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Sustainability of Cities under Population Decline*

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Abstract

The world is undeniably facing trends of aging, declining birth rates and shrinking populations. As a result, rural economies are shrinking rapidly while large cities are absorbing their populations. Each country must make difficult decisions about which cities to preserve in order to sustain the country as a whole. Japan is at the forefront of rapid economic contraction, and we propose a systematic method for assessing the sustainability of cities as living communities. This method is based on the hierarchy property that holds between a larger and smaller city in the composition of tertiary industries. This property allows us to identify the threshold population size of a city for a given set of industries to be able to operate in the city. In particular, by defining the sets of essential industries for modern life, one can identify the population size of a sustainable city. Combined with a separately conducted future projection of individual city sizes, this represents a guideline for a strategic reduction of the country's economic geography by identifying the future spatial distribution of focal cities. This will allow for the reorganization of functional regions around focal cities to ensure that the country can adapt to its declining population.

Keywords: Population decline, Sustainability, Essential city size, Essential industries
JEL classification: R11, R12, R58

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1 Introduction

The world is undeniably facing trends of aging, declining birth rates and shrinking populations. In recent decades, this trend has been particularly pronounced in Asian countries, where immigration has not been a major contributor to population growth. Japan's population peaked at 128 million in 2008 (MIC, 2008) and has been declining for the past 15 years. In 2023 alone, Japan's population dropped by 531,702. If we limit the number to Japanese nationals, the decline was as high as 861,237 (MIC, 2024). Other countries are catching up with Japan. China and South Korea have entered the phase of decreasing population, while other Asian countries and European countries will also face decreasing population within 50 years from now according to the intermediate projection of United Nations (2022).

The trend of population decline has been accelerating in Japan. In the years after 2000, the fertility rate in Japan peaked at 1.45 in 2015 and has been declining rapidly ever since. It fell to 1.20 in 2023 and shows no signs of rising (Fig. 2). Other OECD countries are not far behind Japan, as the average fertility rate of native-born nationals in OECD countries has already fallen to 1.5 in 2019 (OECD, 2023). In 2023, the fertility rate of native-born Germans fell to 1.26, according to the latest press release from the German Federal Statistical Office.

A recent study by Institute for Health Metrics and Evaluation (2024) predicts that the fertility rates of all but 6 sub-Saharan countries will be below the replacement level of 2.1 by 2100. Thus, in the near future, there will no longer be an abundance of immigrants to compensate for the declining populations in Europe and the United States; otherwise, the countries of origin of the immigrants will face a threat to their own sustainability.

In this paper, we examine how the economic geography of each country evolves in the era of rapid population decline. Given the continuing trend of urbanization worldwide,[1] and the robust fact that the city size distribution in a country exhibits an approximate power law with a power coefficient around 1 (e.g., Duranton and Puga, 2014; Gabaix and Ioannides, 2004; Mori et al., 2023), the regional economy in a country consists of a few large cities with an increasing number of smaller cities. Naturally, the least populated cities and their surrounding regions will be the first to disappear. An important policy issue for governments is to identify sustainable cities from among the many small cities at risk of disappearing and to use them as a base for smart consolidation of regional economies and downsizing and reorganization of infrastructure.

In this paper, we focus on Japan, which is at the forefront of the declining population trend. Based on the modern central place theory (Fujita, Krugman and Mori, 1999; Tabuchi and Thisse, 2011; Hsu, 2012; Mori et al., 2023), we first show that the population size of a city (as defined in terms of population agglomeration) is a strong indicator of its industrial composition, especially for tertiary industries.[2] More specifically, the industrial composition of cities approximately exhibits the *hierarchy property* (HP) that an industry present in a smaller city is also present in a

[1]The world's overall urbanization rate has steadily increased from 29.6% in 1950 to 56.2% in 2020 and is expected to reach 68.4% in 2050 (United Nations, 2018). Many countries in Europe, the United States, and Japan have exceeded 70% by 2020 and are expected to reach 80–93% by 2050 (Mori and Murakami, 2024).

[2]We use the 1 kilo meter (km) grid-cell data from the Population Census of Japan to identify each city as a contiguous set of the grid-cells with at least 1,000 people per a square kilo meters and the total population at least 10,000 (Mori et al., 2023; Mori and Wrona, 2024; Mori and Murakami, 2024).

larger city (Mori, Nishikimi and Smith, 2008; Hsu, 2012; Schiff, 2015; Davis and Dingel, 2020; Mori et al., 2023; Mori and Wrona, 2024). This property implies that there is a threshold population size of a city above which a given industry is present in the city, but not otherwise.[3]

Using this property, we compute the *essential city size* (ECS), which is the threshold population needed to sustain industries that provide essential services.[4] We apply the ECS estimated from the 2020 data to the future Japanese cities obtained by Mori and Murakami (2024), and predict the location of sustainable and unsustainable cities at a given time in the future.[5] This prediction provides a systematic basis for distinguishing between sustainable and unsustainable cities and regions in the future, and facilitates planning for smart downsizing of regional economies, including streamlining of transportation networks and infrastructure.

In the following, we first overview the declines of population and fertility in Japan in Section 2. We then present how cities are defined in our study in Section 3, and provide an overview of the future spatial patterns of cities in Japan. In Section 4, we show how the location pattern of tertiary industries closely follows the HP, and present the location patterns of essential industries. In Section 5, we define the ECS and estimate it using available past data, and predict sustainable cities in the future in Section 6, where we adopt the prediction of future city size and location in Japan by Mori and Murakami (2024). Based on the identified location of sustainable cities, we identify the sustainable municipalities supported by these cities. We conclude the paper with the future research agenda in Section 7.

2 Declining population and fertility in Japan

The population of Japan for 2000–2020 and its projection under three scenarios for 2021–2120 by National Institute of Population and Social Security Research (NIPSSR) 2023 are shown in Fig. 1. The intermediate projection assumes the fertility rate (1.33) and mortality rate in 2020, where the mortality rate is assumed to improve over time, while the pessimistic (optimistic) projections assume a lower (higher) fertility rate, 1.13 (1.64), and higher (lower) mortality rates in the future. The total population of 126 million in 2020 is projected to shrink to 100-110 million by 2050, and then the difference between the scenarios increases. By 2100, it is projected to decrease to 50 million, 63 million, and 81 million in the pessimistic, baseline, and optimistic scenarios, respectively.[6]

[3]Industry location is identified by the presence of the industry, that is, the location of at least one establishment.

[4]The essential industries in the present paper consist of "Obsterics and gynecology department," "General medical clinic," "Supermarket," "Convenience store," "Funeal services," and "Laundry services" under the industrial classification based on the NTT Townpage Database. However, the choice of industries included should be considered as an example. Our methodology is general to alternative sets of industries to identify the threshold city size to sustain them in the city.

[5]We plan to obtain the data for earlier years in the near future, which will allow us to account for the potential bias in the essential city size due to the changing location patterns of individual industries over time. In the meantime, however, we focus on presenting the basic concept and methodology for determining the essential city size.

[6]The NIPSSR's projection is optimistic under the apparently declining fertility rate because the fertility rate is assumed to be constant in the future in all of their scenarios. Japan's current fertility rate is already approaching their pessimistic rate.

In the years after 2000, the fertility rate peaked at 1.45 in 2015 and has been declining rapidly ever since. It fell to 1.20 in 2023 and shows no signs of increasing (Fig. 2). The official baseline scenario, or even the pessimistic scenario, now seems optimistic, since population growth is not expected to come from increased immigration, as discussed in the introduction. Therefore, we will focus on the baseline and pessimistic scenarios of population decline. While the expected population loss will affect the entire country, the smallest cities will be the first to suffer and face the threat of extinction. We propose a method to identify the sustainable and unsustainable cities from the view point of the location behavior of essential industries.

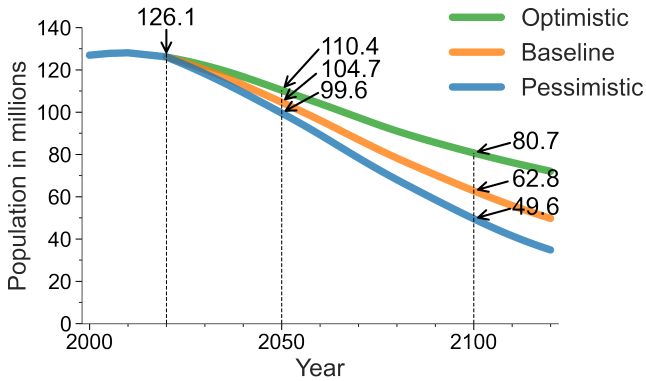

Figure 1. Projections of total population in Japan

Note: The total population of Japan is obtained from the Population Census of Japan (MIC) for years, 2000–2020. For years, 2021–2120, the values are based on the Japan's official population projection to 2120 by National Institute of Population and Social Security Research (2023). The "baseline" scenario assumes "intermediate" fertility rate (1.33) close to the rate in 2020, and an intermediate mortality rate, the "pessimistic" scenario assumes a low fertility rate (1.13) and a high mortality rate, and the "optimistic" scenario assumes a high fertility rate (1.64) and a low mortality rate.

3 Cities as population agglomeration

To identify cities as population agglomeration, we use the population count data in 30"×45" grid cells obtained from the Grid Square Statistics of the Population Census of Japan (MIC,1970–2020).[7] Each city is identified as an *urban agglomeration* (UA) by the set of 1 kilometer (km) grid cells that (i) have a population density of at least 1,000 per square kilometer, (ii) are geographically contiguous, and (iii) have a total population of at least 10,000 (see Appendix A.2 for the city detection procedure). Fig. 3A and B show the cities in 2020 and 2100, respectively, the latter based on the NIPSSR's baseline scenario of Japan's future total population. Each yellow to red area indicates a city, while the gray grid cells are populated but do not meet the conditions to be

[7]For ease of the analysis, we focus on the Japanese archipelago that are connected by road to the four major islands of Japan, Hokkaido, Honshu, Shikoku, and Kyushu in 2020.

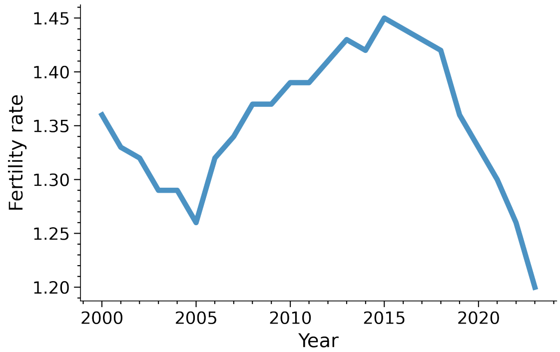

Figure 2. Fertility rates in Japan in 2000–2023

Note: For years, 2000–2022, data are available from the Vital Statistics, Ministry of Health, Labour and Welfare (MHLW) of Japan. The most recent 2023 data can be found in Annual Report on Monthly Vital Statistics, MHLW of Japan.

part of a UA.[8] The set of all UAs is denoted by **U**.[9]

In the baseline and pessimistic scenarios, the total population is projected to decrease from 126 million in 2020 to 62 million and 50 million in 2100, respectively. Accordingly, the number of cities is projected to decline from 431 to 307 and 285 in 2070, and to 228 and 175 in 2120, respectively. The comparison between panels A and B of Fig. 3 shows the substantial loss of urban population in the peripheral regions outside the originally densely populated region along the Pacific coast.

By definition, a city is larger than 10,000 people. However, this smallest city size is usually too small to support the full set of essential tertiary services for life. In what follows, we identify the essential city size to support these essential services.

4 Hierarchy property of the spatial coordination of industries

When we look at the location patterns of industries, we find a great diversity in the "degree of concentration." Some industries are ubiquitous and found in every city, while others are localized in only a few cities, and there are a number of industries in between. In fact, the location of individual industries exhibits strong spatial coordination, as suggested by the central place theory (e.g., Fujita, Krugman and Mori, 1999; Tabuchi and Thisse, 2011; Hsu, 2012; Davis and Dingel, 2020). In this theory, the spatial coordination of industries leads to the diversity of city sizes. Industries co-locate through the demand externality that arises from their common consumers. The industries that are concentrated in fewer locations are found where more ubiquitous industries are also present. The locations where a greater number of industries cluster will also attract population, resulting in larger cities. As a result, a hierarchical property emerges between the

[8] The maps show only the grid cells with at least 100 inhabitants.
[9] The sets of UAs differ in different years. We omit the year if there is no confusion.

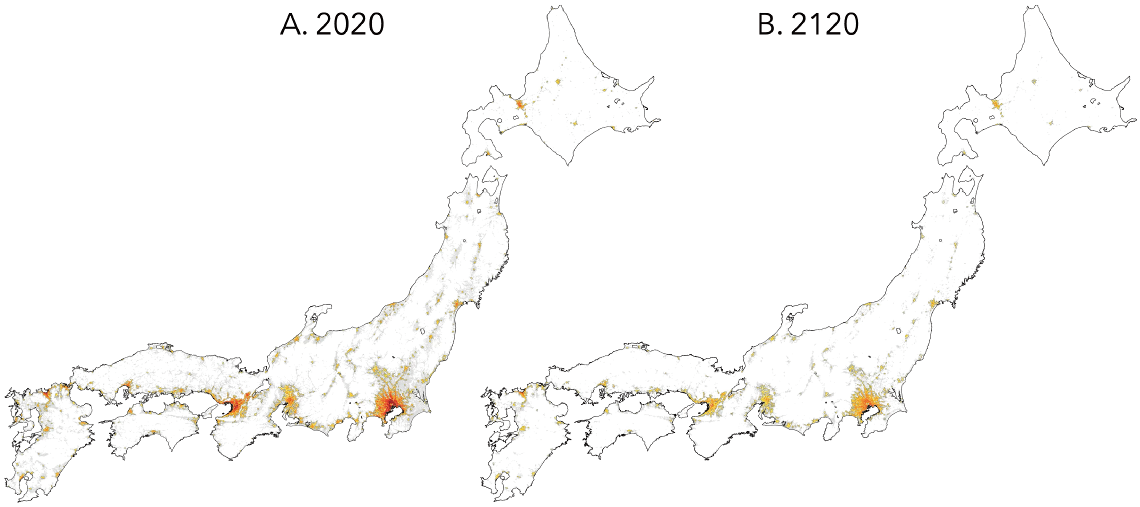

Figure 3. Cities as population agglomeration in 2020 and 2120 (baseline scenario)

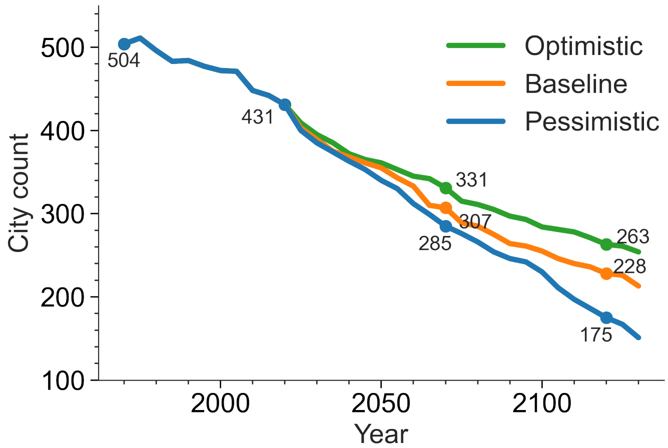

Figure 4. Counts of cities in 1970–2120 predicted by Mori and Murakami (2024) under the three scenarios of population decline in Japan. The realized counts in years 1970–2020, and the predicted counts in years 2025–2120.

industrial compositions of a smaller and a larger city, where industries found in the former are also found in the latter. We use this regularity between industrial location patterns and city size to identify the threshold population size of a city to support a given set of industries.

To see such coordinations by a given set of industries $\mathbf{I}$ in the data, let $\mathbf{U}_i$ be the set of cities in which an industry $i \in \mathbf{I}$ is located, and we call them *choice cities* for industry i. Let us define the degree of localization of an industry i by the number of its choice cities, $U_i \equiv |\mathbf{U}_i|$ (hereafter, the cardinality of a set $\mathbf{X}$ is denoted by its italic letter X). Then the industrial location exhibits an approximate *hierarchical property* (HP) that the choice cities of a more localized industry i are also the choice cities of a more ubiquitous industry j (Mori, Nishikimi and Smith, 2008; Schiff, 2015; Davis and Dingel, 2020; Mori et al., 2023). The hierarchy property holds strictly if $U_i \leq U_j \Rightarrow \mathbf{U}_i \subseteq \mathbf{U}_j$ for $i \neq j \in \mathbf{I}$.

To measure the consistency of the actual location pattern of industries with the hierarchy property, we compute the *hierarchy share* between industries i and j as

$$H_{ij} = \frac{|\mathbf{U}_i \cap \mathbf{U}_j|}{U_i} \in [0, 1]. \tag{1}$$

The larger the value of H_{ij}, the higher the consistency with HP, and $H_{ij} = 1$ for all $i, j \in \mathbf{I}$ if HP holds perfectly.

The average hierarchy share of industry i with all the more ubiquitous industries provides a summary measure of the industry's spatial coordination with other industries:

$$H_i \equiv \frac{1}{\bar{U}_i} \sum_{j \in \mathbf{U}_i} H_{ij}, \tag{2}$$

where $\bar{\mathbf{U}}_i \equiv \{j \in \mathbf{U} : j \neq i, U_i \leq U_j\}$.

In our study, we focus on the establishment location data of 1,858 private sectors from the NTT Townpage database in 2020. This database provides location data for more than two times more detailed industry classification according to NTT's own classification (NTTC) compared to 505 3-digit secondary and tertiary sectors in the Japan Standard Industrial Classification (JSIC) adopted by the Economic Census for Business Frame in 2020 (MIC).

In particular, the NTTC distinguishes tertiary sectors more in detail than the JSIC, although it does not clearly distinguish between secondary and tertiary sectors. For example, the NTTC allows us to identify the presence of major departments in a hospital, while the Economic Census does not distinguish hospitals by their functionality. For our purposes, it is important to be able to find, for example, the presence of an "Obstetrics and Gynecology Department" in a city, since its services are an essential element of the city's autonomous sustainability, as the birth of a child requires timely physical contact between doctors and mothers.

Figures 5 and 6 show the relationship between the number of choice cities and the average hierarchy share of each of the 1,858 industries in the NTTC and the 3-digit 322 tertiary sectors in the JSIC in 2020, respectively.[10]

The hierarchy share ranges from 0.14 to 1 with the average value of 0.77 under the NTTC. The gray band indicates the 95% confidence interval of the hierarchy share under the set of randomized choice cities for a hypothetical industry with a given number of choice cities.[11] With

[10] We include all private NTTC sectors in the graph because it does not clearly distinguish between secondary and tertiary sectors.

[11] More specifically, for each industry $i \in \mathbf{I}$, we randomly sample U_i choice cities from $\mathbf{U}$ without replacement, and then compute the average hierarchy share under the random counterfactual location pattern of each industry. We repeat this procedure 1,000 times to simulate the 95% confidence interval of H_i under the random location patterns of each industry.

the exception of a few highly localized sectors, such as "Sericultural Industry" and "Woven Fabric with Rubber", which are located only in a few rural cities with less than 30,000 inhabitants, spatial coordination a la central place theory is highly significant.

Among the more aggregated 322 JSIC tertiary sectors, the hierarchy property is more apparent, as shown in Figure 6. The hierarchy share ranges from 0.80 to 1.0, with an average of 0.94. All of these shares are highly significant relative to their random counterfactual values. Thus, as central place theory suggests, there is a strong tendency for more localized sectors to co-locate with more ubiquitous sectors.

Figures 7 and 8 show the relationship between population size P_u and industrial diversity, which in our case is the number of sectors I_u in a city $u \in \mathbf{I}$, for the NTTC and JSIC sectors, respectively. In both cases, the Spearman's rank correlation between population size and industrial diversity is above 0.9. Thus, the population size of a city is a strong predictor of the industrial composition of the city, splitting the set of all industries into two subsets, one with relatively more localized industries (with a smaller number of choice cities) and the other with relatively more ubiquitous industries (with a larger number of choice cities). Each threshold population size of a city corresponds to an industry with a certain degree of localization.

In the following, we focus on the location pattern of the "essential industries" listed in Table 1 along with their number of choice cities, which are supposed to provide the essential services for a city to sustain its population autonomously.

The key service, as mentioned earlier, is the obstetrics and gynecology clinic or department in a hospital where medical procedures can be performed, since the child birth requires timely and physical treatment. The NTTC includes "Obsterics and Gynecology Department". Since JSIC does not this detail, we include a broader, "Hospital" industry. "Funeral service" is also essential for a city to be autonomous. Most burials in Japan are cremations, and cremations need to be carried out soon after death. Since most funerals and cremations have been outsourced from the 2000s onwards, the location of such services is essential for the autonomy of cities (Ministry of Health, Labour and Welfare of Japan, 1951–2020).

Other industries, "Laundry Services", "Supermarket" and "Convenience Store" are included, although they are hardly binding because they are the most ubiquitous of all industries, being found in most cities. Regardless of their ubiquity, however, they are essential. In particular, dry cleaning, which is included in "Laundry Services", is one of the key household services that will become increasingly important in an aging society.

The selection of "essential industries" is for demonstration purposes, and we do not aim to systematically justify the selection in this study. Rather, our purpose is to propose a methodology for identifying the threshold population size of a city that can attract for-profit establishments in a given set of industries.

The relationship between the average hierarchy shares and the number of choice cities of the essential industries is highlighted in red in Figures 5 and 6 under the NTTC and JSIC, respectively. While the essential sectors are, not surprisingly, relatively ubiquitous as they are essential to life, there is some variation in their availability. Under the NTTC, the "Obstetrics and Gynecology Department" is relatively localized, as it is found in only 283 cities out of all 431 cities in 2020, while the "Convenience Store" is present in all cities. Since the JSIC does not distinguish between hospitals based on their functionality, we include the "Hospital" category to cover the "Obstetrics and Gynecology Department" in addition to the "Medical Clinic". The "Hospital" is relatively localized among the selected essential industries under the JSIC, as it is found in 367 cities in 2020.[12] In both classifications, "Funeral Services" is another key service that is ubiquitous but not present in every city.

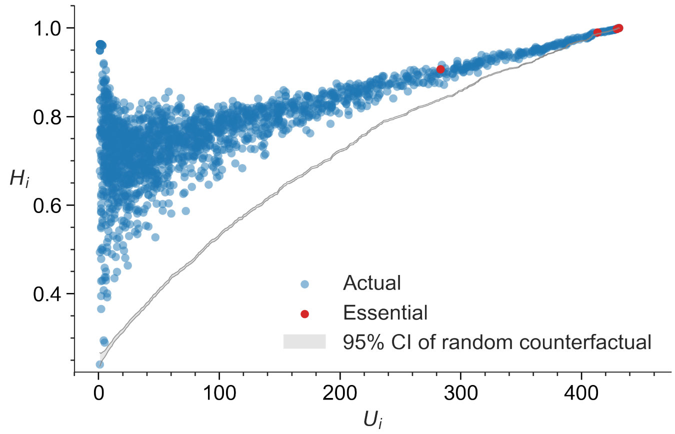

Figure 5. Hierarchy share between a larger and smaller cities

Notes: Each plot shows the average hierarchy share and the number of choice cities of one of the 1,791 NTTC industries in 2020. The "essential sectors" listed in Table 1 are colored in red.

5 The essential city size

The locations of cities that have the full set of essential industries under NTTC and JSIC are indicated by gold circles in Fig. 9A and 10A, respectively.

Provided that the industrial composition of cities exhibits the HP, we can estimate the threshold population size of a city, such that the full set of essential industries are likely to be present in a city of population size above the threshold. We call this threshold city size, *the essential city size* (ECS), and define it as the city size which maximizes the Youden Index (Youden, 1950):

$$P^e \equiv \text{aug}\max_P \text{TPR}(P) - \text{FPR}(P). \tag{3}$$

TPR(P) and FPR(P) represent *the true positive rate* and *false positive rate* under a given threshold

[12]The comparison between the number 283 of "Obstetrics and Gynecology Department" and the number 367 of "Hospital" suggests that not all hospitals have obstetrics and gynecology departments.

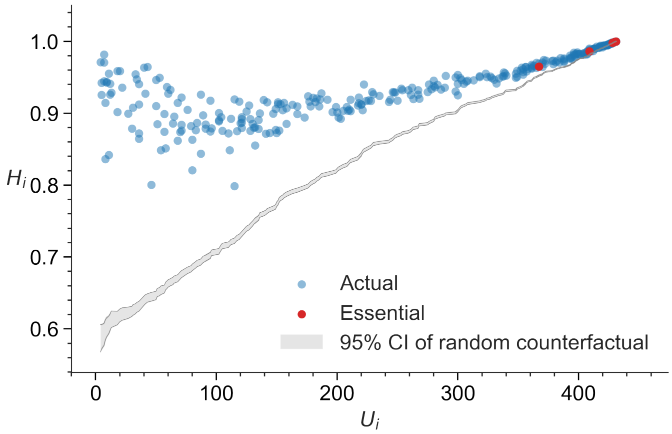

Figure 6. Common industry share in 2020 (JSIC, Tertiary)

Notes: Each plot shows the average hierarchy share and the number of choice cities of one of the 322 3-digit tertiary industries in 2020. The "essential sectors" listed in Table 1 are colored in red.

(1) Industry	(2) NTTC	(3) JSIC
Obsterics and Gynecology Department	283 (0.91)	–
Hospital	–	367 (0.97)
Funeral Services	413 (0.99)	409 (0.99)
Laundry Services	429 (1.0)	430 (1.0)
Supermarket	429 (1.0)	428 (1.0)
Convenience Store	431 (1.0)	431 (1.0)
All essential industries	266	405

Table 1. Essential industries, their number of choice cities and hierarchy shares in 2020

Notes: Columns (2) and (3) show the number of choice cities together with the average hierarchy share (in the parenthesis) of the corresponding essential industries in column (1) under the NTTC and JSIC, respectively. The NTTC code for "Obstetrics and Gynecology Department" is 6380000. The JSIC code for "Hospital" is 831, where "Hospital" is included because the JSIC does not distinguish each specific department in a hospital. (We do not include simpler "Medical Clinic" in the essential industries, since "Obstetrics and Gynecology Department" or "Hospital" typically imply its presence in a city.) Otherwise, the NTTC and JSIC codes are 3501000 and 834 for "Funeral Service", 2323000 and 581 for "Laundry Service", 4231000 and 79A for "Supermarket", and 1905000 and 78A for "Convenience Store".

city size P defined as follows.

$$\mathrm{TPR}(P) = \frac{\mathrm{TP}(P)}{\mathrm{TP}(P) + \mathrm{FN}(P)}, \tag{4}$$

$$\mathrm{FPR}(P) = \frac{\mathrm{FP}(P)}{\mathrm{FP}(P) + \mathrm{TN}(P)}, \tag{5}$$

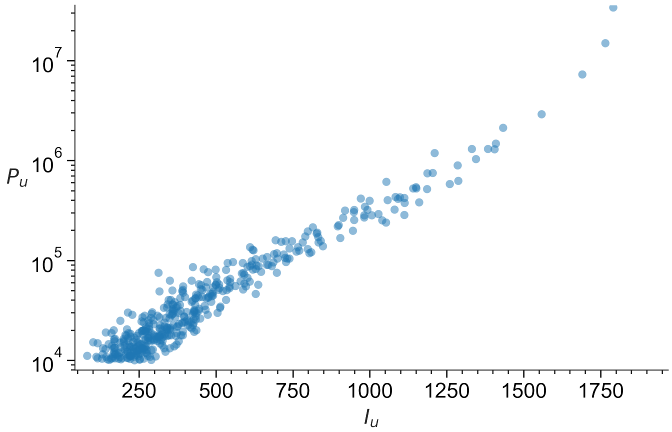

Figure 7. Population size and industrial diversity of cities (NTTC, 2020)

Notes: Each plot shows the relationship between the population size and the number of the NTTC located in a city in 2020. The Spearman's rank correlation between the size and industrial diversity of a city is 0.92.

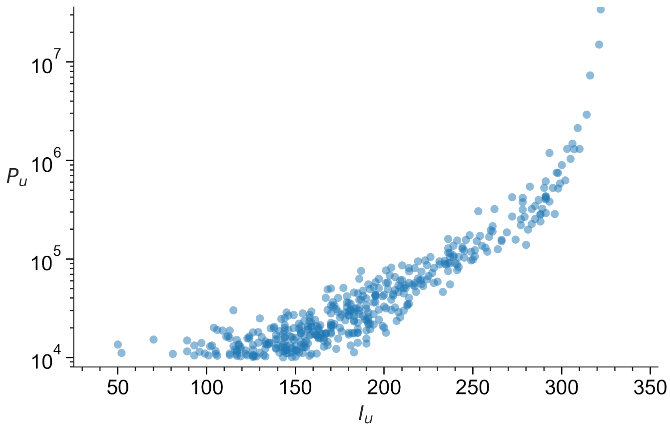

Figure 8. Population size and industrial diversity of cities (JSIC, 2020)

Notes: Each plot shows the relationship between the population size and the number of the JSIC located in a city in 2020. The Spearman's rank correlation between the size and industrial diversity of a city is 0.91.

where $\text{TP}(P)$, $\text{FN}(P)$, $\text{FP}(P)$, and $\text{TN}(P)$ stand for *true positives*, *false negatives*, *false positives*, and *true negatives* under a given city size P, given by

$$\mathrm{TP}(P) = \#\{i \in \mathbf{U} : P_i \geq P \ \&\ i \in \mathbf{U}_e\}, \tag{6}$$
$$\mathrm{FN}(P) = \#\{i \in \mathbf{U} : P_i < P \ \&\ i \in \mathbf{U}_e\}, \tag{7}$$
$$\mathrm{FP}(P) = \#\{i \in \mathbf{U} : P_i \geq P \ \&\ i \notin \mathbf{U}_e\}, \tag{8}$$
$$\mathrm{TN}(P) = \#\{i \in \mathbf{U} : P_i < P \ \&\ i \notin \mathbf{U}_e\}, \tag{9}$$

where $\mathbf{U}_e$ is the set of cities which have the set of all the essential industries.

Fig. 11 shows the TPR, FPR, and Youden Index when the city size is used to judge the presence of the essential industries under the NTTC in 2020. We define the city size at which the Youden Index is maximum as the (baseline) *essential city size* (ECS), and its optimistic and pessimistic alternative thresholds by the minimum and the maximum city sizes for which the Youden Index is in the top 5 percentile. In particular, the FPR is below 0.3, 0.2, and 0.1 at the optimistic, baseline and pessimistic threshold city sizes, respectively [13] We may consider the range of city size between the optimistic and pessimistic thresholds *the critical range* of essential city size.

Fig. 12 shows the similar graphs for the essential industries under JSIC in 2020. A major difference between the NTT and JSIC classification is that the former enables us to identify the locations of "Obsterics and Gynecology Department," whereas the latter does not. Since this service is localized to relatively larger fewer cities, the essential industries in the JSIC necessarily be more ubiquitous than those in the NTTC. Consequently, the ECS is lower under the JSIC than under the NTTC.

In this way, one can systematically identify the sustainable cities based on the theory and evidence of industrial location patterns. While we focus on the essential industries, one can choose a different set of industries to identify cities with different roles, such as the focal cities of a larger region.

Fig. 9A and Fig. 10A show the spatial pattern of the essential industries under the NTTC and JSIC in 2020. In both figures, gold circles indicate cities with the full set of essential industries, while red ones are without at least one of the essential industries. Fig. 9B and Fig. 10B show the selection of cities as viable locations for essential industries under the NTTC and JSIC, respectively. Cities classified as "stable" have population size above the pessimistic threshold, and are thought to be able to maintain the set of essential industries for the foreseeable future, while the "critical" group of cities at the threshold regarding the sustainability for essential industries. Their population size is between the pessimistic and optimistic thresholds. The "unsustainable" cities have population size below the optimistic threshold, and are thought to be at risk of disappearing in the near future. While the threshold city sizes are expected to change over time, their critical ranges are largely stable during the declining phase of Japan's population since 2010 (see Appendix A.3).

[13] It is to be noted that the FPR is zero beyond city size of 100,000, which matches the sustainable population of the *regional living areas* advocated by the Ministry of Land, Infrastructure, Transport and Tourism (MILT) of Japan.

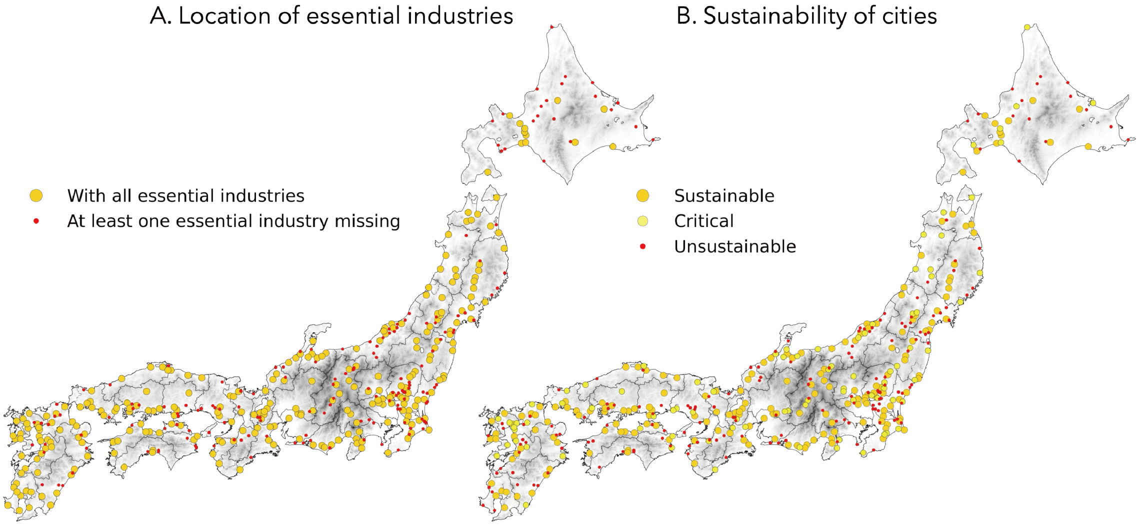

Figure 9. Sustainability of cities (NTTC, 2020)

(A) Location patterns of essential industries under the NTTC. Gold circles indicate 266 cities that have all the 6 essential industries, while the red ones indicate 165 cities which do not have at least one of the essential industries in 2020. (B) "Stable" gold circles indicate 183 cities with population size greater than the pessimistic threshold, "critical" yellow circles indicate 86 cities with population size between the optimistic and pessimistic thresholds, "unsustainable" red circles indicate the rest of the 162 cities that have population size smaller than the optimistic threshold to support the full set of essential industries.

6 Sustainable cities in the future

In an era of rapid population decline, we need to select and focus on the sustainable cities of the future and maintain the entire country by consolidating the regional economy around them. We focus on the private essential industries that seek profit, so their presence in a city indicates the city's self-sustainability. Below we apply our ECS to identify the sustainable cities of the future.

Fig. 13A and B indicate the sustainability of each city on the map in 2070 and 2120, respectively. The city population is taken from the prediction by Mori and Murakami (2024) under the baseline scenario of the population projection by National Institute of Population and Social Security Research (2023). The sustainability of cities are judged according to the ECS estimated for the NTTC essential industries in 2020.

By 2120, in Tohoku, Shikoku, and along the northern coast, essentially only the prefectural capitals will be sustainable. However, their sustainability supported by public institutions and public spending must be considered with a discount. With each city being more than 50km apart and isolated, the sustainability of these cities over the long term is not promising.

The shrinkage of the regional economy proceeds more under the pessimistic scenario of the Japan's population. Fig. 15 shows a severer result in this scenario.

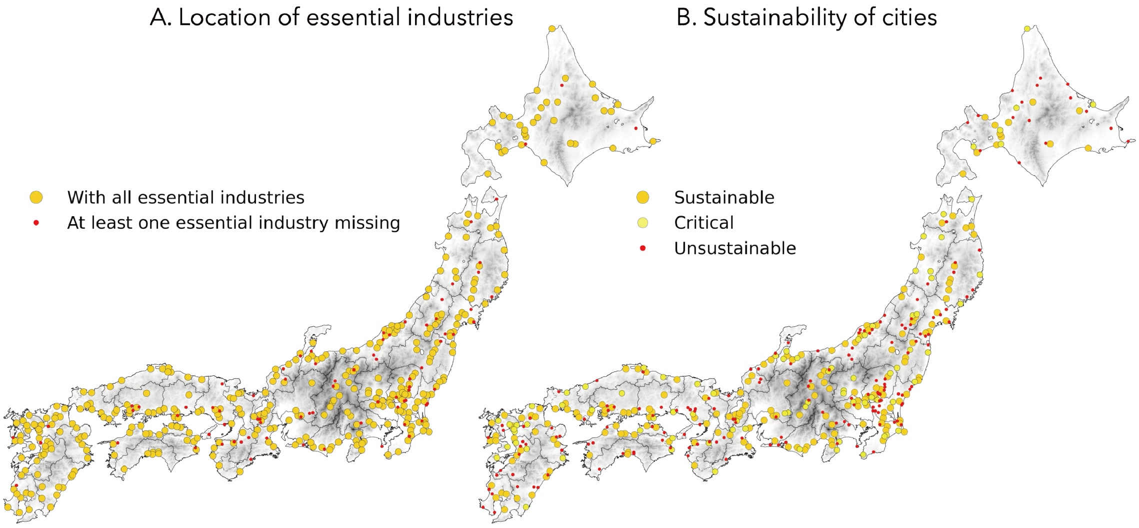

Figure 10. Sustainability of cities (JSIC, 2020)

(A) Location patterns of essential industries under the NTTC. Gold circles indicate 352 cities that have all the 5 essential industries, while the red ones indicate 79 cities which do not have at least one of the essential industries in 2020. (B) "Stable" gold circles indicate 181 cities with population size greater than the pessimistic threshold, "critical" yellow circles indicate 83 cities with population size between the optimistic and pessimistic thresholds, "unsustainable" small red circles indicate the rest of the 167 cities that have population size smaller than the optimistic threshold to support the full set of essential industries.

Fig. 17A and B map sustainable cities to municipalities (the polygons shown in the figure) in 2020 in terms of the essential industries under the NTTC and JSIC, respectively. Specifically, the population of each city larger than the ECS is assigned to municipalities according to the common grid cells between the city and a municipality. We then calculate each municipality's share of the total sustainable city population. Gray municipalities have zero sustainable city population shares. Bluish municipalities are roughly considered to be at risk of disappearing.

Fig. 18 (20)A and B show the growth of sustainable city population shares of municipality between 2020 and 2070 in the baseline and pessimistic scenarios of population decline under NTTC (JSIC), respectively. Gray municipalities have zero sustainable city population already in 2020, while the black municipalities had positive shares in 2020 but are projected to have zero shares by 2070. Very few municipalities have sustainable city population in the east and north of Tokyo, and the economic geography of Japan will be confined to the core region between Tokyo and Fukuoka. Even in the core region, Tokyo's dominance is expected to keep increasing.

Fig. 19 (21)A and B show the growth of sustainable city population shares of municipality between 2020 and 2120 in the baseline and pessimistic scenarios of population decline under NTTC (JSIC), respectively. 722 and 605 of 1,807 municipalities are expected to have sustainable city population in 2120 in the baseline and pessimistic scenarios of population decline, respec-

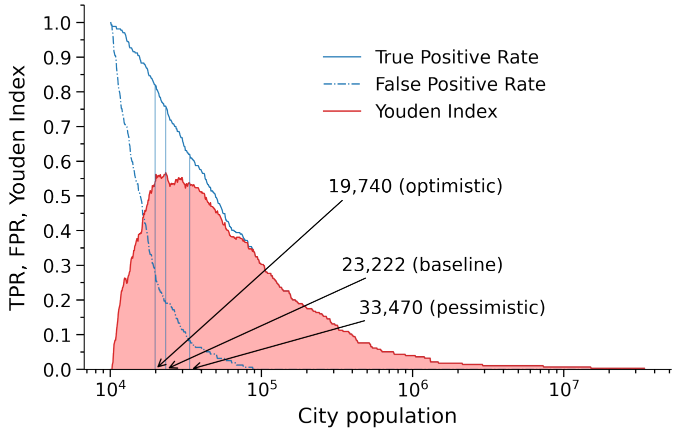

Figure 11. Essential city size (NTT, 2020)

tively. We see clear dominance of large cities such as Tokyo, Osaka, Nagoya, Fukuoka, Sapporo, Hiroshima, Sendai, while substantial decline in the northern coast and the eastern region.

7 Conclusion

This paper developed a methodology to assess the sustainability of a city based on the central place theory. First, by identifying cities as population agglomerations, we have shown that the population size of a city is a strong indicator of the industrial composition of the city, especially for tertiary industries. In particular, the industrial structure of cities generally exhibits the hierarchy property that an industry present in a smaller city is also present in a larger city. This property allows us to identify a threshold city size for a given set of industries, such that these industries are likely to be present if a city's population is above the threshold, and not otherwise. Since the sustainability of a city as a living community can essentially be defined in terms of the tertiary industries essential for life, we were able to identify the corresponding threshold city size, which we called the essential city size (ECS).

For the essential industries, including "Obstetrics and Gynecology Department," "Supermarket," "Convenience Store," "Funeral Services," and "Laundry Services," the ECS was found to be around 20,000– 30,000. Using this ECS, we could propose the set of declining focal cities around which the regional economy should be reorganized.

We can also map the set of cities to administrative units such as prefectures and municipalities, as we did in Section 6. The set of unsustainable cities mapped to municipalities may be

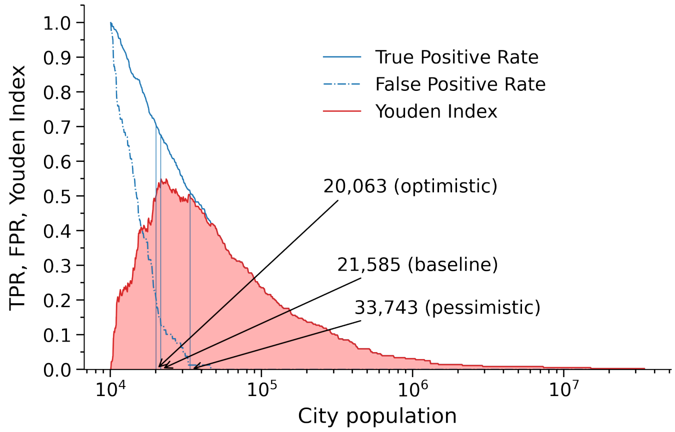

Figure 12. Essential city size (JSIC, 2020)

somewhat similar to the "Municipalities at Risk of Disappearing" advocated by the Population Strategy Council. But our sustainability can be seen as more directly related to a city's livability, and our sustainable cities explicitly select the focal cities around which the regional economy should be organized in the future. Such an exercise will facilitate an efficient design of the consolidation and reform of administrative units.

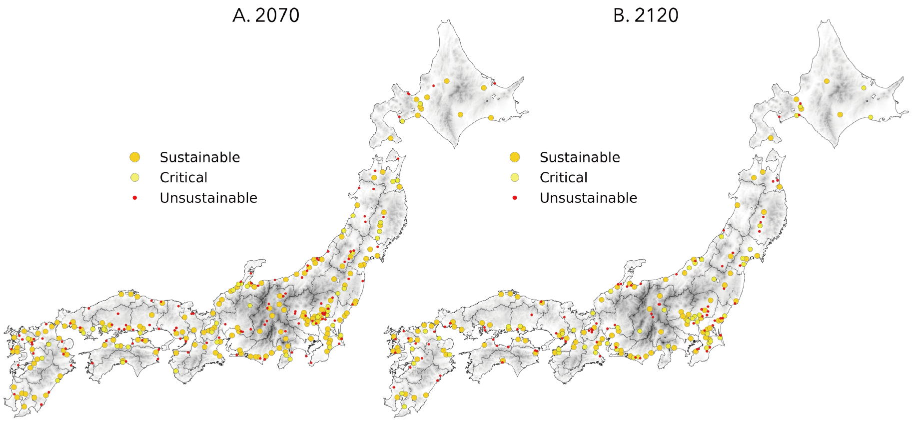

Figure 13. Sustainable cities in 2070 and 2120 (NTTC, baseline scenario)

Panel A (B) shows the sustainability of 245 (153) cities that are projected to remain in 2050 (2100) under the baseline scenario. The "sustainable" yellow circles indicate 115 (70) cities with population size larger than the pessimistic threshold, the "baseline" orange circles indicate 21 (19) cities with population size larger than the baseline threshold but smaller than the pessimistic threshold, and the "optimistic" larger red circles indicate 27 (25) cities with population size larger than the optimistic threshold but smaller than the baseline threshold. The "unsustainable" small red circles indicate the rest of the 82 (39) cities that have a population size smaller than the optimistic threshold to support the full set of essential industries.

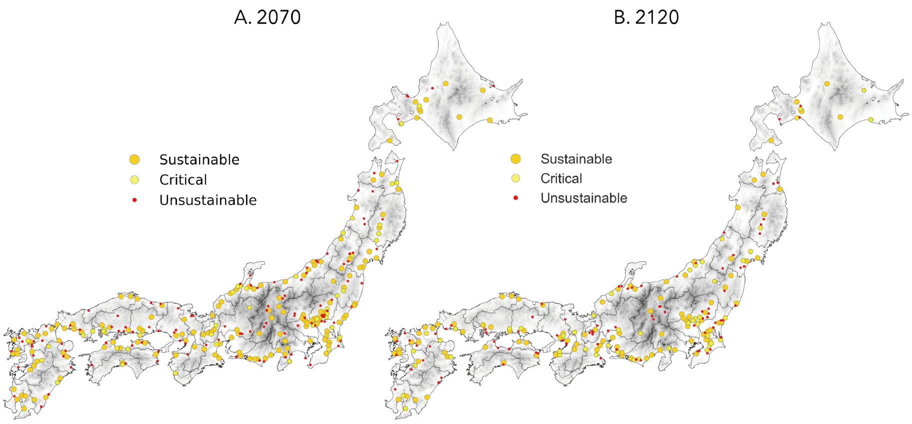

Figure 14. Sustainable cities in 2070 and 2120 (JSIC, baseline scenario)

Panel A (B) shows the sustainability of 285 (175) cities that are projected to remain in 2070 (2120) under the baseline scenario. The "sustainable" gold circles indicate 138 (70) cities with population size larger than the pessimistic threshold, the "critical" yellow circles indicate 49 (43) cities with population size between the optimistic and pessimistic thresholds. The "unsustainable" red circles indicate the rest of the 98 (62) cities that have population size smaller than the optimistic threshold to support the full set of essential industries.

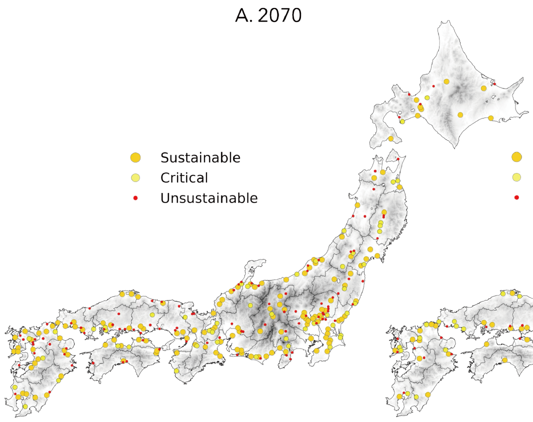

Figure 15. Sustainable cities in 2070 and 2120 (NTTC, pessimistic scenario)

Panel A (B) shows the sustainability of 285 (175) cities that are projected to remain in 2070 (2120) under the baseline scenario. The "sustainable" gold circles indicate 138 (70) cities with population size larger than the pessimistic threshold, the "critical" yellow circles indicate 49 (43) cities with population size larger than the baseline threshold but smaller than the pessimistic threshold. The "unsustainable" red circles indicate the rest of the 98 (62) cities that have a population size smaller than the optimistic threshold to support the full set of essential industries.

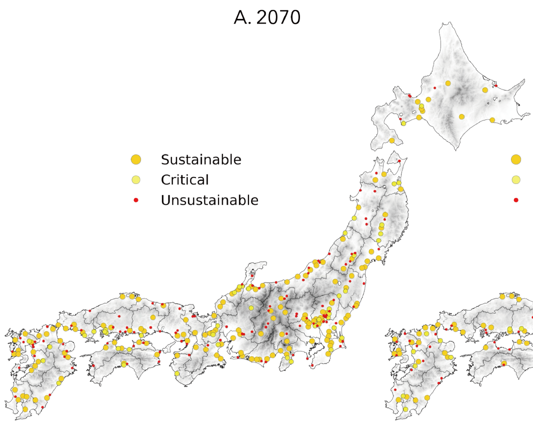

Figure 16. Sustainable cities in 2070 and 2120 (JSIC, pessimistic scenario)

Panel A (B) shows the sustainability of 285 (175) cities that are projected to remain in 2070 (2120) under the pessimistic scenario. The "sustainable" gold circles indicate 138 (70) cities with population size larger than the pessimistic threshold, the "critical" yellow circles indicate 47 (42) cities with population size larger than the baseline threshold but smaller than the pessimistic threshold. The "unsustainable" red circles indicate the rest of the 100 (63) cities that have a population size smaller than the optimistic threshold to support the full set of essential industries.

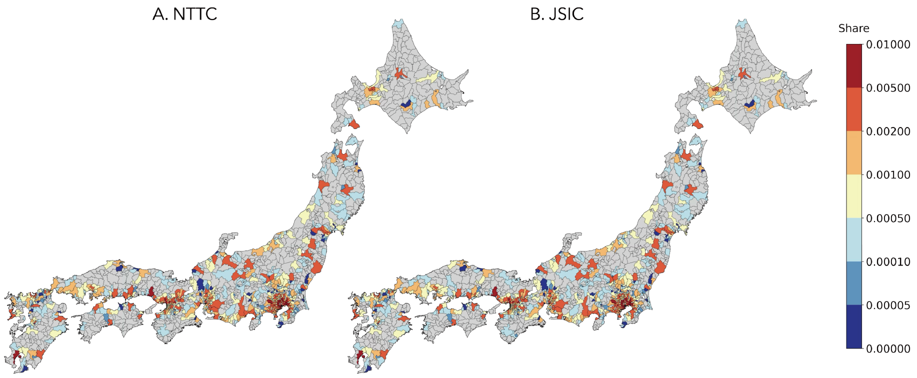

Figure 17. Share of sustainable city population share by municipality in 2020

The sustainability of cities in 2020 is calculated based on the NTTC and JSIC essential industries. The population of each city with a population larger than the ECS is allocated to municipalities according to the common grid cells. The sustainable city population share by municipality is calculated as the share of the total sustainable city population. The grey municipalities have zero share of the sustainable city population. Municipal boundaries are as of January 1, 2021.

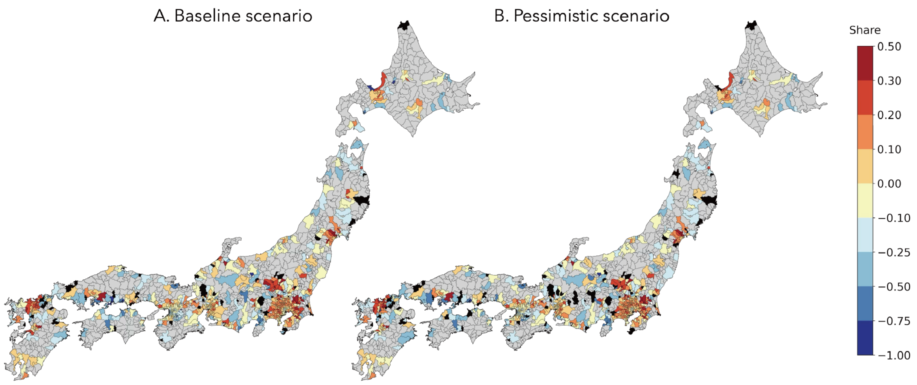

Figure 18. Growth rate of sustainable city population by municipality in 2020–2070 (NTTC)

The growth rate of the sustainable urban population share by municipality between 2020 and 2070 is calculated as the ratio of the share in 2070 to the share in 2020 for each municipality. Gray municipalities have zero shares in 2020, while black municipalities had positive shares but are projected to have zero shares between 2020 and 2070. The ECS is based on the NTTC essential industries in 2020. (A) and (B) show the results in the baseline and pessimistic scenarios of population decline.

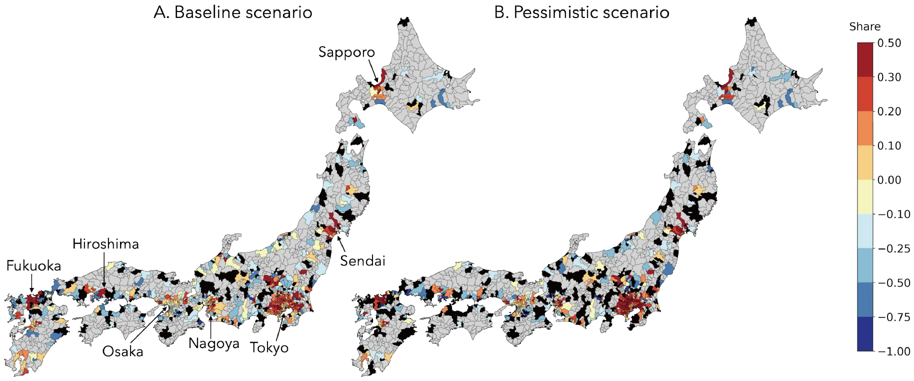

Figure 19. Growth rate of sustainable city population by municipality in 2020–2120 (NTTC)

The growth rate of the sustainable urban population share by municipality between 2020 and 2120 is calculated as the ratio of the share in 2120 to the share in 2020 for each municipality. Gray municipalities have zero shares in 2020, while black municipalities had positive shares but are projected to have zero shares between 2020 and 2120. The ECS is based on the NTTC essential industries in 2020. (A) and (B) show the results in the baseline and pessimistic scenarios of population decline.

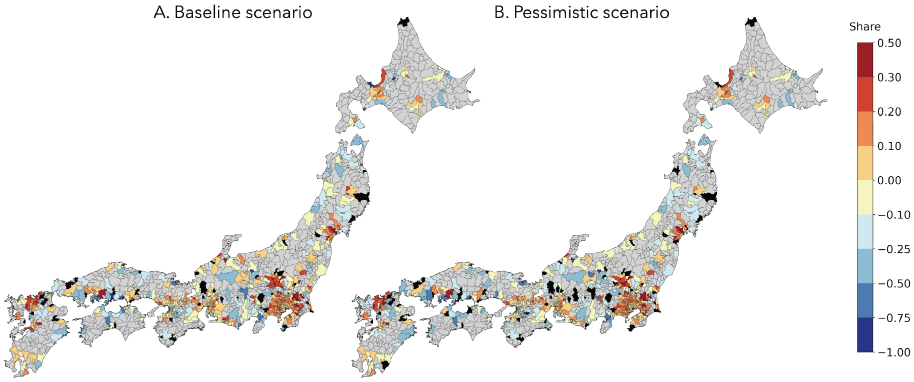

Figure 20. Growth rate of sustainable city population by municipality in 2020–2070 (JSIC)

The growth rate of the sustainable urban population share by municipality between 2020 and 2070 is calculated as the ratio of the share in 2070 to the share in 2020 for each municipality. Gray municipalities have zero shares in 2020, while black municipalities had positive shares but are projected to have zero shares between 2020 and 2070. The ECS is based on the JSIC essential industries in 2020. (A) and (B) show the results in the baseline and pessimistic scenarios of population decline.

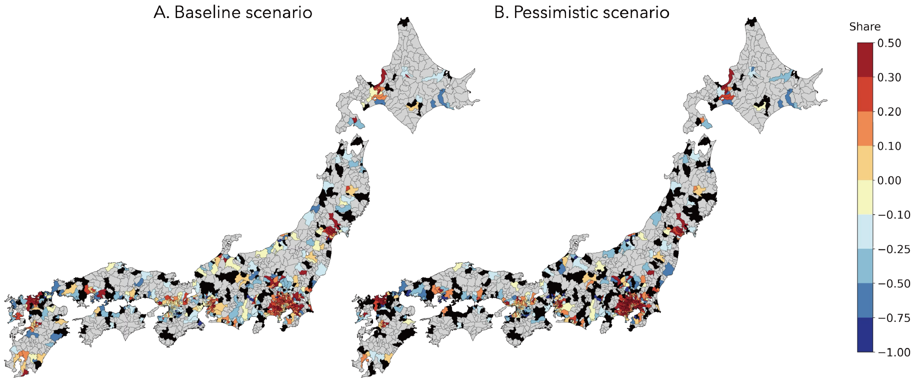

Figure 21. Growth rate of sustainable city population by municipality in 2020–2120 (JSIC)

The growth rate of the sustainable urban population share by municipality between 2020 and 2120 is calculated as the ratio of the share in 2120 to the share in 2020 for each municipality. Gray municipalities have zero shares in 2020, while black municipalities had positive shares but are projected to have zero shares between 2020 and 2120. The ECS is based on the JSIC essential industries in 2020. (A) and (B) show the results in the baseline and pessimistic scenarios of population decline.

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A Appendix

A.1 NTT Town Page Database

The NTT Townpage Database is a service that provides a database of approximately 8 million items, including 5.8 million items from the occupational telephone directories (Townpage) published by NTT East and NTT West, and 2.2 million items of corporate information that NTT Townpage has independently collected and compiled from public sources. The 2020 data used in this paper was specially provided by the NTT Townpage Database in cooperation with the research project of Grant-in-Aid for Scientific Research (S) 24H00012. It contains locations of 1,858 industries that are mapped to the (approximately) 1km grid cells defined in the Standard Grid Square Statistics of the Population Census of Japan (MIC, 1970–2020).

A.2 Urban agglomerations

Each *Urban Agglomeration* (*UA*) in a given time $t = \{1, \ldots, 31\}$ (corresponding to years, 1970, 1975, $\ldots$, 2120) is identified as the set of 1km grid cells that (i) have a population density of at least 1,000 per square kilometer, (ii) are geographically contiguous, and (iii) have a total population of at least 10,000 in time t.

The set of UAs is updated every $t = \{1, \ldots, 31\}$. We keep track of each UA over time by assigning it a unique identifier (ID) throughout the study period as follows:

1. IDs of UAs in time $t = 1$ are set to be their city size ranking in t. For those with the same population size, UAs are ranked according to their average population density in descending order.
2. A UA at time t and a UA at time $t + 1$ are considered the same if they share the largest population as of time t in their areal intersection. (If there are multiple ties, the pair with the largest population density in their areal intersection takes the precedence.) In this case, their IDs at time $t + 1$ are inherited from time t.
3. If UA i in time t has the largest population at time t in the areal intersection with UA j in time $t + 1$, and UA j in time $t + 1$ has the largest population in the areal intersection with a UA other than i in time t, then UA i is considered to be absorbed by UA j in time $t + 1$.
4. If UA j in time $t + 1$ has no intersection with any UA in time t, then UA j is considered to be either a newly formed UA or a UA split from an existing UA. For a newly formed UA or a split UA with no predecessor in older time $< t$, a new ID is assigned in the descending order of their population size in time $t + 1$ (in the case of a tie, the one with the highest average population density is assigned an ID first).
5. If a UA is split from the existing UA at time $t + 1$, but has a predecessor at time before t, the ID of the latest predecessor is restored. If there are multiple most recent predecessors, the one with the largest population in the areal intersection with the UA is chosen (again, in the case of a tie, the predecessor with the largest average population density is chosen).

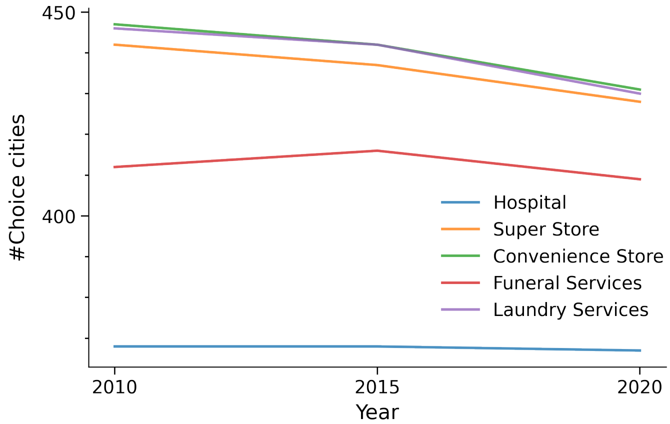

Figure 22. The number of choice cities of the essential industries in 2010–2020 (JSIC)

The figure shows the change in the number of choice cities for each essential industry between 2010 and 2020, the period of Japan's population decline.

Thus, a UA i that was absorbed once by another UA j and later split from UA j will be renamed i again.

A.3 Stability of essential city sizes

For a robustness check, Fig. 22 shows the changes in the number of choice cities for each essential industry (under JSIC) during the period of Japan's population decline since 2010. Their location pattern is fairly stable reflecting gradual decrease in the numbers of choice cities as the number of cities decreased from 448 in 2010 to 431 in 2020. Figs. 23 and 24 show that the critical ranges of the ECS for the essential industries in 2010 and 2015, respectively. They are also stable between 2010 and 2020, where around the population of 20,000 and 30,000 are the optimistic and pessimistic threshold sizes of a sustainable city.[14]

[14] The establishment location data are taken from the Economic Census for Business Frame in 2009, the Economic Census for Business Activity in 2014 and 2020 (MIC, METI). We are expecting to obtain the NTT Townpage data for 1995–2015 to do a similar robustness check.

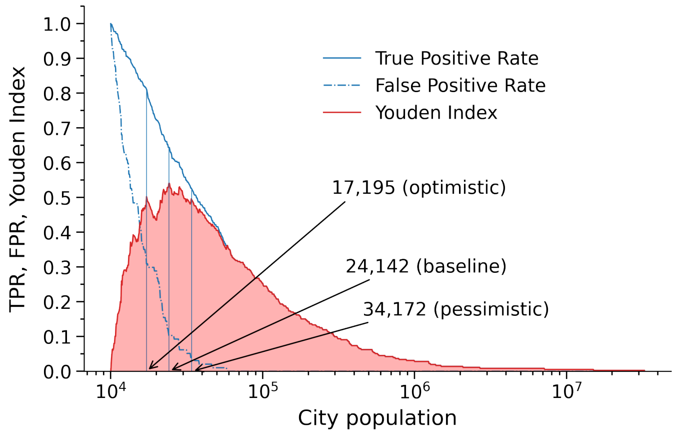

Figure 23. Essential city size in 2010 (JSIC)

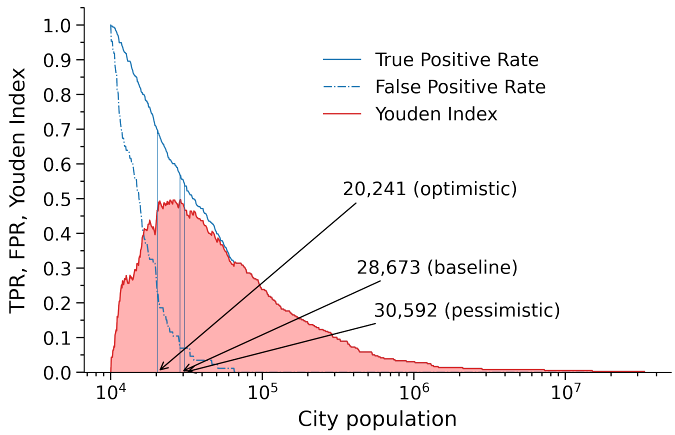

Figure 24. Essential city size in 2015 (JSIC)