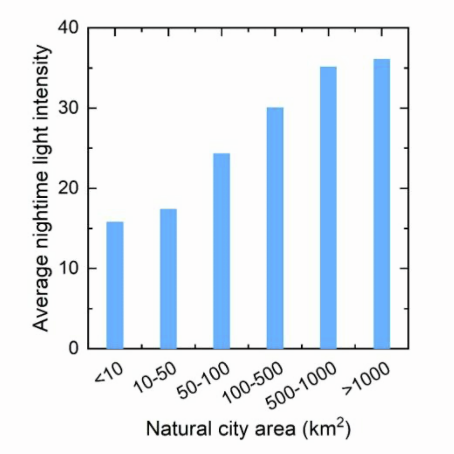

Figure S5. The relationship between average nighttime light intensity and the area of natural cities in 2018, related to Figure 4. This result was generated using the nighttime light images from 2018 benchmarked by the natural city boundaries in 2015. It is shown that with the expansion of city size, nighttime light intensity also increases.

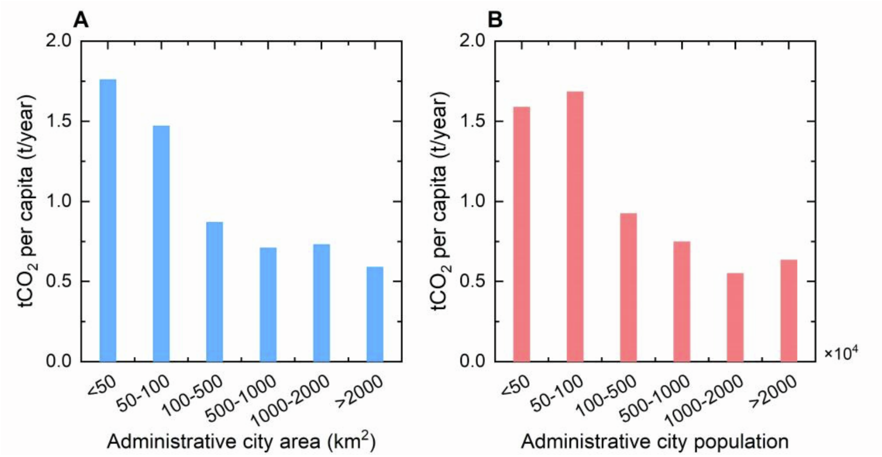

Figure S6. Relationship between CO_2 emissions and city area (A) or city population (B) in 343 representative administrative cities, related to Figure 4. With the migration from non-urban areas or small cities to large cities accompanying the shrinking cities phenomenon, we further explored the effects from the perspective of a global urban system. We examined the relationship between CO2 emissions per capita and city area or population size in 343 representative administrative cities in 2015 (Nangini et al., 2019). The results revealed that with an increase in city size (measured in terms of area or population), the emissions of CO2 in cities decreased.

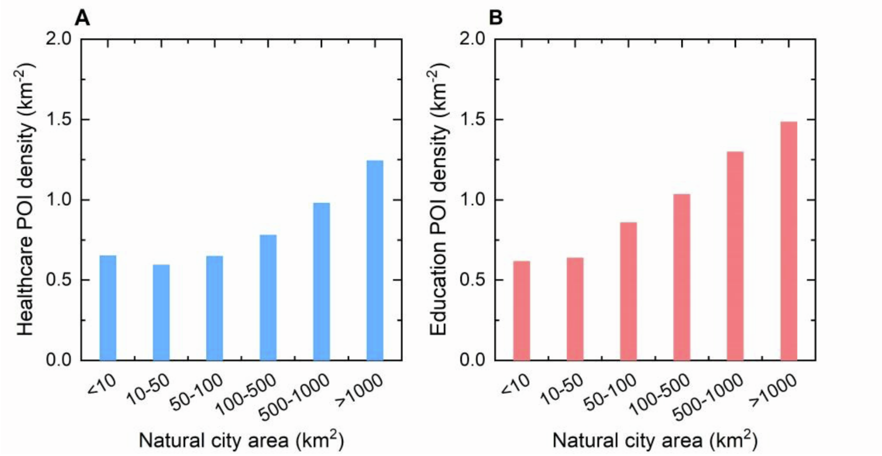

Figure S7. Average densities of healthcare-related points of interests (POIs) (A) and education-related POIs (B) in natural cities in different areas around the world, related to Figure 4. POIs are acquired from Open Street Map (OSM) (Chinese POIs were acquired by the Application Programming Interface (API) in a Map due to its higher quality data). As the natural city area increases, the densities of the two types of POIs increase. There were 835,925 healthcare-related POIs and 1,256,217 education-related POIs in the world in April 2020 from the OSM dataset.

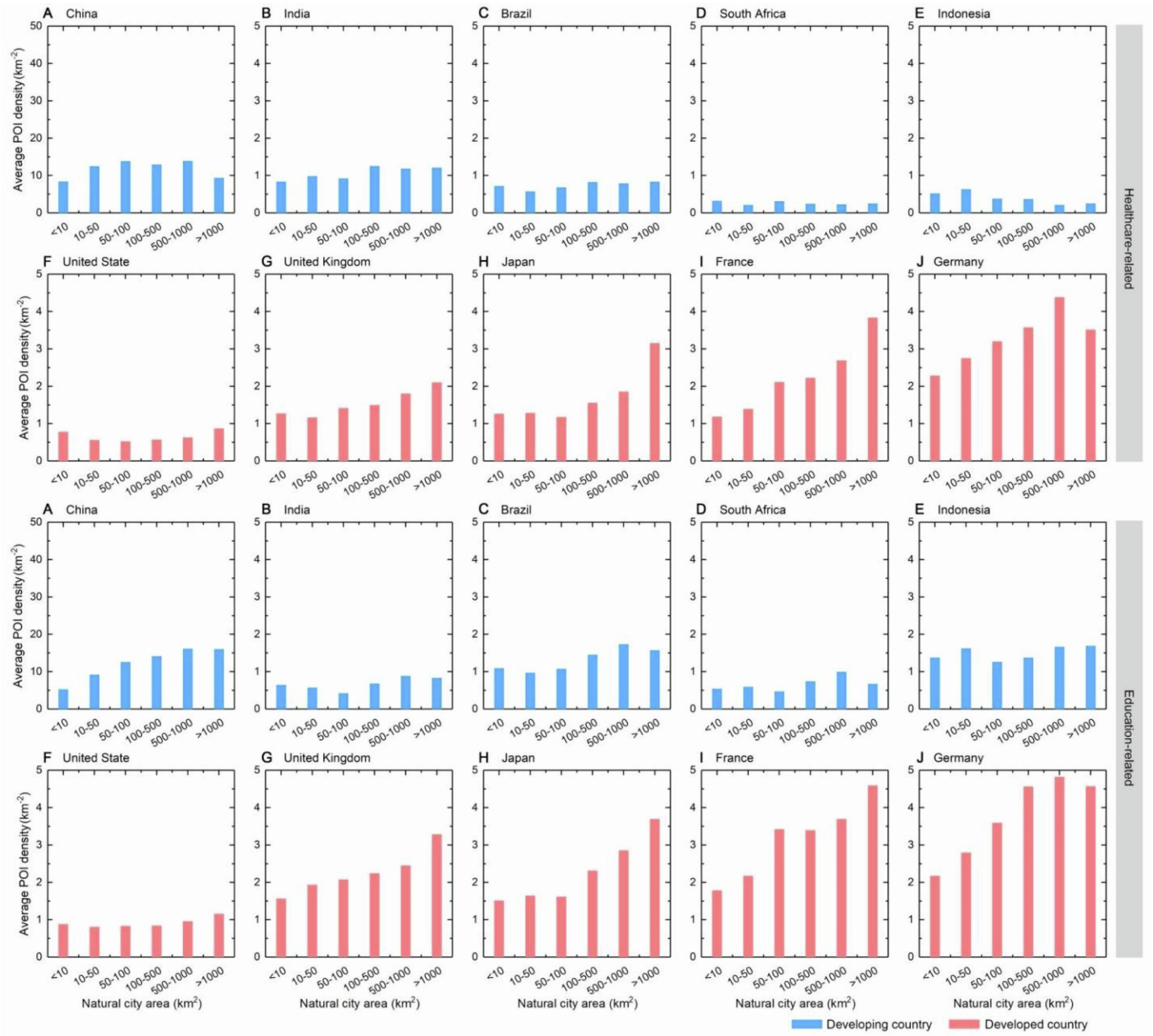

Figure S8. The average education-related POI density for six natural-city area intervals (based on 2015 boundaries) in developing countries (A, China; B, India; C, Brazil; D, South Africa; E, Indonesia) and in developed countries (F, United States; G, United Kingdom; H, Japan; I, France; J, Germany), related to Figure 4. Natural cities in 2015 were selected as the benchmark in the experiment. The healthcare-related POI types include dentists, doctors, hospitals, nursing homes, opticians and pharmacies. The education-related POI types include bookshops, colleges, kindergartens, libraries, schools and universities. The advantages of large cities in healthcare and education exist not only at a global scale but also in the 10 typical countries. The results reveal the healthcare resource advantages of large cities in developed countries, while we did not observe any significant spatial difference in developing countries. For education, it is concentrated in large cities in both developing and developed countries.

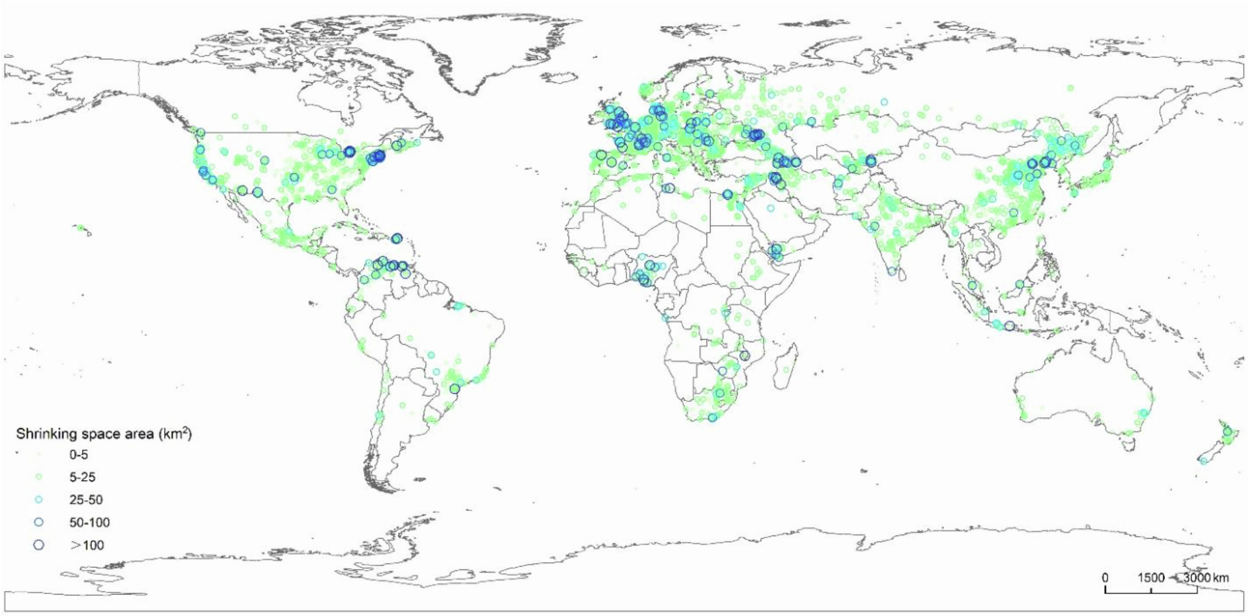

Figure S9. Shrinking space in shrinking cities in the world in 2013–2018, related to Figure 4. Colors and sizes of circles represent different shrinking space areas. Shrinking space are converted from nighttime light image pixels whose intensities decrease over 10% in within shrinking city boundaries. Vacant land constitute over 15% of the total land area in cities, according to previous studies (Bowman, 2004; Nickerson et al., 2011).

Table S1 Literature review of the driving factors of shrinking cities

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Table S2. Previous studies on the negative effects of shrinking cities on different factors, related to Figure 5.

Domain	Factors	Detailed description
Urban space	Urban vacancy: vacant land and abandoned buildings (Lee and Newman, 2017)	Urban shrinkage results in a mismatched supply and demand for space and infrastructure: more space is available for fewer inhabitants (Haase, 2013).
	Underuse of infrastructure (Mäding, 2004)	
Environment	Environmental pollution (Greenberg and Schneider, 1996)	The collection of trash on vacant urban land, such as remaining building materials and household waste, aggravates environmental pollution.
Society	Public health and safety (Frazier et al., 2013; Rybczynski and Linneman, 1999)	Abandoned buildings serve as a "magnet for crime", attracting social disruptive activities such as drug and alcohol abuse, burglary and violence, which can easily trigger a fire or become the outbreak zone of an epidemic.
Finance	Decreases in municipal budgets (Pagano and Bowman, 2004)	Urban shrinkage reduces the property tax revenues.
Population	Human resource depletion (Nefs et al., 2013)	The out-migration of younger individuals accelerates human resource depletion.
	High unemployment rates (Hudson, 2005)	Factories and companies cease operations in such cities, which results in the unemployment rates rising (Nefs et al., 2013).
Economic	Industrial transformation failure (Pallagst, 2009)	Due to the lack of labour and technical support, industrial transformation fails, the economic environment deteriorates further and imbalances in regional development increase.
	Economic depression (Pallagst, 2009)	
	Imbalanced regional development (García-Ayllón, 2016)	
Urban planning problems (Pallagst, 2009; Ryan and Gao, 2019)		It is necessary to shift from growth-oriented planning to smart or right-sized planning for shrinking cities (Wiechmann and Pallagst, 2012).

Table S3. Literature review of the positive impacts of large cities on various factors, related to Figure 7. Studies have shown the positive impacts of large cities on energy consumption, CO_2 emissions, economic growth and several other factors.

Factors (scholar, year)	Journal
Energy consumption (Newman and Kenworthy, 1989)	*Gower Publishing*
Public services and infrastructure, CO_2 emissions, energy consumption, ecosystem (Schellnhuber et al., 2010)	*Cambridge University*
Economics, innovation (Bettencourt et al., 2010)	*PLOS ONE*
Infrastructure, GDP, education, economics, research institutions (Bettencourt and West, 2010)	*Nature*
Environment, energy consumption, health and public safety, innovation (Glaeser, 2011)	*The Penguin Press*
The efficiency of energy consumption, environmentally friendly economic growth (Morikawa, 2012)	*Energy Economics*
CO_2 emissions (Fragkias et al., 2013)	*PLOS ONE*
Greenhouse gas (GHG) emissions (Tamayao et al., 2014)	*Environmental Research Letters*
CO_2 emissions in buildings and over-the-road sectors (Gudipudi et al., 2016)	*Energy Policy*
Building energy use, local environment, climate change mitigation (Güneralp et al., 2017)	*Proceedings of the National Academy of Sciences of the United States of America*
CO_2 emissions, climate change	*Environment and Planning B*
CO_2 emissions (Ribeiro et al., 2019)	*Nature Communications*
Health and Human Services, education (Yadavalli et al., 2019)	*UN-Habitat: State of the Cities 2019*

Table S5. The hypothesis test (t-test) of national urbanization strategies and the proportion of shrinking cities in 2013–2018 (two samples test), related to Figure 8. The t-test results in show that the confidence levels of the two-sample test for the three periods are greater than 0.05 (P (T <= t)> 0.05), and the two-tailed critical value falls outside the rejection domain (t-stat <t (critical value)), indicating that the null hypothesis is true.

Testing Outcome	B 2013–2018	N 2013–2018	N 2013–2018	P 2013–2018	B 2013–2018	P 2013–2018
average	0.190	0.222	0.222	0.188	0.190	0.188
Variance	0.067	0.074	0.074	0.046	0.067	0.046
Number of observations	55	48	48	89	55	89
t Stat	-0.610		0.808		0.054	
P (T<=t)	0.543*		0.421*		0.957*	
t (Critical value)	1.984		1.978		1.977	

*The significance level is 0.05. B represents balanced urbanization strategies; N represents negative urbanization strategies; and P represents positive urbanization strategies.

Table S4. Statistical analysis of urbanization strategies adopted by countries around the world, related to Figure 6.

Countries	Negative strategies						Positive strategies						Urbanization strategy	Countries	Negative strategies						Positive strategies						Urbanization strategy
	N1	N2	N3	N4	N5	N6	P1	P2	P3	P4	P5	P6			N1	N2	N3	N4	N5	N6	P1	P2	P3	P4	P5	P6	
Afghanistan	●	○	○	○	●	○	○	○	●	●	●	○	P	Libya	●	○	○	●	○	○	○	○	●	○	○	●	B
Albania	●	○	●	○	●	●	●	●	●	●	●	●	P	Liechtenstein	●	○	○	○	○	○	○	●	●	○	○	○	P
Algeria	●	●	●	○	●	●	●	●	●	●	●	●	P	Lithuania	○	●	○	●	○	●	●	●	○	●	●	●	P
Andorra	●	○	○	○	●	○	○	○	○	○	○	○	N	Luxembourg	●	○	○	●	○	○	○	●	○	●	○	●	P
Angola	○	○	●	○	●	●	○	○	●	●	○	●	B	Madagascar	●	○	●	○	●	○	●	●	●	●	●	○	P
Antigua & Barbuda	○	●	○	○	●	○	●	○	●	●	●	●	P	Malawi	●	●	●	○	●	●	○	○	●	●	●	●	N
Argentina	●	○	●	●	●	●	●	●	●	●	●	●	P	Malaysia	○	●	●	●	●	●	●	○	○	○	●	●	N
Armenia	●	○	●	○	●	●	●	○	●	●	●	○	B	Maldives	●	●	●	○	●	●	●	○	●	○	●	●	N
Australia	●	●	●	○	●	●	●	●	●	●	●	●	P	Mali	●	○	●	○	●	●	○	○	●	●	●	●	B
Austria	○	○	○	○	●	○	●	●	●	●	○	○	P	Malta	●	○	○	○	●	○	●	●	●	●	○	○	P
Azerbaijan	●	○	●	●	●	●	●	●	●	●	●	○	B	Marshall Is.	●	○	●	○	●	○	●	○	●	●	○	○	B
The Bahamas	○	○	●	○	●	○	●	○	○	●	○	○	B	Mauritania	○	●	○	●	○	●	●	○	●	●	●	●	P
Bahrain	○	○	●	○	○	○	○	○	○	○	○	●	B	Mauritius	○	○	○	○	●	●	●	●	●	●	●	○	P
Bangladesh	●	●	●	●	●	●	●	○	●	●	●	●	N	Mexico	○	○	●	○	●	●	●	○	○	●	○	●	B
Barbados	○	○	●	○	●	●	●	○	●	●	●	●	P	Micronesia	●	○	○	●	●	○	●	●	○	●	●	○	N
Belarus	●	●	●	○	●	●	●	○	○	●	○	○	N	Monaco	●	○	○	●	○	○	●	●	○	○	○	●	P
Belgium	○	○	○	○	●	●	●	●	●	○	○	●	P	Mongolia	●	●	●	●	●	●	●	○	●	●	●	●	N
Belize	●	○	●	○	●	○	●	○	●	○	●	●	P	Montenegro	●	○	○	○	○	○	●	●	○	●	●	●	P
Benin	●	●	●	○	●	○	○	○	●	●	●	○	N	Morocco	●	●	○	●	●	●	●	○	●	○	●	●	N
Bhutan	●	●	●	○	●	●	○	○	●	●	●	●	N	Mozambique	●	○	○	●	●	○	●	●	○	●	●	●	P
Bolivia	●	○	●	○	●	●	●	○	●	●	●	●	P	Myanmar	●	●	●	○	●	●	●	○	●	●	●	●	B
Bosnia & Herzegovina	●	○	●	○	●	●	●	○	●	●	●	●	P	Namibia	●	●	●	○	●	●	○	○	○	●	●	●	N
Botswana	●	○	○	○	●	○	○	○	●	●	●	○	P	Nauru	●	○	○	○	○	○	○	○	●	●	○	○	P
Brazil	●	●	●	○	●	●	●	○	●	●	●	●	B	Nepal	●	●	●	○	●	●	●	○	●	●	●	●	B
Brunei	●	○	●	○	●	●	○	●	○	●	○	○	N	Netherlands	○	○	●	○	●	●	●	○	●	○	●	○	B
Bulgaria	○	○	○	○	●	○	●	●	●	●	●	●	P	New Zealand	●	○	●	○	●	○	○	●	○	●	○	●	B
Burkina Faso	●	●	●	○	●	●	○	○	●	●	●	○	N	Nicaragua	●	○	○	○	●	○	●	●	○	●	●	●	P
Burundi	○	○	●	○	●	●	●	●	●	●	●	○	P	Niger	●	●	●	○	●	○	○	○	●	●	●	●	B
Cape Verde	○	●	○	●	○	●	●	○	●	●	●	●	P	Nigeria	●	●	○	○	○	●	○	●	○	●	●	○	B
Cambodia	●	○	●	○	●	●	○	○	●	●	●	●	P	Niue	●	○	○	●	○	○	●	○	○	●	○	○	P
Cameroon	●	●	●	●	○	●	●	●	●	●	●	●	N	Norway	●	○	●	●	●	●	●	○	●	●	○	●	N
Canada	●	○	●	○	●	○	○	●	○	●	○	●	B	Oman	●	○	●	●	●	●	○	●	●	●	●	●	B
Central African Republic	●	○	○	○	●	●	○	○	●	●	●	○	B	Pakistan	●	●	●	○	●	●	●	○	●	●	●	●	B
Chad	●	○	●	○	●	●	○	○	○	●	●	○	N	Palau	○	○	○	○	●	○	●	○	●	●	○	○	P
Chile	○	○	○	○	●	○	●	●	●	●	●	●	P	Panama	○	○	○	○	●	●	○	○	●	●	●	●	P
China	○	●	●	○	●	●	●	●	●	●	●	●	P	Papua New Guinea	●	○	●	○	●	●	○	○	○	●	●	●	N
Colombia	○	○	○	○	●	○	●	●	●	●	●	●	P	Paraguay	●	○	○	○	●	●	●	●	●	●	●	●	P
Comoros	○	○	●	○	●	●	○	○	○	●	●	○	N	Peru	○	●	●	○	●	●	●	●	●	●	●	●	P
Congo	●	○	●	○	●	●	○	○	●	●	●	●	B	Philippines	●	●	●	●	●	●	●	●	●	●	●	●	B
Congo, DRC	●	○	●	●	○	○	○	○	○	○	○	●	N	Poland	○	○	●	●	●	●	●	●	●	●	●	●	P
Cook Is.	●	○	○	○	●	●	○	○	○	●	●	●	B	Portugal	○	○	●	○	●	●	●	○	●	●	●	●	P
Costa Rica	●	○	●	○	●	●	●	○	●	●	●	●	N	Qatar	●	○	○	●	○	○	●	●	●	○	●	●	P
Cote d'Ivoire	○	●	○	●	○	●	●	○	●	○	●	●	B	North Korea	●	○	●	○	●	○	●	●	○	●	○	●	P
Croatia	●	○	●	○	○	●	●	●	●	○	○	●	P	Moldova	●	○	●	○	●	●	●	●	●	●	●	○	P
Cuba	●	○	○	○	●	○	●	●	○	●	○	○	P	Romania	●	○	●	○	●	●	●	●	●	●	●	●	P
Cyprus	○	○	●	○	●	●	●	●	●	○	●	●	P	Russia	●	○	○	○	●	○	●	●	○	●	○	●	P
Czech Republic	●	○	●	○	●	○	○	○	●	●	●	○	B	Rwanda	●	●	●	○	●	●	○	○	●	●	●	●	B
Denmark	●	○	●	○	●	●	○	○	●	○	○	●	N	St. Kitts & Nevis	●	○	●	○	●	●	●	○	○	○	●	●	B
Djibouti	●	●	○	○	●	○	○	○	○	●	●	○	N	St. Lucia	○	●	○	●	○	●	●	○	○	●	●	●	P
Dominica	●	○	●	○	●	●	○	○	●	●	●	●	B	St. Vincent & the Grenadine	●	○	○	○	●	●	●	○	●	●	●	●	P
Dominican Republic	●	●	●	○	●	●	●	○	●	●	●	●	B	Samoa	●	○	●	○	●	●	●	○	●	●	○	○	N
Ecuador	●	●	●	○	●	●	○	○	●	●	●	●	N	San Marino	●	○	○	●	○	○	●	●	●	●	○	○	N
Egypt	●	●	●	○	●	●	●	●	●	●	●	●	P	Sao Tome & Principe	●	○	●	○	●	●	○	○	○	●	●	●	N
El Salvador	●	○	●	○	●	○	○	○	●	●	●	●	P	Saudi Arabia	●	○	●	○	●	●	○	●	○	●	●	●	B
Equatorial Guinea	●	○	●	○	●	●	○	○	●	●	●	●	B	Senegal	●	●	○	○	●	●	○	●	●	●	●	●	P
Eritrea	●	○	○	○	○	○	●	○	○	●	●	●	P	Serbia	●	○	●	○	●	○	●	●	●	●	●	●	P
Estonia	●	○	○	○	●	○	●	●	●	●	○	○	P	Seychelles	●	○	○	●	○	●	○	○	○	○	○	○	N
Ethiopia	●	●	○	○	●	●	●	●	●	●	●	●	P	Sierra Leone	●	○	●	○	●	●	●	○	●	●	●	○	B
Fiji	●	○	●	○	●	●	●	○	●	●	●	●	P	Singapore	●	○	○	●	○	●	○	●	●	○	○	●	B
Finland	○	○	●	○	●	●	●	●	●	○	●	●	P	Slovakia	○	○	●	○	●	○	●	○	●	○	●	○	P
France	●	○	●	○	●	○	○	●	○	●	○	●	B	Slovenia	●	○	●	○	●	○	○	●	○	●	○	●	B
Gabon	●	○	●	○	●	○	●	●	●	●	●	●	P	Solomon Is.	●	○	●	○	●	●	●	○	●	●	●	●	P
The Gambia	●	○	●	○	●	●	○	○	●	●	●	○	N	Somalia	●	○	●	○	●	○	○	○	●	●	●	●	P
Georgia	○	●	○	○	●	●	○	○	●	●	●	●	P	South Africa	●	○	●	○	●	●	●	○	●	●	●	●	P
Germany	●	○	●	●	●	○	○	●	○	●	○	●	N	South Korea	●	○	○	○	●	○	○	○	●	●	●	○	P
Ghana	●	●	●	○	●	●	○	○	●	●	●	○	N	Spain	●	○	○	●	○	●	●	○	●	●	●	●	P
Greece	●	○	●	○	●	○	●	●	●	●	●	●	P	Sri Lanka	●	●	●	●	●	●	●	●	●	●	●	●	B
Grenada	●	●	●	○	●	●	●	○	●	●	●	○	N	Sudan	●	○	●	○	●	●	●	○	○	●	●	●	B
Guatemala	●	●	●	○	●	●	●	○	●	●	●	●	B	Suriname	●	○	○	○	●	○	○	○	○	●	●	○	B
Guinea	●	●	●	○	●	●	○	○	●	●	●	●	N	Sweden	●	●	○	○	●	○	●	●	○	●	○	○	B
Guinea-Bissau	●	○	●	○	●	○	●	○	○	●	●	○	B	Switzerland	●	○	○	○	○	○	●	○	○	○	○	○	N
Guyana	●	○	●	○	●	●	●	○	●	●	●	●	P	Tajikistan	○	○	●	○	●	○	●	○	●	●	●	●	P
Haiti	○	●	○	●	○	●	○	○	○	●	●	●	B	Macedonia	●	○	●	○	●	○	○	○	●	●	○	●	B

Honduras	●	●	●	○	●	●	●	○	●	●	●	●	B	Thailand	○	●	○	●	○	●	○	○	●	○	●	●	B
Hungary	●	○	○	○	●	○	●	●	○	●	●	●	P	Timor-Leste	●	●	○	●	○	●	○	○	○	●	●	○	N
Iceland	●	○	○	○	●	○	○	●	○	●	○	○	B	Togo	●	●	●	○	●	○	●	●	●	●	●	○	P
India	●	●	●	●	●	●	●	●	●	●	●	●	B	Tonga	●	○	●	●	○	○	●	○	○	●	○	○	N
Indonesia	●	●	●	●	●	●	●	●	●	●	●	●	B	Trinidad & Tobago	●	●	●	○	●	●	●	●	●	○	●	●	B
Iran	●	●	●	○	●	●	●	●	●	●	●	●	P	Tunisia	●	●	●	○	●	●	●	●	●	●	●	●	P
Iraq	●	○	●	●	●	●	○	○	●	●	●	●	N	Turkey	●	●	●	○	●	○	●	○	●	●	●	○	B
Ireland	●	○	●	○	●	○	●	●	●	●	●	●	P	Turkmenistan	●	○	○	●	○	●	●	●	○	○	●	○	N
Israel	●	○	○	○	○	○	●	●	●	●	●	○	P	Tuvalu	●	○	●	○	●	○	○	○	●	●	●	●	P
Italy	●	○	○	●	●	○	○	●	○	●	○	●	B	Uganda	●	●	●	○	●	○	○	○	●	●	●	●	B
Jamaica	●	○	○	○	●	●	●	○	●	●	●	●	P	Ukraine	○	○	○	○	●	●	●	○	●	●	●	●	P
Japan	●	●	●	○	●	○	●	○	●	○	●	○	N	United Arab Emirates	●	○	●	○	●	○	●	●	○	●	●	●	P
Jordan	●	●	●	○	●	●	●	●	●	●	●	●	P	United Kingdom	●	○	○	○	●	○	●	●	●	●	○	●	P
Kazakhstan	●	●	●	○	●	●	○	○	●	●	●	●	N	Tanzania	●	●	●	○	●	●	●	○	●	●	●	●	B
Kenya	●	●	○	○	●	●	●	○	●	●	●	●	P	United States	●	○	●	○	●	●	●	●	●	○	●	●	P
Kiribati	●	○	○	○	●	○	●	○	●	●	●	●	P	Uruguay	○	○	○	○	●	●	●	●	●	●	●	●	P
Kuwait	●	○	○	●	○	●	○	●	●	●	○	●	P	Uzbekistan	●	●	●	●	●	○	●	○	○	○	●	●	N
Kyrgyzstan	●	●	●	○	●	○	●	○	●	●	●	○	B	Vanuatu	●	○	●	○	●	●	●	○	●	●	○	●	B
Laos	○	○	●	○	●	●	○	○	●	●	○	●	B	Venezuela	●	●	●	○	●	○	●	○	●	●	●	●	P
Latvia	●	○	●	●	●	○	○	●	○	●	○	●	N	Vietnam	●	●	●	○	●	●	●	○	○	●	●	●	N
Lebanon	●	●	●	●	●	●	●	●	●	○	○	○	N	Yemen	○	●	○	○	○	●	○	○	●	●	○	●	P
Lesotho	●	●	●	○	●	○	●	○	●	●	●	●	P	Zambia	●	○	○	●	○	●	●	○	○	●	●	●	P
Liberia	●	○	●	○	●	●	●	○	●	●	●	○	B	Zimbabwe	●	●	●	○	●	●	●	○	○	●	●	●	N

Note: The information comes from "Policies on Spatial Distribution and Urbanization", published by the United Nations in 2016 (United Nations, 2016). B represents a balanced urbanization strategy; N represents a negative urbanization strategy; P represents a positive urbanization strategy. N1: Reducing migration from rural to urban areas; N2: Decentralizing large urban centres into smaller urban, suburban or rural areas; N3: Providing incentives to establish or retain industries in rural areas; N4: Relocating industries from large urban centres to rural areas; N5: Developing rural infrastructure and facilities; N6: Promoting rural development strategies to decrease push factors on urbanization; P1: Increasing energy efficiency in transport and housing; P2: More stringent environmental regulations for industries within or surrounding large urban centres; P3: Improving solid waste management systems; P4: Securing access to water and sanitation for poor urban residents; P5: Securing land tenure and adequate housing for poor urban residents; and P6: Ensuring land, housing, services and a livelihood for poor urban residents.

Table S6. The Friedman test of national urbanization strategy and the proportion of shrinking cities in 2013–2018 (Multiple samples test), related to Figure 8. The results of Friedman's multi-sample test show that the null hypothesis is true. This implies that national urbanization strategies have little influence on population migration and spatial distributions.

The null hypothesis	Test	Sig. F	Conclusion
B 2013–2018, N 2013–2018 and P 2013–2018 have the same variable distribution	Friedman (Two-way analysis of variance by rank)	0.690	Fail to reject the null hypothesis

*The significance level is 0.05. B represents balanced urbanization strategies; N represents negative urbanization strategies; and P represents positive urbanization strategies.

Table S7. Comparison analysis of predicted nightlight changes for 2018–2050 based on three urban boundaries, related to Figure 9. The natural city boundaries from 2010 and the predicted natural city boundaries for 2050 converted from Liu et al. (2018)'s data as the basis for verification. NC denotes natural cities, and SC denotes shrinking cities. The first three rows show the forecast results from nighttime light images without adjustment or constraints. The last six rows show the forecast results with constraints on the 2050 country-level population based on predictions from the United Nations and the five SSPs.

Benchmark	Resolution/m^2	# NC	# SC	# (SC/NC)/%	NC area/km^2	SC area/km^2	(SC/NC) area/%
NC2010	30×30	21,058	7,285	34.6	722,061	191,364	26.5
NC2015	30×30	21,965	7,821	36.3	798,825	232,951	29.1
NC2050	1000×1000	19,342	6,916	35.7	814,873	250,615	30.7
NC2015_UN	1000×1000	19,431	7,166	36.8	728,987	212,864	29.2
NC2015_SSP1	1000×1000	19,431	6,248	32.3	728,987	203,387	27.9
NC2015_SSP2	1000×1000	19,431	6,546	33.9	728,987	209,948	28.8
NC2015_SSP3	1000×1000	19,431	7,450	38.2	728,987	229,631	31.5
NC2015_SSP4	1000×1000	19,431	6,835	35.4	728,987	221,612	30.4
NC2015_SSP5	1000×1000	19,431	6,231	33.5	728,987	198,284	27.2

Table S8. Detailed effects from regreening vacant lands 30 countries with the largest numbers of shrinking cities in 2013–2018, related to Figure 4. Rainfall detention represents quantities of rainfall elimination for a representative one-hour storm event in different countries. Carbon pool is the potential for carbon sequestration with different regreening approaches. Estimates for rainfall detection are based on Kelleher et al.'s (Kelleher *et al.*, 2020) work; estimates for carbon pools are based on Tang et al.'s (Tang *et al.*, 2018) work.

Country	Vacant area/km^2	600m Buffer/km^2	Rainfall detention /(m^3/h)	Carbon pool/ Ng C (5 years)
China	10,383.21	25,159.97	11,469,013	86.94±2.46
United States	18,488.82	50,993.01	22,645,684	154.8±4.38
France	5,623.16	14,154.88	8,487,490	47.08±1.33
Russia	3,258.62	9,669.98	2,567,487	27.28±0.77
United Kingdom	6,650.05	18,253.26	13,892,220	55.68±1.57
Germany	2,536.41	7,276.55	3,030,483	21.24±0.6
India	1,676.11	4,270.03	3,108,268	14.03±0.4
Ukraine	2,989.87	6,120.01	3,555,049	25.03±0.71
Poland	2,929.55	8,545.77	3,010,166	24.53±0.69
South Africa	1,435.89	3,471.18	1,217,061	12.02±0.34
Spain	1,376.48	3,748.61	1,515,132	11.52±0.33
Italy	1,293.85	3,688.95	1,843,700	10.83±0.31
Mexico	1,265.71	3,275.06	1,642,188	10.6±0.3
Romania	1,200.34	2,786.83	1,325,714	10.05±0.28
Brazil	1,502.14	3,821.74	4,529,578	12.58±0.36
Canada	3,261.07	8,891.22	2,991,904	27.3±0.77
Uzbekistan	1,773.31	4,139.75	624,527	14.85±0.42
Japan	691.72	1,840.23	1,975,653	5.79±0.16
Syria	679.85	1,709.29	389,615	5.69±0.16
Denmark	1,416.55	3,530.81	1,705,196	11.86±0.34
Iraq	1,075.63	2,408.67	393,822	9.01±0.25
Hungary	531.64	1,529.95	736,100	4.45±0.13
Sweden	648.91	2,390.08	693,359	5.43±0.15
Egypt	1,023.20	2,285.51	3	8.57±0.24
Slovakia	743.47	1,899.17	9,943	6.22±0.18
Australia	480.52	1,225.48	439,378	4.02±0.11
Iran	485.61	1,199.99	193,824	4.07±0.11
Switzerland	757.81	2,315.05	1,748,172	6.34±0.18
Netherlands	812.55	2,439.47	1,083,876	6.8±0.19
Belgium	426.47	1,376.60	616,652	3.57±0.10

Table S9. Detailed information of the estimates of carbon pools in four terrestrial ecosystems, related to Figure 4.

Terrestrial ecosystems	Total/ Pg C	Biomass/ Pg C	Soil/ Pg C
Forest	1.51 ± 0.08	0.98 ± 0.12	0.51 ± 0.10
Shrubland	0.83 ± 0.04	0.73 ± 0.06	0.09 ± 0.03
Grassland	0.83 ± 0.05	0.79 ± 0.08	0.04 ± 0.02
Cropland	0.88 ± 0.02	0.85 ± 0.03	0.03 ± 0.01

Table S10. Detailed effects from constructing compact cities within the 30 countries with the largest numbers of shrinking cities in 2013–2018, related to Figure 4. Compacted area indicates the sum of compacted area of shrinking cities. Next three columns are reduction percentage of financial burden on educational infrastructures, healthcare infrastructures and road network in shrinking cities of each country. The last column represents the total length of road network in shrinking cities to be compressed.

Country	Compacted area/km^2	Healthcare infrastructures/%	Education infrastructures/%	Road network/%	Road network/km
China	2595.80	23.04%	21.43%	22.35%	8,663
United States	4,807.09	13.39%	13.79%	14.11%	38,290
France	2,305.50	24.32%	23.66%	25.16%	16,149
Russia	716.90	23.07%	23.63%	24.43%	4,941
United Kingdom	2,793.02	20.25%	19.74%	20.13%	17,508
Germany	405.83	17.78%	18.16%	18.72%	6,381
India	301.70	17.13%	16.07%	18.03%	2,038
Ukraine	1,016.56	24.66%	25.06%	27.92%	5,853
Poland	878.86	17.72%	17.35%	17.76%	9,192
South Africa	330.25	16.98%	16.75%	17.78%	2,485
Spain	385.41	25.26%	24.89%	25.40%	4,742
Italy	194.08	17.40%	16.97%	16.96%	2,830
Mexico	316.43	18.80%	25.09%	19.38%	3,755
Romania	408.11	22.30%	23.69%	23.59%	1,654
Brazil	195.28	16.32%	16.24%	16.54%	5,626
Canada	717.43	13.87%	14.37%	14.79%	7,934
Uzbekistan	727.06	19.35%	21.82%	23.63%	2,301
Japan	83.01	15.49%	17.07%	17.74%	2,211
Syria	346.72	44.99%	48.47%	48.57%	2,178
Denmark	609.12	19.29%	18.01%	18.31%	2,828
Iraq	344.20	21.79%	23.89%	25.26%	1,875
Hungary	127.59	15.61%	16.47%	16.89%	915
Sweden	272.54	19.20%	20.50%	20.68%	1,629
Egypt	327.43	18.86%	18.84%	18.37%	1,788
Slovakia	260.21	22.06%	21.35%	21.32%	1,950
Australia	76.88	14.39%	14.22%	16.32%	331
Iran	67.98	13.23%	14.69%	18.59%	414
Switzerland	204.61	22.03%	22.14%	22.44%	3,620
Netherlands	81.26	17.37%	18.93%	19.68%	2,625
Belgium	72.50	17.82%	18.72%	18.70%	706

Table S11. Detailed information of road network reduction for constructing compact cities, related to Figure 4.

Continents	Road network		Roads		Paths	
	Total length/km	Reduction percentage	Total length/km	Reduction percentage	Total length/km	Reduction percentage
Africa	13,201	23.0%	3,341	5.8%	9,860	17.2%
Asia	39,087	26.0%	10,006	6.6%	29,081	19.3%
Australia	922	17.4%	647	12.2%	274	5.2%
North America	50,164	14.2%	30,332	8.6%	19,831	5.6%
South America	16,062	22.0%	10,671	14.6%	5,391	7.4%
Europe	87,809	20.4%	43,091	10.0%	44,717	10.4%
World	207,245	19.4%	102,102	9.6%	105,142	9.8%

Table S12. International quantitative standards for urban shrinkage, related to Figure 4 and 9.

Scope/(Scholar, year)	Degree of population loss	Duration of population loss	Urban area	Other characteristics
Global/(Oswalt and Rieniets, 2006)	Total population loss > 10% or an annual average population loss rate ⩾ 1%	–	Admini strative boundary	Economic decline and a decay in spatial quality
Global/(Pallagst, 2009)	Total population loss > 10%	–	Administrative boundary	Economic decline and a decayin spatial quality
China/(Zhou et al., 2019)	Nightlight intensity reduced ⩾ 10%	–	Administrative boundary	–
China/(Jiang et al., 2020; Pallagst, 2009; Zhou et al., 2019)	Nightlight intensity reduced ⩾ 10%	3 years	Natural city with an area more than 5 km^2	Economic decline and population loss are completely synchronized
Global/ (Shrinking Cities International Research Network (SCIRN))	Population losses in large areas	> 2 years	Built-up urban areas with a minimum population of 10,000 residents	Undergoing economic transformation with some symptoms of a structural crisis
United States/ (Schilling and Logan, 2008)	persistent population loss > 25%	40 years	Administrative boundary	Increasing housing vacancy and abandonment rates
Germany/(Delken, 2008)	The total population reduction ⩾ 3%	15 years	Administrative boundary	Economic decline and a decay in spatial quality
Europe/(Wiechmann and Wolff, 2013)	A remarkable population loss of more than 15% annually	≥ 5 years	Urbanized area with a minimum population of 5,000 residents	–
Portugal/(Guimarães et al., 2015)	Continuous population loss	> 10 years	Administrative boundary	Economic decline and a decay in spatial quality

Table S13. Identification of shrinking cities based on different thresholds for the shrinking ratio, related to Figure 4 and 9. Three groups of thresholds were used in the comparison experiments. The first group was -10% for four phases, which was applied in the main text. The second group was 0 for four phases, which implies that any decrease in nighttime light intensity in one natural city will define a shrinking city. Third, we applied different thresholds for the different phases based on their different durations: 8 years, 12 years, 5 years and 32 years. The 5-year duration of the third phase was selected as the baseline with a threshold = -10% for shrinking city identification. As a consequence, the thresholds for the shrinking ratio in the first, second and fourth phases are -16%=-(1-(1-10%)$^{8/5}$), -23%=-(1-(1-10%)$^{12/5}$) and -49%=-(1-(1-10%)$^{32/5}$), respectively.

Threshold	Phases	# NC	# SC	# (SC/NC)/%	NC area/km^2	SC area/km^2	(SC/NC) area/%
-10%	1992–2000	13,936	1,295	9.3	427,792	22,613	5.4
	2000–2012	18,157	2,821	15.5	583,691	47,537	8.1
	2013–2018	21,058	5,237	24.7	715,638	114,158	15.8
	2018–2050 (UN)	19,431	7,166	36.8	728,987	212,864	29.2
0	1992–2000	13,936	2,992	21.5	427,792	105,902	24.8
	2000–2012	18,157	5,125	28.2	583,691	193,486	33.1
	2013–2018	21,058	8,720	41.4	715,638	255,946	35.9
	2018–2050 (UN)	19,431	8,929	45.9	728,987	274098	37.6
-16%	1992–2000	13,936	925	6.7	427,792	15,294	3.6
-23%	2000–2012	18,157	1,463	8.1	583,691	28,648	4.9
-10%	2013–2018	21,058	5,237	24.8	715,638	114,158	15.8
-49%	2018–2050 (UN)	19,431	3,735	19.2	728,987	88,936	12.2

Table S14. Comparison results between the null model and the proposed model for the validation of the forecast, related to Figure 9. A linear regression was applied to the corresponding pixel values in the nighttime light images from 2013 to 2018 to generate the forecast for 2050. Although the forecast cannot be verified, we examined similar prediction results for 2018, which came from nighttime light images from 2013 to 2017 to prove the rationality of our method. We prepared the nighttime light images using three models: the first is the true nighttime light image from 2018; the second is the nighttime light image from 2017 as a null model; the third is the predicted nighttime light image predicted using the corresponding pixels in the images from 2013 to 2017 and constrained by the accumulated nation-level nighttime light image in 2018, which is our proposed model. Two Pearson's correlations are computed between the true data and the data from the null model/the proposed model. There are 2,605,461 valid pixels and 21,108 natural cities. The city-level mean intensity change is the difference between the city-level mean intensity in the data from the null model/the proposed model and that from the data in 2013. he results indicate that our linear regression result is close to the true value. Moreover, although the proposed model is not superior in predicting the pixel-level correlations, it has similar performance to the null model in the city-level correlation. Our research uses a city-level perspective to forecast shrinking cities on the globe, and the rationality of applying the linear regression is verified.

Data description	The nighttime light image in 2017 (null model)	The predicted nighttime light image based on 2013 to 2017 data and constrained to the country-level (proposed model)
Pixel-level correlation	0.943	0.821
City-level mean intensity correlation	0.970	0.908
City-level mean intensity change correlation	0.980	0.972