博士論文

都市緑地の格差：人口動態の変化を背景とした公平な都市緑地計画の課題と戦略

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2024年7月

Disparities in urban green space: challenges and strategies for equitable urban green space planning against the background of demographic change

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July 2024

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ABSTRACT

Urban green spaces (UGSs) are crucial for providing ecosystem services that significantly benefit human health. However, the acceleration of urbanization has led to uneven development in urban environments, giving rise to environmental justice issues. This is particularly evident in the access to UGSs, where disparities among residents can lead to severe health inequalities. In Japan, after a long period of population growth, there has been a continuous trend of decline. The government has taken a series of measures to adapt to population changes, but while these policies have alleviated some of the negative effects of demographic shifts, they may also exacerbate the inequitable distribution of environmental resources, further intensifying environmental justice issues. This study aims to investigate the trends of inequality in access to UGSs in Japanese cities against the backdrop of long-term population changes and discusses UGS planning to achieve equitable access for residents in this context. Through an analysis of the Gini coefficient of inequality in UGSs in Japanese municipalities from 2000 to 2020, I have observed an intensifying trend in the inequality of UGSs. Addressing the gap in access to UGSs among residents, this study explores from the perspectives of urban dimensions, block dimensions, and population dimensions. Firstly, I established the relationship between the unequal distribution of UGSs and urban form, providing strategic guidance for urban built area planning in the context of

a decreasing population. Following this, based on analysis at the scale of urban blocks, I explored the connection between inequality in UGSs and UGS spatial pattern, proposing methods to promote balanced development of UGSs through planning of UGS spatial pattern. Finally, from a demographic perspective I propose a new measure of UGS inequality. This approach considers the quality of UGS and population structures. I use the developed methodology to explore the relationship between UGS and demographic changes, indicating how the design of environmental facilities and site layout of UGS should be adapted to the needs of urban development brought about by population changes. Combining the above analysis, this paper proposes corresponding urban planning policy recommendations aimed at supporting the achievement of equitable and sustainable UGS planning and development. Through these policy recommendations, I aim to provide effective solutions to alleviate environmental justice issues in the urbanization process, ensuring that all residents can equitably enjoy the health and welfare benefits that UGSs bring.

Chapter I. Introduction

1. Background and literature review

1.1 Benefits of UGSs

With urbanization, the proportion of the population living in urban areas is expected to reach 68 % by 2050 [1]. Urbanization has increased the burden on the urban environment, and climate change has become a critical threat to human health [2,3]. In 2022, the World Health Organization (WHO) and UN-Habitat called for integrating human health into urban and territorial planning to support the 17 Sustainable Development Goals (SDGs) and emphasized that human health is not only limited to SDG3 (health and well-being) but also supports and links to other SDGs [4].

Urban green spaces (UGSs) are a vital component of cities, providing essential ecosystem services (ESs). As the understanding of the ESs provided by green spaces has deepened, several studies have attempted to link UGSs, ESs, and human health [5,6]. Regarding mitigating the UHI effect, UGSs reduce the risk of human diseases and mortality through climate regulation [7–9]. For instance, Iungman et al. (2023) investigate 93 European cities and found that UGSs are effective in reducing the UHI effect [7]. When UGS coverage was increased to 30 %, urban temperatures decreased by an average of 0–4 °C, preventing approximately 2644 premature deaths. Regarding air pollution, UGSs can improve air quality to reduce the risk of disease, such as

cardiovascular and respiratory issues, through particle deposition, dispersion, and modification [10–12]. In a study of 379,238 participants, higher UGS around residences was found to be associated with a lower risk of developing type 2 diabetes, and 37 % of the estimated effect could be explained by a reduction in PM2.5 concentrations [13]. The water regulation capacity of UGSs can effectively reduce the risk of flood-related natural disasters, thereby reducing residents' psychological burden [14,15]. Meanwhile, wetlands assume the function of water pollution purification [16]. One study has shown that long-term exposure to contaminated water environments is associated with poor stress recovery [17]. These UGS services improve the well-being and health of residents without them realizing it, even if they are not actively involved.

Regarding the social environment, UGSs provide spaces for social interaction among urban residents, encouraging various forms of communication and interaction to enhance social cohesion, local identity, and nature education [18–20]. Residents' access to active lifestyles and social networks from UGSs can be a potential factor in influencing health [21,22]. Moreover, UGSs provide residents with opportunities for recreation and tourism. Aesthetics and activities in UGSs have been shown to be effective in promoting the physical and mental health of residents [23–26]. For instance, Deng et al. (2020) have found that nature-related visual and auditory stimuli significantly promote stress recovery [27]. Finally, UGSs maintain urban biodiversity and contain beneficial microorganisms [28]. An increasing number of studies have demonstrated that exposure to microorganisms contributes to the prevention of depression and digestive and cardiovascular diseases [29,30]. In addition, studies have shown that greenery around residential areas provides more well-being and health compared to urban-scale greenery

[31,32]. These UGS services require active participation by residents in activities such as exercise, aesthetics, and learning, and are closely related to the quality of environmental facilities in UGSs.

1.2 Environmental justice issues—UGS inequality

In the process of urban development, equity is a social expression that is continuously pursued [33]. Environmental justice means that all people should have the right to a healthy and safe environment, with the specific aim of addressing the unequal distribution of environmental burdens and preventing socially disadvantaged groups from being disproportionately exposed to environmental risks [34]. The concept of environmental justice aims to improve the well-being of society by ensuring that all people have equitable access to environmental resources. The essence of environmental justice issues is people's demand for social equality, namely, the pursuit of an equal living environment, and the surrounding greenery is one of its important manifestations [35–37]. Despite the recognition of the important role of UGS in human society, many studies have shown that the distribution of UGSs around residential areas is often unequal due to factors such as income, ethnicity, and gender [35,37,38]. In the United States and most of the Global North, UGS inequality persists, often intertwined with structural racism, planning, and culture [39–41]. Some racist policies have led to power disparities that concentrate low-income populations or races in UGS-deficient communities, and wealthier communities to build more UGSs, inspiring gentrification [42,43]. For example, Baltimore, Maryland, has long been influenced by laws or planning mechanisms that forcibly segregate the African American and White populations, which has led to

inequitable park allocations and serious environmental justice issues [42]. Meanwhile, initiatives to promote equality in UGS often conflict with dominant narratives [44], which treat UGSs as "nice to have" or "universally good" tools, further maintaining and reinforcing UGS inequality and gentrification [45,46]. In Japan, UGS inequality is rarely discussed; however, that does not mean it does not exist [47]. In fact, transportation-driven urban planning continues to stimulate gentrification [48,49]. Along with gentrification, environmental justice issues have long been replayed in Japan [50,51]. A study from Yokohama found that new parks appear to be leading to the migration of the affluent [52]. The government does not consider socio-demographic characteristics of UGS planning and developers' pursuit of "profit-maximizing" construction, which has led to the construction of more parks in affluent neighborhoods [52]. This has gradually amplified the distributional inequities of existing parks. Since the 1990s, the bursting of the Japanese economic bubble and long-term economic downturn have gradually increased the gap between rich and poor residents, and social stratification has become apparent [53]. The polarized social stratification has further influenced the spatial structure of the city, thus promoting residential segregation [54,55]. Environmental justice is problematic when there are growing differences in the surroundings of different social groups living in different regions. In Tokyo, researchers found that the degree of residential segregation has gradually expanded, and the phenomenon of "super-gentrification" has also appeared, with more "elites" entering the originally gentrified areas [51]. Various reasons directly or indirectly affect the distribution of UGSs, resulting in the inequality of UGS.

UGSs around residences promote residents' physical and mental health by encouraging

them to go outdoors and exercise [56–58]. Although researchers generally agree that disadvantaged groups typically gain more benefits from UGSs [59,60]. Adequate exposure to UGS can effectively reduce the health inequalities associated with income deprivation [61]. The reality, however, is that disadvantaged populations often do not have access to adequate UGSs [62,63]. Inequitable access to UGSs intersects with factors such as socioeconomics and race, which in turn can exacerbate health inequalities [64]. Health inequalities due to park and UGS access were further magnified during the pandemic. Spotswood et al. (2021) found that disadvantaged communities in the U.S. are more severely impacted by COVID-19 because they have fewer UGS [65]. In addition, UGS accessibility is influenced not only by distance and size, but also by quality, including the character and environment [66]. Some studies have found that disadvantaged communities are often associated with access to poorer quality parks [66,67]. For example, Lee (2022), who conducted environmental assessments of parks in four regions of South Korea, found that older adults in lower socioeconomic communities were more likely to have poorer quality parks [68]. Other studies have claimed that residents who access high-quality UGSs are associated with healthier physical conditions compared to UGSs with poorer facility environments [69–71]. In conclusion, UGS can provide many benefits to urban residents and can be effective in mitigating health inequalities when distributed equally, but unequal accessibility can also further exacerbate health inequalities caused by socioeconomics.

A growing number of scholars have begun to address environmental justice issues arising from the allocation of UGSs [35]. They have examined UGS exposure, accessibility, and gentrification from a geographic perspective, primarily through spatial

analyses that consider factors such as population density, income, race, age, education, and housing prices [72–76]. For instance, Boone et al. (2009) have measured UGS in Baltimore using Tyson polygons and found that African Americans were more likely to have access to parks than white residents but had access to less park areas within walking distance [42]. A few studies have also considered the patterns of UGS distribution across vegetation types. Nesbitt et al. (2019) have measured three types of UGSs (mixed vegetation, woody vegetation, and parks) in ten U.S. cities to reflect differences in the distribution of potential ESs [73]. Moreover, there is no shortage of political and civil society perspectives on the distribution of power in the use and role of UGS governance [77,78] that illustrate how unequal patterns of benefits from UGS-provided ESs are mediated by policy and participants [79,80]. In this context, using "UGS per capita" to measure the green status of cities does not meet the challenges of UGS equality today [81,82]. In summary, researchers have commented on the benefits of UGS equality from a variety of perspectives. They argue that reducing UGS fragmentation around residents should be an important goal for sustainable urban development and strongly recommend that the distribution of UGSs around residents should be continuously studied, whether in developing or developed countries [35,81,83,84]. However, most of the current research focuses only on exploring the drivers of UGS inequality and the specific reasons for its emergence, and very little research focuses on what cities should do to mitigate UGS inequality [85]. As a result, there is still a lack of adequate and effective means to address UGS inequality.

1.3 UGS development in the context of demographic change

Recently, global inter-regional demographics have changed dramatically, not only in terms of population size but also in terms of population structure. Regarding population size, while many developing cities are experiencing rapid population growth, an increasing number of cities are experiencing population decline [86]. Regarding population structure, in some regions (e.g., sub-Saharan Africa), the population aged between 25 and 64 years is growing much faster than other age groups, while in other regions, older adults comprise the fastest-growing age group [87]. For example, in Japan, the declining population, aging and low birth rate are becoming more pronounced. The total population of Japan is expected to decrease by 19% in 2050 (based on 2020), while the share of the elderly population will rise to 37% [88]. Rapid population change not only exacerbates the burden of age-related diseases [89], but also increases the risk of various infectious diseases [90,91], placing urban health under enormous pressure.

Due to the rapid expansion of cities throughout the world in recent decades, many scholars have focused their urban studies on cities with rapidly growing populations [75,92,93]. However, many cities, whether in Europe, the United States, or Japan, are also experiencing urban contraction [86]. The rapid urban shrinkage has caused a decrease in the population and a decline in the urban economy. Nevertheless, it has also led to an increase in the number of abandoned buildings and vacant land (e.g., brownfields, abandoned lots, and unoccupied properties) and a deterioration of the living environment of residents [94]. To address the social problems caused by urban shrinkage, governments are implementing various measures to achieve rational adaptation of urban

space [86,95], such as right-sizing [96], smart shrinkage [97], and compact city [98]. Although these policies can mitigate the negative impacts of urban shrinkage to some extent, they can also exacerbate the risk of unequal distribution of urban resources, including UGS, which ultimately exacerbates environmental justice issues [99,100]. Nevertheless, there are no studies that definitively confirm the inevitable link between shrinking cities and the exacerbation of UGS justice problems. However, it has been suggested that areas with lower population densities may lead to more severe UGS inequality problems [76,101]. The main characteristic of shrinking cities is population decline, which may lead to a decrease in urban population density. Therefore, it is necessary to monitor UGS inequality in shrinking cities.

Some scholars argue that urban shrinkage, despite its many challenges, also brings new opportunities for cities [102,103]. The growing number of unused urban spaces in shrinking cities not only harms the physical and mental health of residents [104], but also encourages criminal activity [105]. However, greening unused land can lead to more opportunities for shrinking cities and provide many recreational benefits for urban residents, including ecological, recreational, aesthetic, and safety benefits [106–108]. Especially in shrinking cities experiencing economic recession, UGSs offer a more sustainable solution for urban space because they require low overhead, are low maintenance, and engage the community, compared to converting vacant land to other public infrastructure [109–112]. Given that much of the underutilized land is in disadvantaged communities with equitable access to UGS, it is possible to reverse the mismatch between supply and demand for UGS and improve the equitable distribution of UGS to close the environmental justice gap in health and well-being [41]. Although concerns have been

raised about the “UGS paradox,” the “just green enough” solution not only fits the characteristics of urban vacant lots, but also promotes a more equitable distribution of UGS [37,113]. It can be argued that open space created by urban shrinkage provides an opportunity to improve the equality that is difficult to achieve in cities with growing populations. On the other hand, urban shrinkage has led to urban transformation, both in terms of industry and urban form. In Japan, for example, a development strategy for “compact cities” has been proposed in response to urban shrinkage, encouraging residents to move to densely populated neighborhoods [114]. The resulting shift in urban form will pose a new challenge to UGS supply and demand, but it will also be the best time to reverse UGS inequality.

In Japan, after a long period of population growth, there has been a continuous trend of decline [86]. Declining and ageing populations bring with them widening income disparities, high rates of relative poverty and unused land. In Japan, where the population is declining and there is an “inequality society”, the study of social equality is expected to become an important issue [54]. Specifically, environmental differences are widening due to population decline, municipal consolidation, and social inequality, and there are regional differences in residents' needs for public services and UGS. Efforts are needed to prevent environmental equality from deteriorating as a result of population decline, to improve environmental equality and to enhance regional attractiveness, and research is needed to achieve this. If environmental justice is not emphasized in urban development, it may lead to the spatial separation of the rich and the poor, further aggravating the decline of urban population. Therefore, regardless of the response, cities need to reconsider their existing UGSs and adjust their composition

to the current state of urban degradation. The government has taken a series of measures to adapt to population changes, but while these policies have alleviated some of the negative effects of demographic shifts, they may also exacerbate the inequitable distribution of environmental resources, further intensifying environmental justice issues. Currently, many studies on UGS equality exist in China, the United States and other countries, but fewer in Japan [73,75,76,115,116]. These studies often focus only on cities with rising populations and not on cities with shrinking populations. Therefore, it is necessary to conduct an in-depth examination of UGS inequality against the background of Japan's population decline.

In addition, urban development continues to undergo dynamic change [117]. As with most urban infrastructure, there is a time delay in planning for UGSs. This requires urban planners to better understand and population dynamics in order to develop more forward-looking planning strategies. Agenda 21 emphasizes that population, equality, health, and the environment should be important factors in urban and territorial sustainable development [118]. UGS equality planning based on demographic trends and structures can help disadvantaged groups benefit more from UGSs [119]. For example, building prescient UGSs in shrinking cities facing declining and aging populations could help cities achieve equitable green access in the future and also helps cities complete their economic transformation [120].

Recognizing this, it becomes particularly important to track and understand trends in the distribution of UGS over time at the city, national, and even broader regional scales. Policymakers should continuously examine UGS planning issues in the process of urban

development in order to seek equitable and sustainable urban development. Nevertheless, current research is still lacking in analyzing the temporal dynamics of UGS inequality, and most studies rely on cross-sectional data at a single point in time, which makes it difficult to reveal the changes in the dynamics of UGS [116,121,122]. Only a few studies have explored the development of UGS inequality through time, but far fewer. For example, Yasumoto et al. (2014) measured differences in UGS accessibility over time (1988–2005) in Yokohama City using demographic indicators [52]. The lack of attention to population dynamics will make it difficult to adopt forward-looking planning efforts, both in developing cities with growing populations and in shrinking cities that are facing population decline.

1.4 Drivers of UGS inequality

Understanding that cities around the world are experiencing UGS inequality, researchers have begun to focus on the various drivers of UGS inequality in an attempt to find strategies to mitigate UGS inequality [123]. In general, researchers have argued that people's access to UGS is influenced by urban development, population, and the amount and distribution of UGS [123].

1.4.1 Urban form as drivers of UGS inequality

UGS are intertwined with the urban built structure and are profoundly influenced by urban development [124]. Different urban forms and urban development patterns as well as land use types influence the morphology, number, and distribution of UGS [125,126].

Urban form is a characterization of the evolving dynamics of cities, which is influenced by historical, economic, and environmental factors, and can be considered as an integrated socio-ecological-technological indicator of urban systems [127,128]. Currently, research on the urban form is mainly devoted to solving urban microclimate problems [129,130], heat island effect [131,132], particulate matter [93,133], building wind environment [134], traffic [135], and other urban problems. They tend to quantitatively analyze urban spatial morphology based on different scales, using specific metrics to evaluate urban form to assess the impact of urban spatial morphology on urban problems [135–137]. Su et al. (2021) quantified macro-scale indicators of urban form using four dimensions (e.g., compactness) and analyzed the effects of urban form on surface temperature [138]. Makido et al. (2012) measured the relationship between urban form and CO2 emissions in 50 Japanese cities using the urban form indicator [139]. Currently, there are very few studies that examine the structure of UGS based on urban form (Grafius et al., 2018; Nor et al., 2017; Xu et al., 2018). Limited studies have discussed the relationship between the influence of city shape on the equality of UGS based on one or two dimensions. Xu et al. (2018) used cellular automata to compare the effects of compactness and centrality of different "predicted cities" on the inequality of UGSs separately. Wang et al. (2019) found a significant effect of building structures and configurations on the equal distribution of green infrastructure (GI) by comparing three types of residential areas with different building structures based on the neighborhood scale. However, UGS is influenced not only by urban policies, but also by urban building structures and spatial form [125,140,141]. The distribution, density, and quantity of buildings and land use in cities determine to some extent the spatial pattern of UGS and thus affect its quantity and

quality [142,143]. Therefore, a discussion on the equitable distribution of UGS based on urban spatial morphology is essential and will help to promote a fairer and more sustainable urban planning strategy.

Unfortunately, we still lack relevant knowledge about spatial form and UGS inequality in shrinking cities [144,145]. Therefore, in the process of spatial adjustment in shrinking cities, the distribution of urban resources should be constantly reviewed to ensure the sustainability and socially equitable development of cities [100].

1.4.2 UGS spatial morphological patterns as drivers of UGS inequality

Numerous studies have found that resident exposure to UGS is directly related to the number and distribution of UGS [123,146,147]. Moreover, different types of UGSs showed different patterns of equitable distribution [73]. While these studies provide indirect evidence of the close relationship between UGS structure and its equitable distribution, they all do not take into account the UGS structure itself.

Various methodologies and tools have evolved within urban ecology to analyze spatial configurations, illuminating the relationship between UGS spatial patterns [148–150]. These include analytical techniques like FRAGSTATS [151–153], which employs a variety of landscape indicators such as area/density, the patch shape index, and proximity metrics. These indicators are instrumental in evaluating landscape patterns' urbanization gradient [153] and in assessing strategies for biodiversity preservation [149]. Additionally, other metrics like least cost paths [154] and genetic algorithms help in adopting a more

ecologically sensitive approach to spatial pattern assessment [155–157]. Researchers have discussed the impact of UGS structure on urban sustainability from various perspectives, such as temperature [158,159], pollutants [160], and mental health [161]. However, there is still a lack of sufficient evidence regarding the spatial structure and distribution of UGS itself in relation to the equality of UGS. Guan et al. (2023) calculates five landscape metrics for exploring the relationship between the spatial structure of UGS and the equitable distribution of UGS, and finds that UGS density, shape, and maximum patch size had a positive effect on the UGS inequality [115]. However, these landscape metrics describe the structure of the UGS relatively abstractly based on the magnitude of the values and cannot visualize the spatial structure of the UGS, thus making it difficult to visually understand.

Furthermore, graph-based methods are also prominent, including tools like Conefor Sensinode [162], which assesses habitat patch connectivity by evaluating nodes, links, and graph-specific metrics such as the number of links, number of components, and the integral index of connectivity. Similarly, the Circuitscape tool is employed to compute and visualize resistance, conductance, current flows, and voltage across landscapes [163]. While these tools are essential for examining structural landscape metrics and connectivity, they rely heavily on graph, network, and circuit theories and face limitations due to the variability in human interpretations of results [164].

To make it easier for professionals to understand the spatial structure of the UGS, Vogt et al., (2007) have developed a Morphological Spatial Pattern Analysis (MSPA) based on picturization [165]. MSPA has proven to be an effective method for identifying and

measuring the structure of UGSs at different scales [165,166]. MSPA is a visual analysis method based on mathematical morphology that applies a series of morphological operators to depict the skeleton of an object [167]. It classifies individual pixels into seven classes through binary patterns: cores, edges, islets, loops, bridges, perforations, and branches [166]. The seven classes can be used to represent seven structures of UGSs, which together form the complete UGS. This classification facilitates a deeper exploration of UGS in diverse urban settings, enabling the identification and quantification of various spatial patterns and distinguishing functional connectivity roles, like bridges for species dispersal [168,169]. MSPA has been predominantly utilized within forested landscapes to identify ecological connectors [170,171], analyze forest structure and composition [172], prioritize sites for ecological restoration [173], and delineate riparian corridors for conservation and management [174]. Currently, researchers have discussed the impact of UGS structure on urban sustainability through MSPA, such as heat islands [175] and particulate matter [176]. Regarding UGS inequality, Wang et al. (2019) have tentatively speculated that at the community level there is a correlation between MSPA bridges and the inequality distribution of GI [141]. However, it is still not possible to determine the impact of the remaining MSPA classes on the inequality of GI, as this study only compared the equality index of GI among three settlement types and by MSPA class ratios. Exploring UGS inequality using MSPA helps reveal the relationship between UGS inequality distribution and morphology to help planners understand the layout more effectively of UGS patterns. Compared with FRAGSTATS, which synthetically describes the morphology of UGSs through landscape indicators, MSPA distinguishes the structure of UGSs more intuitively, because MSPA can easily describe the structure of UGSs in specific spatial locations [176]. This has helped researchers

propose effective spatial strategies based on the corresponding characteristics of the structure classes of MSPA [176].

1.4.3 UGS quality and demographic preferences as drivers of UGS inequality

From a population perspective, rapid demographic change reshapes the demand for and use of UGSs. Rapidly changing urban populations can lead to rapidly changing supply and demand pressures and demand patterns for UGSs over time [120,177]. Different areas may face different challenges and needs depending on their demographic dynamics. Influenced by urban renewal and planning policy factors, parts of the city may experience rapid population growth, which may trigger a shortage of UGS supply and demand [122]. In contrast, those areas experiencing population loss face the challenge of adjusting UGS size and function to accommodate the decline in UGS users [96,178]. Therefore, demographic changes within urban areas further exacerbate the complexity of planning for equality in UGSs.

In the case of UGSs, the service capacity of a UGS depends not only on its size but also on the environmental amenities within the UGS [68,179]. High-quality UGSs are more likely to encourage residents to exercise and are associated with better resident well-being [180,181]. On the demand side, different UGSs are not similarly attractive to residents, who prefer to visit UGSs with suitable environments and larger areas; thus, there is competition between UGSs [182]. However, demographic differences between regions may lead to differences in UGS demand and use patterns, which can affect their levels of physical activity and frequency of use [183,184]. For example, shade and trails in

UGSs are important activity factors for older adults [185], whereas playgrounds promote physical activity among children [186]. Furthermore, there are significant gaps in the travel ability of different population subgroups. Older adults and children are less able to walk than adults [187,188], making it more difficult for them to reach UGSs [189,190].

To better explore UGS inequality, Researchers have developed various spatial measurement models to assess the accessibility of urban services (e.g., medical facilities and UGSs). The container method is the original accessibility model used to measure the number of accessible service facilities within a given geographic unit (e.g., a census tract) [191,192]. However, the container method creates the problem of impermeable boundaries and modifiable area units [193,194]. The measurements change with the spatial scale of the geographical unit. Meanwhile, residents do not typically consider geographic unit boundaries as barriers to accessing service facilities. To address these issues of the container method, the spatial proximity method can be utilized [195]. For example, the Tyson polygon approach divides polygonal service areas centered on population points to determine the distance of each population point from the nearest service facility [36,42]. However, residents do not always choose UGSs closest to their homes as destinations. The floating catchment area (FCA) method measures the number of residents and services covered within a catchment area at a specific distance and calculates the ratio of services accessible within the area [196,197]. However, the FCA method assumes that all facilities within a catchment exclusively serve the residents within that catchment, without considering the possibility of facilities also serving residents in other catchments [198]. In other words, if two catchments overlap in the same

UGS, the UGS needs to serve the residents of both catchments A and B. Therefore, the FCA method may double-count a UGS's service capacity because it does not consider another catchment’s use of the UGS when calculating for one catchment.

Luo and Wang (2003) proposed the 2SFCA method, which further addresses the limitations of the spatial proximity method and has gained wide recognition [198]. The 2SFCA method is a dichotomous technique based on a gravity model that considers the interaction between supply and demand [198]. Although the traditional 2SFCA method can quickly identify underserved areas, it has certain limitations. Recently, researchers have proposed improvement strategies from different perspectives to optimize the traditional 2SFCA method.

Initially, researchers optimized the distance decay in the 2SFCA method by dividing the catchment area into multiple travel time zones and setting the corresponding allocation weights, arguing that the closer the service facility, the easier it is to obtain [199]. Dai (2010) introduced a distance decay function (Gaussian function) to adjust the distance decay effect in a catchment area using the traditional 2SFCA method, achieving continuous decay without dividing the catchment. Subsequently, other researchers attempted to understand residents’ multimodal travel patterns. For example, Mao and Nekorchuk (2013) weighted different travel modes to measure the accessibility of medical facilities between block groups, reducing the estimation error of traffic heterogeneity and homogeneity on accessibility [200]. Liang et al. (2023) compared the differences in the supply and demand of UGS accessibility for residents under four

modes of transportation using a modified 2SFCA method [201].

Additionally, some researchers have considered supply and demand improvements. From the facility supply capacity perspective, Dony et al. (2015) quantified UGS attractiveness factors based on UGS size and the number of facilities to create catchment areas of different sizes [193]. Zhang et al. (2022) considered the quality of UGS environment facilities from multiple dimensions to accurately quantify UGS attractiveness [179]. From the resident demand perspective, Luo (2014) introduced the Huff model into the 2SFCA (Huff-2SFCA) method by calculating the probability of residents' choice of medical points, in order to consider the competition between different medical points [202].

Despite the obvious correlation between demographic change and UGS accessibility, the existing literature lacks a comprehensive analysis, particularly since differences in UGS demand and usage patterns resulting from population structure between urban areas have not been carefully considered. Past studies have attempted to use the 2SFCA method to understand UGS accessibility for specific populations, although some limitations remain [100,182,203,204]. Few studies have measured UGS accessibility using Supply and Demand Improvement 2SFCA (SD-2SFCA), which considers the attractiveness of UGS quality and resident choices [182]. However, these methods have not been fully adapted to the structural differences under demographic change; they do not consider the preferences of different population groups for UGS environment amenities and gaps in travel ability. Second, previous studies have typically calculated UGS supply–demand ratios using only specific population statistics, clearly overestimating

each UGS's supply–demand capacity. Because UGSs are open to all populations and do not exclusively serve specific populations, using only specific population data ignores the crowding out of UGS services by other populations. Therefore, there is an urgent need for an accessibility indicator that can consider the population's demographic structure to adapt to the context of demographic change. Moreover, new methods are utilized to explore how differences in UGS environmental facilities and demographics affect UGS inequality.

2. Research purposes

The purpose of this study is to examine trends in urban UGS inequality in Japan in the context of long-term demographic change, and to explore measures and methods for realizing UGS equity planning in this context. Specifically, based on the gaps in previous research, I propose the following research questions:

1) What is the trend of UGS inequality at the municipality level in Japan over the period 2000-2020?

2) From the urban dimension, is there a correlation between urban form and UGS inequality?

3) From the neighborhood dimension, is there a correlation between the spatial form pattern of UGS and UGS inequality?

4) From the population dimension, is there a correlation between UGS environmental facilities and demographics and UGS inequality?

5) Can a new framework and methodology be developed to measure UGS inequality in the context of demographic change?

To respond to the above research questions, I first explore trends in UGS inequality at the municipality level in Japan from 2000 to 2020, and explore differences in urban UGS inequality across geographic regions and city sizes. Based on the results of the first study, I further explore the relationship between UGS inequality and urban form as well as UGS spatial pattern, focusing on cities with declining populations. Finally, I propose a new method for measuring UGS inequality to accommodate future demographic changes. Based on the new method, I also explore how differences in UGS environmental facilities, residents' preferences, and travel ability affect UGS inequality.

3. Innovative points of the research

For the first time, this study considers the various drivers of inequality UGS inequality in terms of the urban dimension, the neighborhood dimension, and the population dimension. Considering the gaps in previous research, the innovations of this study are specifically characterized by the following four points:

1) It provides long-term evidence of UGS inequality in Japanese municipalities.

2) Identifies the relationship between UGS inequality and urban form from an urban dimension.

3) Identifies the relationship between UGS inequality and UGS spatial form patterns from the neighborhood dimension.

4) Clarified the relationship between UGS inequality and UGS environmental facilities and demographics in terms of the population dimension.

5) Developed a new methodology and framework for measuring UGS inequality in the

context of demographic change.

4. Definition of terms

UGS: For the purposes of this study, unless otherwise specified, UGS usually refers to land and wetlands in urban areas that contain a variety of vegetation cover [205]. Only in Chapter V of this thesis, I use a narrower definition of UGS, i.e., urban parks, because of the high degree of urbanization of the subject site.

UGS inequality: In this study, the UGS inequality I refer to is spatial inequality of UGSs. Spatial inequality of UGS focuses on the disparities in the distribution of UGS resources or services among all residents, regardless of their socioeconomic status and conditions [206]. It advocates for equal treatment of the entire population, with geographic units having larger populations receiving more UGS resources and services.

I measure spatial inequality of UGS in two parts: UGS area inequality and UGS service inequality. First, in chapters II to IV, I measure the differences in UGS area around residential areas. By creating 500-meter Euclidean distance buffers around each residential point and calculating the UGS area within these buffers, I evaluate the area inequality of UGS among different residential areas within the city. This part of the study focuses more on the passive values provided by UGS, such as cooling effects and reduction of PM2.5, which can impact residents' health and well-being without direct interaction [6]. Thus, in these chapters, UGS area inequality measures differences in how residents are subliminally benefited by nearby UGSs.

However, the spatial inequality of UGS is influenced not only by area but also by environmental quality [193]. In chapter V, I incorporate the environmental facility quality of the UGS into the measurement model by examining differences in the services provided by the UGS environmental facilities around the residence. By measuring the 15-minute walking network distance to UGS for residents, I calculate the relationship between population demand at each residential point and the UGS service supply considering environmental facilities quality, thereby assessing the service inequality of UGS within the city. This part of the study focuses more on the active values provided by UGS, such as opportunities for exercise, aesthetic enjoyment, and learning that residents obtain by actively entering UGS [6].

Shrinking cities: Although the definition of shrinking cities may vary in the literature, it commonly applies to cities experiencing population decline [207]. Many scholars have extensively studied the changes in urban populations, the underlying reasons, and the impact of these changes on urban environments. Historical research indicates that factors leading to urban shrinkage include changes in industrial structure, suburbanization, an aging population, declining birth rates, changes in socialist regimes, natural disasters, and climate change.

Urban form**:** Urban form evolves over a long period of time, through the combined effects of urban topography, economy, and population [208]. Urban form, in this study, follows the broadest definition that encompasses the physical structure, size, and population distribution developed during urban development [209]. Referring to previous

studies, I used different landscape metrics based on remotely sensed imagery and demographic indicators to measure the physical form of the city [209,210].

Spatial morphological pattern of UGS: Landscape spatial pattern refers to the spatial arrangement and combination of landscapes of different sizes and shapes, including the type, number, spatial distribution, and arrangement of landscape elemental components, e.g., different types of patches can be spatially expressed as random, homogeneous, or stochastic distribution. It is a specific manifestation of landscape heterogeneity and the result of various ecological processes operating at different scales [211]. The spatial configuration of UGS in this thesis refers to the arrangement and combination of UGS in patches of different shapes and sizes. Understanding the correlation between the spatial pattern of UGS and the UGS inequality can help to understand the impact of UGS spatial structure on the UGS inequality.

5. Methodology and structure

5.1 Research methodology

This research uses multiple methods, and the specific application methods are as follows.

1) Literature survey method

First, a comprehensive review of the existing literature was conducted to identify gaps in current research in the field and to lay the groundwork for specific directions and

priorities for this study.

2) Geospatial Analysis

For the geospatial analysis component, I employ both ArcGIS and Python as the primary tools to conduct a comprehensive suite of geospatial processing and analyses. This includes, but is not limited to, overlay analysis, buffer analysis, and origin-destination (OD) analysis. Leveraging these tools, I can facilitate the efficient processing and analysis of vast quantities of geospatial data, thereby uncovering patterns and insights that are pivotal to the study's objectives.

3) Gini coefficient analysis

The Gini coefficient was initially used as an indicator for calculating income inequality, and has since been widely used to measure inequality in environmental exposure and resource allocation [212,213]. For example, Druckman and Jackson (2008) improved upon the traditional Gini coefficient to estimate regional inequality in resource allocation [214]. Boyce et al. (2016) used the Gini coefficient to measure the environmental inequality of industrial air pollution in all 50 states of the United States [215]. Additionally, some studies have introduced the Gini coefficient into the measurement of health well-being risks, to determine the health inequality among residents in a certain area [216]. In terms of measuring UGS inequality, previous studies have widely demonstrated the effectiveness of the Gini coefficient. Researchers use the Gini coefficient to measure the differences in UGS area, service capacity, or ecosystem service value between neighborhoods, thereby judging the inequality of UGS access among residents [147,182,217,218]. Briefly, the Gini coefficient is the proportion of the area between the line of absolute equality and

the observed Lorenz curve to the area between the line of absolute equality and the line of absolute inequality [219]. The Gini coefficient ranges from 0 to 1. A larger value indicates a more inequitable distribution of UGS.

4) Statistical analysis

This study adopts a multiple approach to statistical analysis, leveraging a diverse array of techniques to meticulously examine the preliminary data gathered. Among these methods are non-parametric tests and regression analysis, each chosen for its specific suitability to the data and research questions at hand. Given the variety of statistical methods applied across different chapters, I ensure a thorough exposition of the respective analytical techniques in their corresponding sections. This structured approach allows for a nuanced understanding of the data, facilitating a comprehensive exploration of the study's findings.

5) Composite Analysis Methods

In addition to the primary analytical approaches, this study incorporates a range of composite analysis methods to further enrich this research. Notably, I utilize MSPA and the 2SFCA method among others. These techniques play a critical role in supplementing the research content across various chapters. For instance, MSPA is instrumental in quantifying the spatial morphological patterns of UGS, providing deeper insights into their distribution and characteristics. Detailed discussions and summaries of these methods are provided in the relevant chapters, offering a comprehensive overview of the analytical framework.

5.2 Study composition

The thesis is divided into four parts: theoretical study, empirical study, synthesis and discussion, and conclusion (Fig. 1.1).

Chapter I, Theoretical Research, introduces the current situation and new challenges facing UGS, as well as the dilemmas and opportunities of inequality in UGS in the context of demographic change (focusing on population decline), thus presenting the purpose of this study. Based on the summarization and review of previous studies, the current research gaps are presented and the research questions and innovations that are the specific focus of this study are presented.

The main body of the dissertation consists of the empirical research sections in Chapters II through V, which are divided into two areas: the first measures the long-term trend of UGS exposure to inequality (Chapter II); while the second explores the relationship between UGS inequality and various drivers (Chapters III–V).

First, In Chapter II, the Gini coefficient is used to reveal the long-term trend of inequality in the exposure of UGS at the level of Japanese municipalities in the context of demographic change, as well as the differences in inequality across geographic regions and city sizes. Based on this, I focus attention on cities with declining populations. Thus, Chapter III explores the relationship between UGS inequality and urban form in shrinking cities from the urban dimension. Chapter IV considers the correlation between the degree of UGS inequality and the pattern of UGS spatial form

from the neighborhood dimension. In Chapter V, I introduce a new approach. Through a case study, I use this method to investigate UGS inequality under the influence of population structures and UGS environmental facilities.

Chapter VI is the synthesis, which first summarizes the results of the empirical study and then further discusses strategies for mitigating UGS inequality in the context of demographic change based on the contextual policies of Japanese cities.

Chapter VII is the conclusion, which summarizes the full paper and presents the limitations of this study and directions for future research.

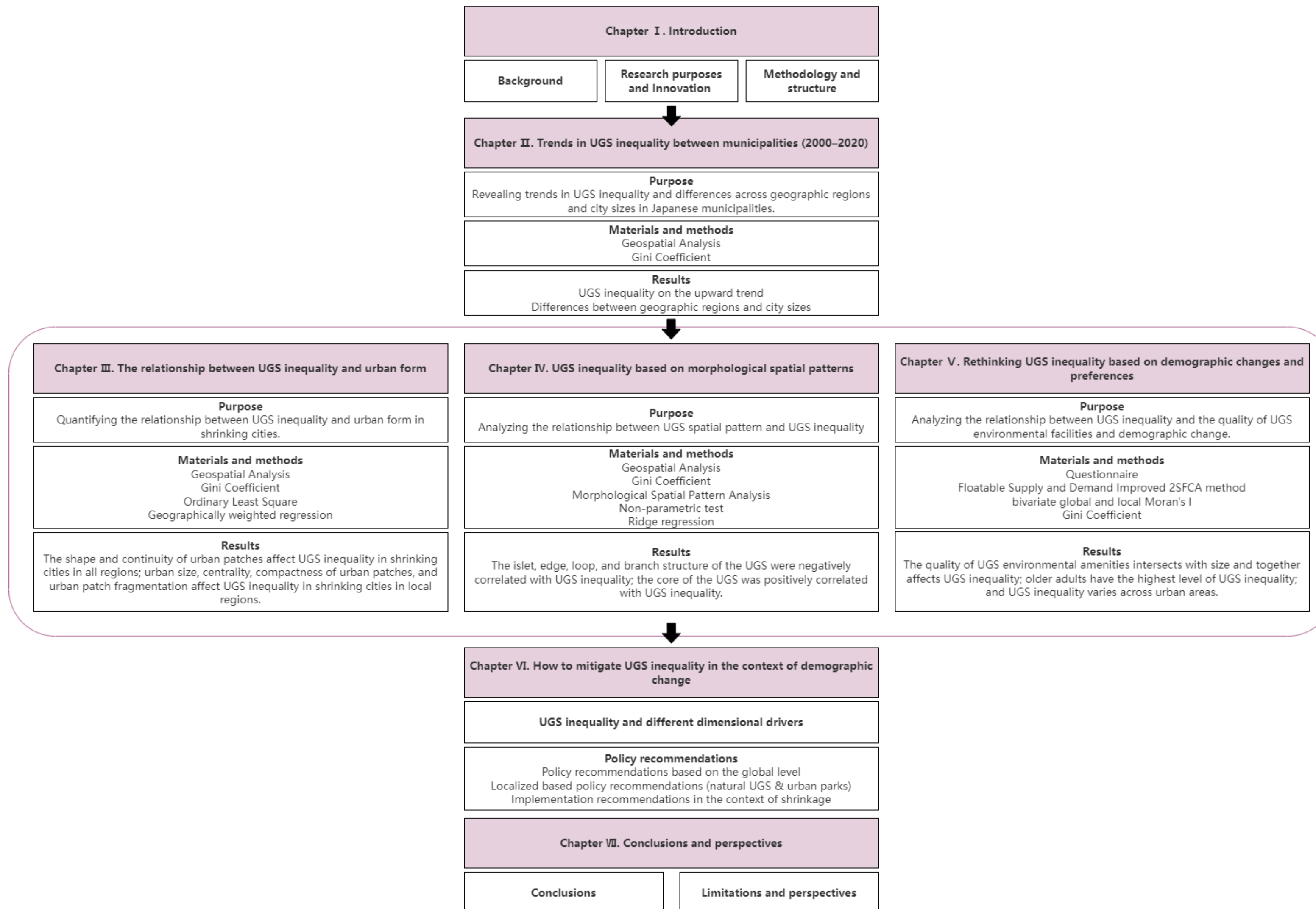

Fig. 1.1 Research framework

Chapter II. Trends in UGS inequality between municipalities (2000–2020)

1. Purpose of this chapter

I quantified the UGS inequality around residences at the municipal level in Japan from 2000 to 2020 in a longitudinal perspective to reveal the trend of UGS inequality around residences at the municipal level in Japan as well as the differences among geographic regions and city sizes. Specifically, the objectives of the chapter were to 1) explore trends in UGS inequality at the municipality level, 2) explore regional differences in UGS inequality at the municipality level, and 3) explore differences in UGS inequality at the municipality level across city sizes.

I obtained land cover land use (LULC) maps and population grid datasets for 2000, 2010, and 2020. Second, I quantified the UGS area within a 500-meter buffer zone around each population grid in Japanese municipalities. Finally, I use the Gini coefficient to quantify UGS exposure inequality, comparing the differences in UGS exposure inequality between municipalities of different city sizes and geographic regions.

2. Materials and methods

2.1 Study area

Japan is one of the most urbanized countries in the world. As of 2020, 91.8 % of the population lived in urban areas [220]. Japan comprises 47 prefectures with several municipalities in each prefecture serving as local self-governments. Japan is usually divided into seven geographical regions: Hokkaido, Tohoku, Kanto, Chubu, Kansai, Chugoku & Shikoku, and Kyushu & Okinawa (Fig. 2.1). Municipalities are divided, based on population size, into metropolitan cities (ordinance-designated cities and special districts), mid-sized cities (populations >100,000), small cities (populations <100,000), and towns/villages (towns and villages) [221]. These municipalities are not different in essence as they are the most basic local self-government in Japan [222]. In the 21st century, Japan implemented a policy of urban consolidation, and the number of municipalities in Japan gradually decreased. In 2000, there were 3252 municipalities, which shrank to 1750 municipalities by 2010, and further decreased to 1741 municipalities by 2020 (excluding the northern region).

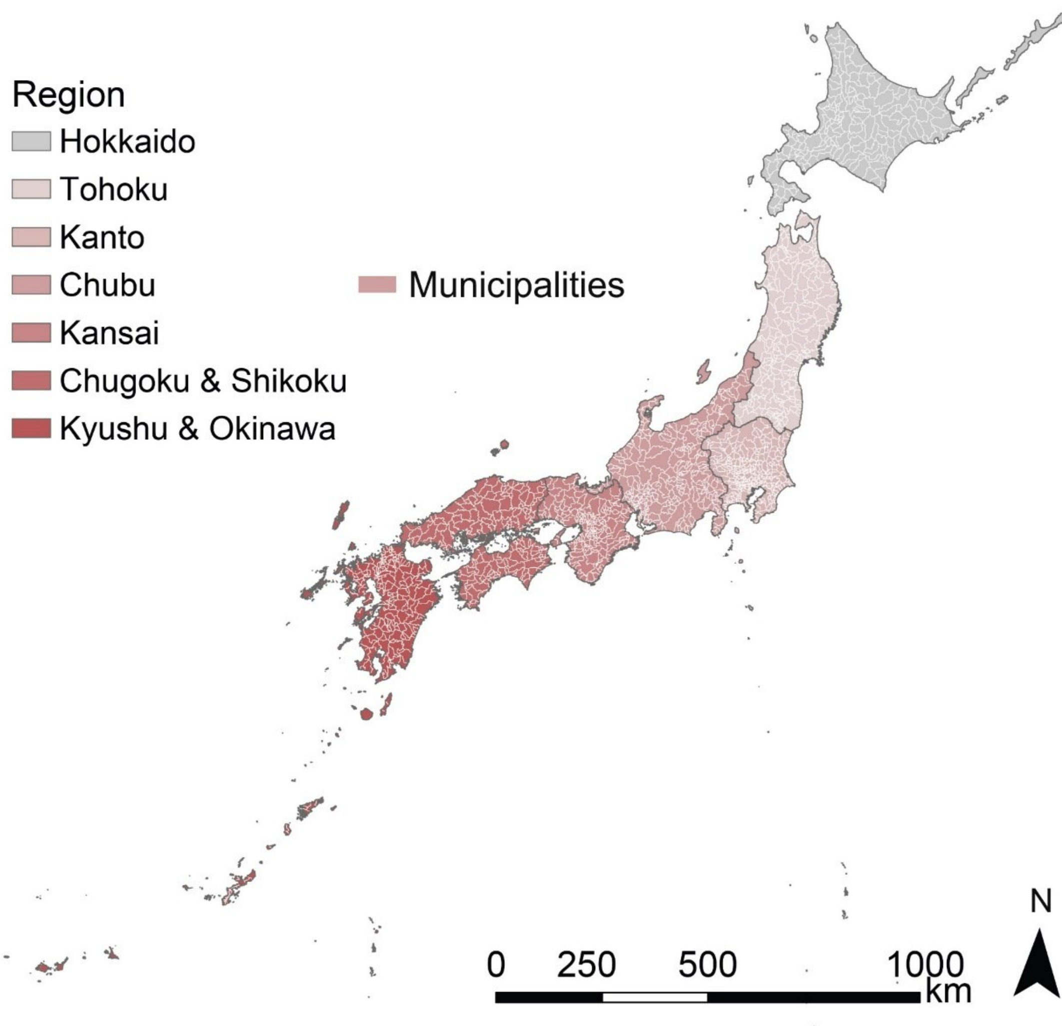

Fig. 2.1 Study area, Japan

2.2 Measuring changes in UGS inequality

I first acquired global land cover maps (GLC_FCS30) at 30-meter resolution for the years 2000, 2010, and 2020 [223]. GLC_FCS30 is the currently available high-resolution land cover data and contains 29 land cover classes. In this study, UGS is defined as all land covered by vegetation and wetlands in urban areas [205]. Second, I used the 2000, 2010, and 2020 census dataset (500m) (https://www.e-stat.go.jp/), which is the highest fine-grained authoritative population aggregation data currently available originating

from Statistical Bureau of Japan.

In this study, I used the Gini coefficient to measure the degree of inequality in per capita UGS area across all population grids within a city. In this chapter, UGS inequality is expressed as UGS area inequality, which measures the subliminal benefits provided by the UGS, services that can be enjoyed passively without the need for residents to visit. The expression of the Gini coefficient can be realized by the construction of a Lorenz curve, where the vertical axis represents the cumulative share of the cumulative urban UGS exposure area, and the horizontal axis reflects the cumulative share of the population from the lowest UGS exposure to the highest UGS exposure. The coefficient is calculated based on the ratio between the Lorenz curve and the area between the lines of absolute equality and the area between the lines of absolute equality and the line of absolute inequality (Fig.2.2). The Gini coefficient ranges from 0 to 1. As inequality worsens, the value of the Gini coefficient increases. The specific formula for calculation is:

$$Gini = 1 - \sum_{i=1}^{n} \frac{P_i}{P} (\alpha_{i-1} + \alpha_i) \qquad (2–1)$$

where $Gini$ is the Gini coefficient of UGS exposure at the municipality level; P represents the total population within the municipality; P_i is the population size of grid i; and α_i is the percentage of UGS exposure area accumulated by population grid i.

Based on the quintile rule of the Gini coefficient [224], the Gini coefficients representing UGS inequality were divided into five classes: perfect equality (0.000–0.200), relative equality (0.201–0.400), relative inequality (0.401–0.600), inequality (0.601–0.800), and

extremely inequality (0.801–1.000). In general, most studies consider that the threshold for the Gini coefficient is set at 0.4. A Gini coefficient above 0.4 is usually considered unacceptable and indicates significant inequality [225–227]. In the field of environment and urban planning, a Gini coefficient above 0.4 usually indicates significant inequality in the distribution of resources [225]. Such inequality may result in some communities enjoying abundant UGS, clean air and a good living environment, while others face scarcity of resources, high levels of pollution and poor quality of life.

In this study, a 500-meter buffer zone was set to measure the area of UGS to which residents are exposed in their daily lives. A buffer distance of 500-meter has been emphasized in a large number of studies to be effective in predicting the impact of UGS exposure on human health through reduction of air pollutants, cooling, and stress recovery [228–231]. For example, Chen et al., (2019) found that the UGS size was associated with a reduction in the concentration of PM2.5 and the effect was most pronounced in the range of 400-500m [232]. Some studies have found that the maximum range of the cooling effect of UGS is around 500 to 600m [233,234]. Benefiting from the ESs provided by the UGS, the UGS reduces the resident's reduced risk of disease and mortality [235,236]. Many experts and governments have recommended that residents have access to UGS within 300–500 m of their homes [147,237–239]. For example, the city of Berlin recommends that residents have at least 0.5 ha of UGS within 500 m of a residential area [237]. Kabisch et al. (2016) have measured UGS availability in European cities using 300 m and 500 m buffers [238].

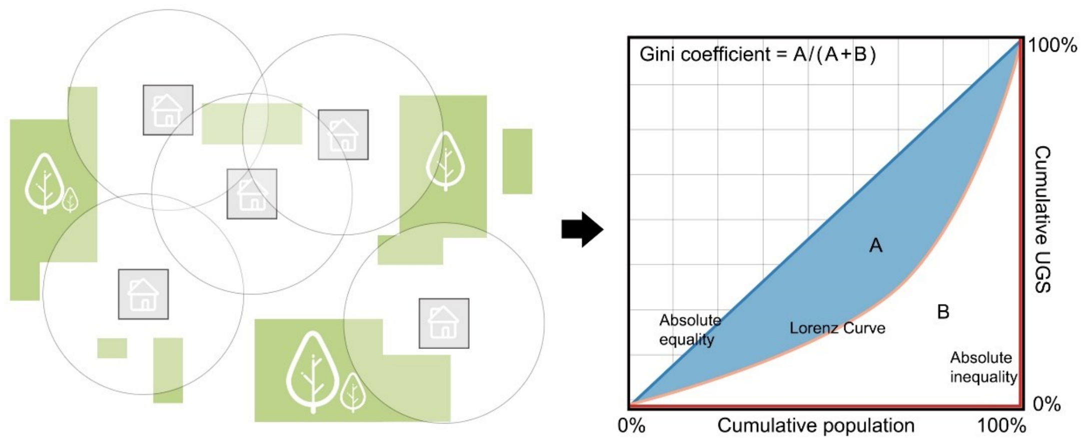

Fig. 2.2. Illustration of calculating UGS inequality

Changes in urban UGS inequality at the municipality level were obtained by calculating the amount of change in the Gini coefficient within a given year interval. I calculated the change in UGS inequality for the years 2000–2010 and 2010–2020. Positive values imply a worsening trend in UGS inequality at the municipality level within a given year interval, and negative values imply an improving trend in UGS inequality at the unequal municipality level.

3. Results: UGS inequality trends

I used the Gini coefficient to calculate UGS inequality at the municipality level in Japan. The results showed that the Gini coefficient at the municipality level in Japan showed an increasing trend between 2000 and 2020 (Fig. 2.3). The mean value of the Gini coefficient for municipality was 0.528±0.128 in 2000, which rose to 0.685±0.108 in 2010 and further to 0.698±0.107 in 2020. The proportion of municipalities with a

Gini coefficient greater than 0.4 rises from 83.4% in 2000 to 98.7% in 2010 and 98.8% in 2020.

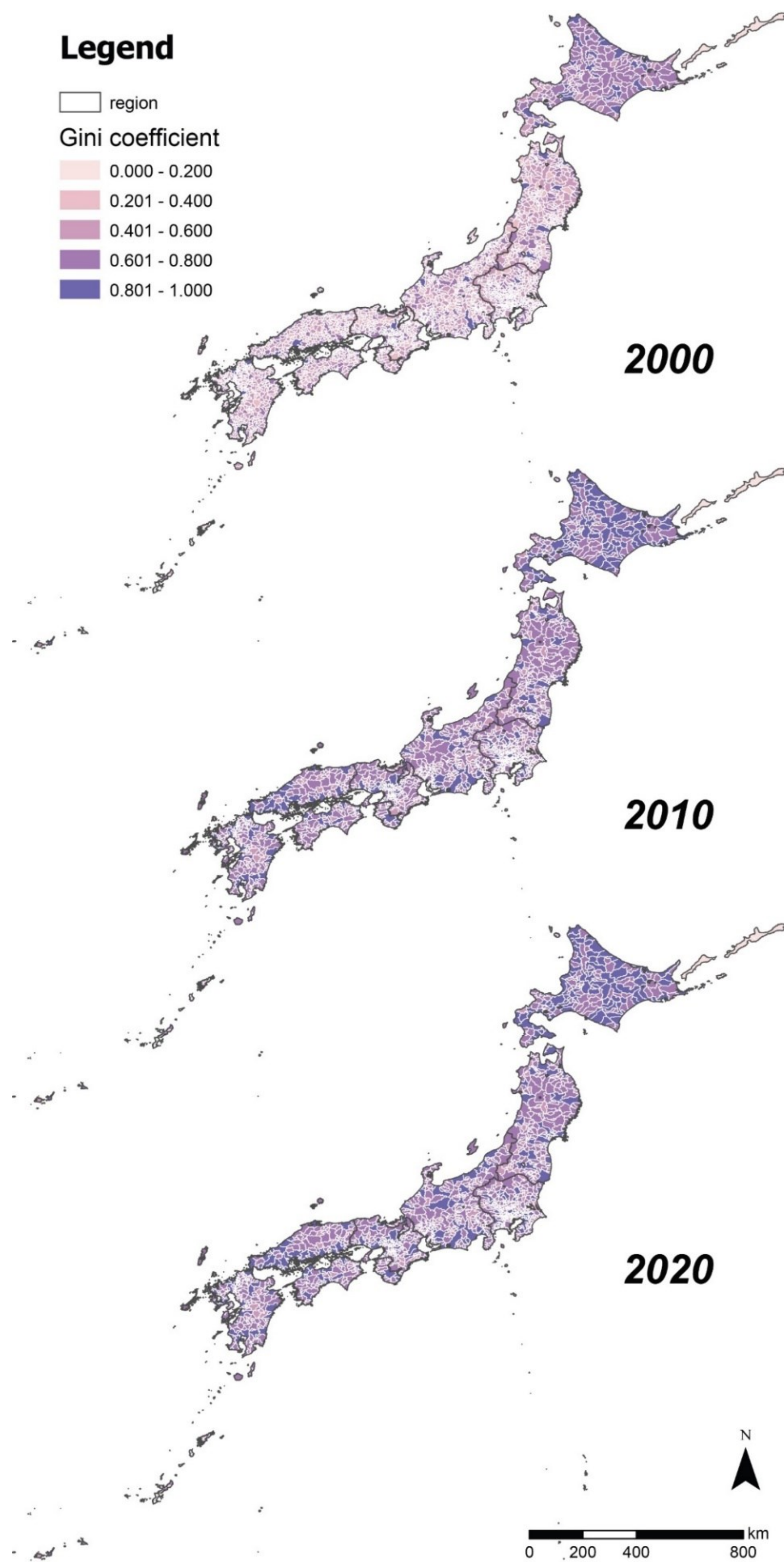

Fig. 2.3 Trends in UGS inequality at the municipality level

Further, I analyzed the differences in UGS inequality at the municipality level among different regional groups (Fig. 2.4), where the Gini coefficients were significantly different among different regional groups. I found that UGS inequality at the municipality level in all regions showed an increasing trend. Among them, UGS exposure inequality is consistently the worst in the Hokkaido region. The Tohoku region had the lowest UGS inequality at the municipality level in 2000 (Mean: 0.496 ± 0.119); the Kanto region had the lowest UGS inequality in 2010 and 2020 (2010: 0.661 ± 0.118; 2020: 0.674 ± 0.116). However, the Gini coefficients of the municipalities in the Kanto region are the most discrete, with the largest interquartile range (IQR) in all years.

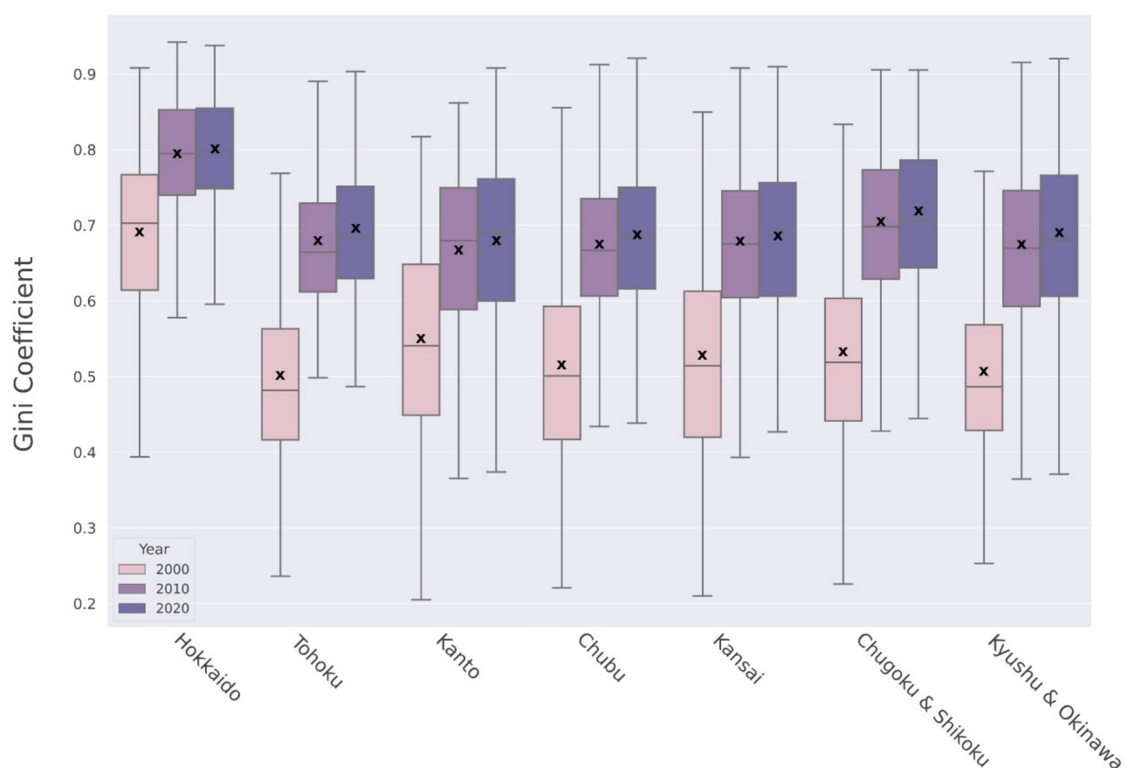

Fig. 2.4 UGS inequality box plots for different regional groups

Finally, I also compared the differences in the Gini coefficients of municipalities between different city size groups. The results show that there are significant differences in the Gini coefficients of municipalities between different city size groups (Fig. 2.5). In particular, the UGS inequality is the lowest for municipalities in the town/village group, while it is the highest for the mid-sized city group. Nonetheless, the municipalities in the town/village group had the most significant increase over the 20-year period, with a 34.4% increase in their mean value. In addition, the IQR of the Gini coefficient for the metropolitan group is the largest, implying that differences in the degree of UGS inequality are most pronounced within the metropolitan group. However, the Gini coefficients of the municipalities in the metropolitan group did not change much in the first two decades of the twentieth century, with their mean value rising by only 9.1 %.

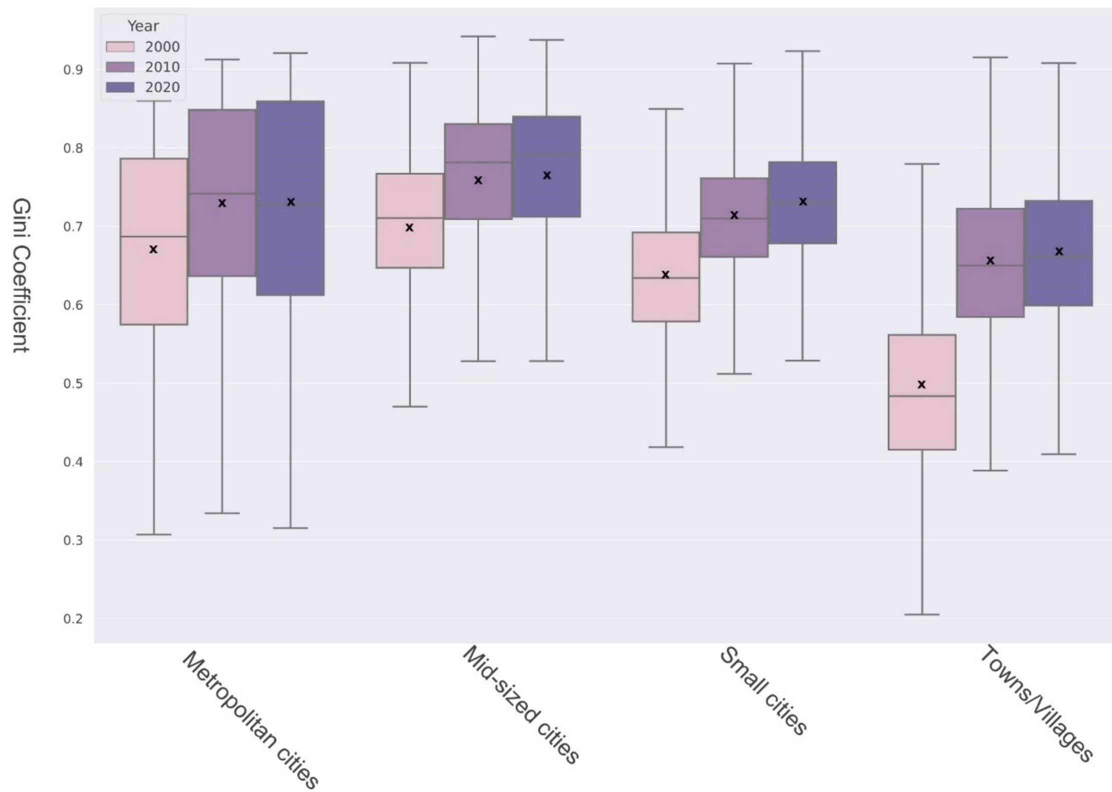

Fig. 2.5 UGS inequality box plots for different city size groups

4. Discussion:

4.1 Trends and differences in UGS inequality

The results find that UGS inequality at the municipality level in Japan shows a significant upward trend over the 20-year period, but the growth rate all slowed down between 2010 and 2020. This change may be related to the interaction of urbanization process and population dynamics. During the early decade of the 21st century, Japan rapidly moved into urbanization, with its urbanization rate increasing by 12.3% [220]. Urban expansion during this period brought many fragmented residential patches to the periphery of the city, providing more opportunities for people living nearby to approach

natural UGSs [121]. Residents within urban centers have difficulty accessing these UGSs, thus exacerbating the growth of UGS inequality. Japan's population declined after peaking in 2008, triggering a government policy to promote a “compact city” model, which aims to maintain the density of urban areas by reducing the number of residences [240]. This strategy has prompted residents to migrate to more centralized inner-city areas, slowing the expansion of the urban periphery. Between 2010 and 2020, the growth of Japan's urbanization rate slows down, increasing by only 0.8 % [220]. In addition, the inward contraction of the population increases the efficiency of UGS utilization within cities, thus mitigating the worsening of UGS inequality (Fig. 2.6).

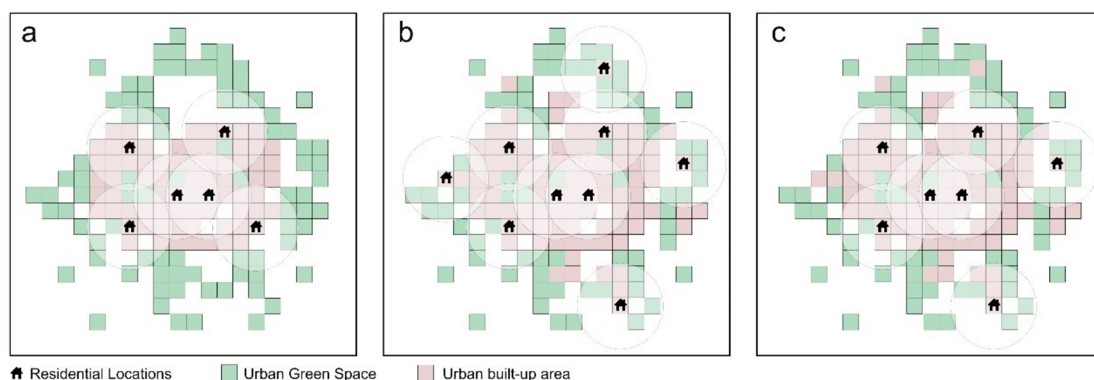

Fig. 2.6 Schematic representation of inequitable ecosystem services caused by urban sprawl. a) Before urban sprawl; b) After urban sprawl; b) Implementing compact cities.

When analyzing UGS inequality in different city size groups in Japan, mid-sized cities showed the most significant inequality. Typically, UGS inequality in cities is mainly caused by unequal access to green environments for residents due to differences in urban gradients [121,217]. Compared to mid-sized cities, metropolitan cities pay more attention to the planning and construction of urban infrastructure. Data from the Statistical Bureau of Japan show that the average area of parks built in metropolitan

cities is approximately four times larger than that of mid-sized cities [241]. When comparing small cities and town/village group municipalities, mid-sized cities usually lack sufficient natural UGS to fill urban areas.

Over the two decades from 2000 to 2020, UGS inequality among municipalities in the town/village group has worsened; in contrast, the trend is less pronounced in the metropolitan group. In Japan, metropolitan areas usually control urbanization more strictly by establishing “Urbanization Control Areas” to control urban sprawl (Fig. 2.7). In contrast, municipalities in the town/village group do not impose similarly stringent restrictions [242]. As a result, the development of small cities has tended to spread out in a more haphazard manner than that of metropolitan cities. In addition, population decline and the siphoning effect of metropolitan areas in Japan have further exacerbated the differences in population change among cities of different sizes [243].Metropolitan cities have maintained their intra-city population densities through compact city development strategies, whereas small cities have experienced a constant loss of population. Population decline has further led to residential segregation of residents of peripheral urban areas from those of central areas. For example, the Hokkaido region, which is dominated by small cities and towns/villages (about 95%), faces very serious UGS inequality. Compared to other regions, low-density urban development in the Hokkaido region has led to dispersed residences and thus exacerbated the risk of residential segregation [244,245]. Landscape heterogeneity around segregated residences may have contributed to UGS inequality.

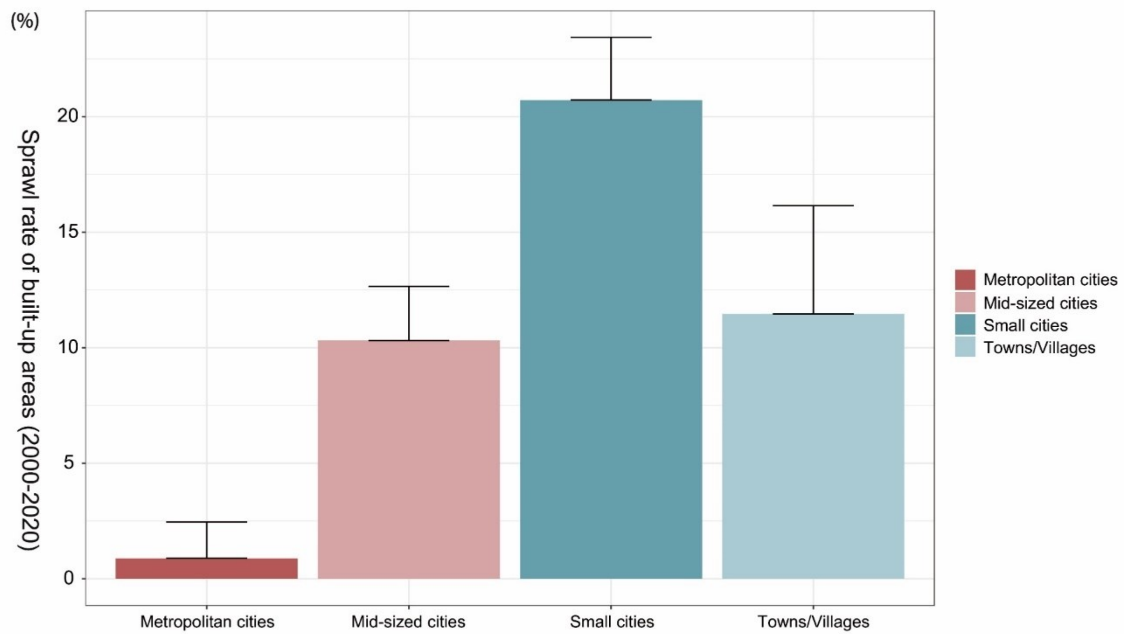

Fig. 2.7 Mean values of built-up area sprawl rates at the municipality level between different city size groups (2000.2020)

4.2 Limitations and future directions

This study has some limitations. 500-meter population grid data and 30-meter resolution GLC_FCS30 were selected for analysis in this study. Although we have screened and compared data from multiple sources and are confident that the selected dataset (2000–2020) is currently the most reliable, potential measurement errors may still arise, including scale effects and the absence of small UGSs (<0.09 ha). This is an unavoidable bias in a wide range of geospatially relevant studies [238,246,247]. Future studies could benefit from higher fine-grained geospatial data for more accurate UGS estimation and monitoring. Second, this work only considered the area of UGS and did not consider differences in the quality of UGS, or the ES provided by different UGS types. Future research could quantify the differences in well-being provided by UGS

through further precise measurements of the quality of UGS and the ES they provide. Finally, this study only considered the passive benefits that UGS provides to residents in a subliminal manner and did not consider the active benefits of residents visiting UGS. Therefore, it is important to clarify that the UGS inequality measured in this study only represents differences in passive exposure to UGS.

5. Conclusion

The process of urbanization not only leads to the loss of UGS but may also result in UGS inequality, leading to environmental justice issues. In this chapter, I quantified the UGS inequality around residences at the municipality level in Japan from 2000 to 2020 from a time-series perspective to reveal the trend of UGS inequality around residences at the municipality level in Japan. The main results show that: 1) the UGS inequality at the municipality level in Japan is on an upward trend from 2000 to 2020; 2) the UGS inequality in municipalities of different city sizes shows significant differences; and 3) the UGS inequality varies among municipalities in geographic regions. Based on the results of this chapter, I suggest that the Japanese government should pay attention not only to the area of UGS, but also to the equitable distribution of UGS to realize the sustainable development of UGS.

Chapter III. The relationship between UGS inequality and urban form

1. Purpose of this chapter

Based on the research results in the previous chapter, I found that UGS inequality is the highest in medium-sized cities, and UGS inequality in small cities is increasing significantly. Most of these cities are cities with shrinking populations and are facing the dilemma of population decline. Therefore, I will focus on shrinking cities and further explore how to alleviate UGS inequality through urban form planning from the urban dimension.

This chapter quantitatively analyzes the relationship between UGS inequality and urban form in shrinking cities through specific urban form indicators. Specifically, it hopes to achieve the following objectives: 1) investigate the spatial distribution characteristics of UGS inequality in shrinking cities in Japan; 2) characterize the urban spatial morphology of shrinking cities in Japan from various aspects; 3) quantify the relationship between spatial morphology and UGS inequality in shrinking cities; and 4) provide sustainable strategies for UGS planning based on the development policies of shrinking cities to mitigate urban environmental inequality problems.

2. Materials and methods

2.1 Study area

Since the 1950s, some of Japan's cities have been experiencing rapid and prolonged population declines [86], which have become particularly pronounced since 2008. The National Institute of Population and Social Security Research (2017) projects that Japan's population will decline to 106 million in 2050, with a growing number of cities facing population decline and urban shrinkage [248]. The area of vacant land in Japan increased by 18.6% from 2003 to 2013, of which the area of abandoned residential land increased by 35.1% [249]. The abandonment of some residential land due to population decline is the most important reason. At the same time, the economic impact has forced some of the lands to stop development, and further spread the vacant land in shrinking cities.

The Japanese government has proposed an urban planning policy of "compact cities," in response to the predicted urban shrinkage [250]. It implies that the spatial pattern and land use of Japanese cities will gradually change, so it is necessary to continuously review the urban pattern of Japan from an environmental justice perspective and adjust urban development strategies promptly.

To ensure that a good characterization of shrinking urban form is obtained, the selected cities are those that have been shrinking, at least in the short term [86]. Therefore, I selected all Japanese cities that have declined in population from 2000 to 2015 [251]. A total of 147 cities were included (Fig. 3.1), which cover all seven regions of Japan:

Hokkaido; Tohoku; Kanto; Chubu; Kansai; Chugoku & Shikoku; Kyushu & Okinawa.

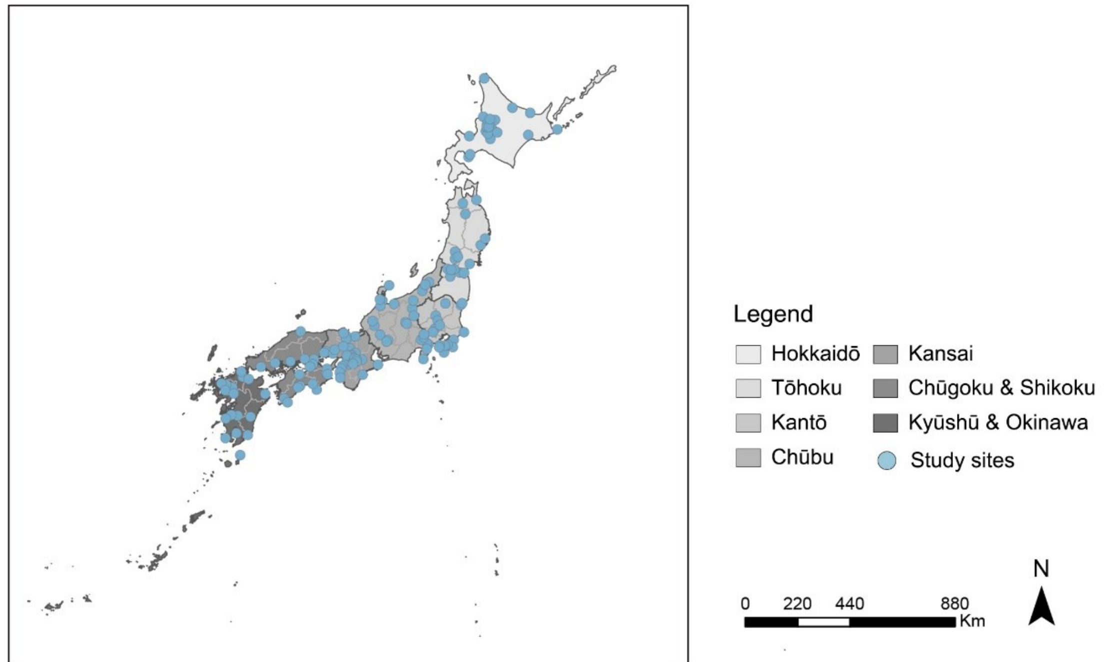

Fig. 3.1 Study areas: 147 shrinking cities in Japan

2.2 Data collection and preparation

In this chapter, the UGS uses the broad UGS definition of green space coverage. First, this study used a global land cover map (2017 FROM-GLC10), with a resolution of 10 m [252]. The dataset was created based on the Sentinel-2 remote sensing image (10 m) database, and the Google Earth Engine, and validated with sample data from 2015. FROM-GLC10 (2017) classifies land cover into 10 classes [253]. The advantage of this dataset is that it has high accuracy and is completely free to access. Second, the population data for 147 shrinking cities were derived from the free 100 m grid population data [254]. This dataset was mapped from the 500 m grid population dataset

produced by the 2015 Japanese census [255]. It has higher precision compared to the 500 m grid population dataset. Finally, I compiled the vacant land rate, urban population and increase/decrease rates, and per capita income indicators for all 147 shrinking cities, using the 2018 Residential/Land Statistics dataset [256], the National Situation Survey dataset [257], and statistical white papers for each city.

2.3 Indicators of UGS inequality

Considering that vacant land in shrinking cities may be transforming into informal UGSs in the absence of management, these UGSs often do not provide the same ESs (e.g., security, social cohesion) as others [144]. As these vacant lands are often generated in socially vulnerable communities [258], they can have an impact on the measurement of UGS equality in shrinking cities. In this study, UGS is defined in a broad sense, which is all UGSs covered by vegetation and water bodies [259]. Therefore, I considered "Impervious area" in FROM-GLC10 (2017) as urban built-up area (UA) and "cropland," "forest," "Grassland," "Shrubland," "Wetland," and "Tundra" as UGSs, as done by Yang et al. (2020) [116].

UGS inequality is quantified as the difference in UGS area per capita for all population grid buffers within the city to obtain a specific value. Similar to the previous chapter, UGS inequality measures the subliminal benefits provided by UGS, services that can be enjoyed passively without the need for residents to visit. I used the Gini coefficient, applied to UGS inequality, to measure UGS inequality in these 147 cities. First, 500 m buffers were created for all population grids within the city. Second, the area of UGS

per capita was measured separately for each buffer. Finally, the difference in UGS area per capita within each buffer was calculated using the Gini coefficient. Specifically, it can be expressed as:

$$G = 1 - \sum_{i=1}^{n} \frac{P_i}{P} (\alpha_{i-1} + \alpha_i) \quad (3\text{–}1)$$

where P represents the total population of the city; P_i represents the population in the i grid cell; and α_i is the cumulative percentage of UGS within the buffer zone of the i grid cell, to the total amount of UGS.

I used ArcGIS 10.7 to calculate the UGS area per capita in the buffer zone and Stata 12.0 [260] to quantify the Gini coefficient of each city.

2.4 Urban form indicators

Urban form evolves over a long period of time, through the combined effects of urban topography, economy, and population [208]. Urban form, in this study, follows the broadest definition that encompasses the physical structure, size, and population distribution developed during urban development [209].

Previous studies have developed many different landscape indicators, based on remote sensing imagery, to measure the physical morphology of cities [209,210]. Considering the multidimensional nature of urban form, researchers usually describe urban form from multiple dimensions [93,131,209]. Representative indicators are selected for each dimension to describe the morphology of cities in that dimension [131]. Considering the multidimensional nature of cities, I selected eight dimensions to describe urban form:

urban size, degree of urbanization, centrality, growth pattern, shape, compactness, degree of fragmentation, and continuity (Table 3.1).

Urban size is measured using the common logarithm of the area of UA [131,261]. The degree of urbanization is described using the urban land index (UI) as a percentage of the total urban area [262]. Both indicators have been widely used in past studies to characterize the size and degree of development of cities [131,262]. The centrality of cities is estimated through the Global Moran's I, which distinguishes potential spatial structure (compactness or sprawl), and describes three scenarios of urban centrality: monocentric; polycentric; and "checkerboard" patterns [210]. The indicator has been widely used to measure the centrality of urban populations associated with a variety of urban issues. Examples include transportation [263], heat island effect [131], energy consumption [264] and accessibility [265]. The standard elliptical eccentricity calculates the growth pattern of urban form through the distribution of the center of a mass of urban patches. The area-weighted mean shape index (AWMSI) is used to describe the shape of urban patches. Compared to the shape index (LSI), the AWMSI takes into account the size of urban patches, with larger patches having a greater impact on the index [266]. AWMSI has been shown to be widely proven to effectively characterize the complexity of urban patches or landscape patches. Past research has often linked it to issues such as urban climate [131], pollutants [139], and transportation [267]. The mean compactness (COMP) is the overall compactness of urban patches and calculated based on the minimum outer circle [145]. COMP reflects the degree of urban development concentration in terms of land use/cover and has proven effective in morphometric measurements of shrinking cities [145]. The Dispersion Index (DI) was used to assess the degree of fragmentation of

urban patches [268]. This is a newly developed urban form indicator, constructed based on the maximum patch area and the number of patches out of the spatial structure of urban patches [269], which has been used by Liu et al., (2021) in a study exploring the correlation between urban form and the heat island effect. Finally, the Percentage of Like Adjacencies (PLADJ) was used to describe the continuity among urban patches [135]. PLADJ is a common measure of urban form and has been widely utilized in urban form studies and has effectively demonstrated the relationship between urban patch continuity and PM2.5 [270], heat island effect [271], and ecosystem services [272]. Figure 3.2 illustrates the urban morphological characteristics represented by the values of the urban form indicators; for example, the urban patches in Tagawa City are more irregular than those in Ostuki City, and therefore the value of AWMSI is higher in Tagawa City (Fig. 3.2).

Table 3.1 Calculation formulae and details of urban form indicators

Dimension	Index	Formula	Note
Urban size	Log$_{10}$(UA)	–	The larger the value, the larger the urban size.
Urbanization	UI	$UI = \frac{UL}{TL} \cdot 100$	Where UL represents the built-up area of the city, and TL is the total area of the city. The larger the value, the higher the degree of urbanization.
Centrality	Moran's I	$Moran's\ \mathrm{I} = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}(x_i - x)(x_j - x)}{\left(\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}\right)(x_i - x)^2}$	Where n represents the number of impervious areas; x_i and x_j are the populations of patches i and j; x is the average of the regional population, and W_{ij} denotes the weight between patches i and j. Moran's I values from -1 to 1 indicate a "chessboard," polycentric, and monocentric patterns, respectively.
Growth pattern	Eccentricity	$Eccentricity = \sqrt{1 - \left(\frac{minor}{major}\right)^2}$	Where minor is the semi-minor axis of the ellipse formed by the plaque; $major$ is the semi-major axis of the ellipse formed by the plaque. An eccentricity of 0 represents the growth pattern of concentric circles; the higher the eccentricity, the more the growth pattern tends to be linear.

Shape	AWMSI	$AWMSI = \sum_{j=1}^{n}\left[\left(\frac{0.25p_{ij}}{\sqrt{a_{ij}}}\right)\left(\frac{a_{ij}}{\sum_{j=1}^{n}a_{ij}}\right)\right]$	Where p_{ij} represents the perimeter of patch ij; and a_{ij} represents the area of patch ij. The higher the AWMSI, the more irregular the shape of urban patches.
Compactness	COMP	$COMP = \frac{1}{n}\sum_{i=1}^{n}\frac{a_i}{A_k}$	where n is the number of urban patches; a_i is the urbanized area of patch i; and A_k is the minimum circular area of class k. The larger the value, the more concentrated the urban patches.
Fragmentation	DI	$DI = \frac{NP_n + (100 - LP_n)}{2}$ $NP_n = \frac{NP - 1}{\sum_{j=1}^{n}a_{ij} - 1}\cdot 100$ $LP_n = \frac{LP - \frac{1}{\sum_{j=1}^{n}a_{ij}}}{100 - \frac{1}{\sum_{j=1}^{n}a_{ij}}}\cdot 100$	Where i is class i; NP is the number of patches; NP_n is the standardized form of NP; LP is the percentage of the largest patches in class i; LP_n is the standardized LP; a_{ij} is the area of patch j in class i. The larger the DI (0 ≤ DI ≤ 100), the higher the degree of urban patch dispersion.
Continuity	PLADJ	$PLADJ = \left(\frac{g_{ij}}{\sum_{k=1}^{n}g_{ik}}\right)\cdot 100$	Where g_{ij} is the number of adjacencies between patches of class i, and g_{ik} is the number of adjacencies between patches of class i and k. The higher the value of PLADJ (0 ≤ PLADJ ≤ 100), the higher the urban patch continuity.

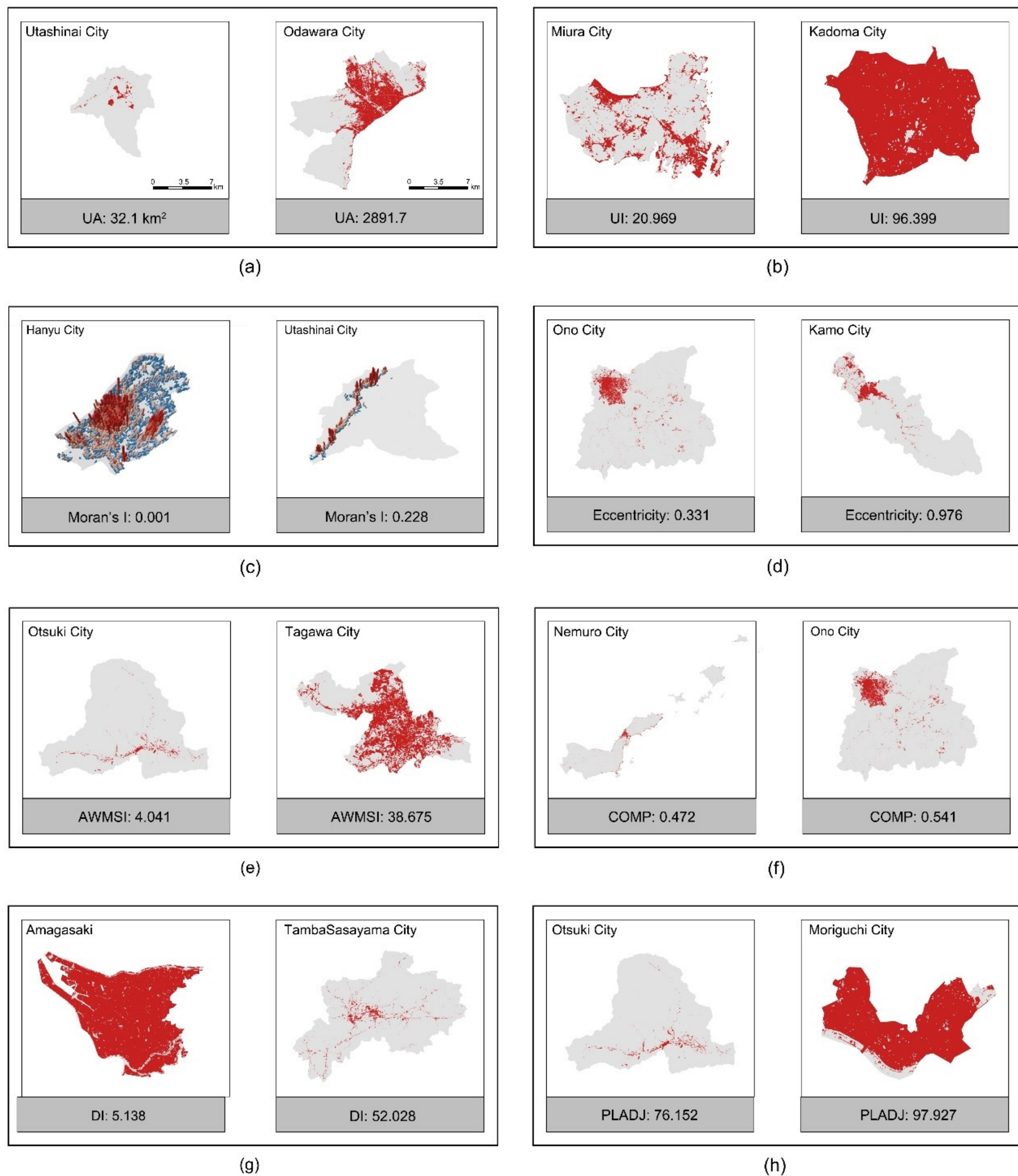

Fig. 3.2 Illustrate different dimensions of urban form indicators with representative cities: a) Urban size; b) Urbanization; c) Centrality; d) Growth pattern; e) Shape; f) Compactness; g) Fragmentation; h) Continuity

The AWMSI and PLADJ of the urban form indicators were calculated using FRAGESTATS 4.2 [151], and the rest of the metrics were calculated using ArcGIS 10.7.

2.5 Indicators of urban characteristics

In addition to urban form indicators, I added the relevant indicators used to describe urban characteristics as covariates to further examine the relationship between urban form and UGS inequality in shrinking cities. Indicators of urban characteristics were urban population, population density, per capita income of residents, vacant land rate, and population shrinkage rate. The number of urban population and per capita income of residents reflect the level of development and the economic status of the city. The level of development and economic status of a city may influence the planning and development of UGS [273,274]. Population density reflects urban development strategies, and high-density cities may result in a reduction of per capita UGS [273]. The rate of population decline, a characteristic indicator of shrinking cities, describes the state of urban shrinkage. Population decline may lead to increased residence segregation, and generate social inequities [41]. Urban vacant land is considered to potentially introduce errors in the assessment of UGS equality in shrinking cities [144]. The vacant land rate indicator is used as a covariate to assess whether these errors are eliminated. To avoid the effects of data skewness and magnitude, the three variables of population — (log10(Population)), population density (log10(PD)), and per capita income of residents (log10(Income)) — were transformed with the usual logarithms.

2.6 Statistical analysis

This study contains two sets of variables: 1) indicators of urban form and 2) indicators

of shrinking cities' characteristics. Before conducting the regression analysis, a variance inflation factor (VIF) was first used to test the multicollinearity of the explanatory variables. The results showed that there was a multicollinearity problem in the variables (VIF>5). Therefore, the log10 (population) and UI variables were excluded from further analysis.

Ordinary least squares (OLS) regression was used to analyze the relationship between UGS equality and urban form indicators. OLS can be used to determine the value of the regression coefficient, by calculating the least error sum of squares between the theoretical and observed values of the model (Wang et al., 2020b). Specifically, it can be expressed as:

$$y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n + \varepsilon \tag{3–1}$$

where, y is the dependent variable; β_0 is the constant; X_n is the independent variable; β_n is the partial regression coefficient; and ε is the residual.

OLS is a regression method based on global parameter calculations, which can explain the relationship between dependent and independent variables globally, but cannot respond to differences in the effects of variables for local areas [93]. However, the first law of geography states that this relationship exists between all things, with stronger correlations between adjacent things [275]. To better explain the relationship between UGS inequality and urban forms, and overcome this challenge, I used geographically weighted regression (GWR). Compared to the OLS regression, the GWR model allows for local estimation of parameters, thus explaining the non-stationary relationship between variables at the local level [276]. The model is as follows:

$$Y_i = \beta_0(\mu_i,\upsilon_i) + \sum_{j=1}^{k}\beta_j(\mu_i,\upsilon_i)X_{ij} + \varepsilon_i \quad (3\text{–}2)$$

where, Y_i and X_i are the dependent and independent variables; (μ_i,υ_i) are the coordinates of sample i; $\beta_0(\mu_i,\upsilon_i)$ is the constant term; $\beta_j(\mu_i,\upsilon_i)$ is the regression coefficient β_j for sample point i; and ε_i is the random error term.

The distance between the samples determines the strength of spatial connectivity, and a distance decay function is needed to determine the spatial extent dependence [277]. By comparing different kernel functions (Gaussian and Bi-squared) [278], this study uses a bi-square distance decay function for spatial weighting. It is specifically expressed as:

$$\begin{cases} w_{ij} = \left[1-\left(d_{ij}/b\right)^2\right]^2, & if\ d_{ij} < b \\ w_{ij} = 0 & , if\ d_{ij} \geqslant b \end{cases} \quad (3\text{–}3)$$

where, w_{ij} is the weight of sample i on sample j; d_{ij} is the distance between samples i and j; and b is the kernel bandwidth. As the bandwidth increases, the weights of the local regression model converge to unity. This study uses the small-sample bias-corrected Akaike Information Criterion (AICc) approach to find the optimal distance of the adaptive bi-square kernel bandwidth. The adaptive kernel bandwidth varies according to the density of samples in the study area, and is considered more suitable for use in study areas where the sample data are not distributed uniformly [279,280].

The performance of the GWR model is compared with the OLS model, using four metrics: 1) the R^2 of the model; 2) the value of the AICc of the model; 3) the F-test of the GWR model; and 4) the Moran's I of the model residuals. A higher R2 means that

the independent variable explains more variance of the dependent variable [280]. AICc is a measure of model complexity and goodness-of-fit, and a smaller AICc indicates a better model fit [281]. I used the F-test (F_1-test) developed by Leung et al. (2000) to test the null hypothesis that the GWR model has no improvement in goodness-of-fit over the OLS model [282]. Finally, Moran's I was used to determine the spatial autocorrelation of the model residuals. If there is spatial autocorrelation in the residuals of the OLS model, the model is considered inefficient [280].

In this study, SPSS 26.0 and the "GWModel" package [283] in R studio were used to calculate the OLS model and the GWR model, respectively. Moran's I was calculated using ArcGIS 10.7.

3. Results and discussion

3.1 Descriptive statistics and distribution characteristics

As shown in Table 3.2, shrinking cities in Japan have a more uneven overall distribution of UGS (mean Gini coefficient = 0.711 ± 0.076 SD). The Gini coefficients of UGS inequality for all cities are above 0.4, indicating that all cities have varying degrees of UGS inequality. There are large differences in population density and urban size between shrinking cities, while income differences are smaller. Even among all cities facing declining populations, some cities do not have serious urban shrinkage problems, while others have serious shrinkage problems (min=1.51; max=40.21; SD=7.17). The same phenomenon of vacancy rate and urban shrinkage rate exists, thus showing a large

variation (min=6.48; max=50.71; SD=5.80). Most of the shrinking cities in Japan manifest polycentricity (mean=0.004±0.027 SD), linear development (mean=0.756±0.152 SD), and high connectivity (mean=86.714±5.063 SD). The concentration of urban patches was relatively even, but the urban patch shape and patch fragmentation considerably varied among cities.

Table 3.2 Descriptive statistics of variables

	Minimum	Maximum	Mean	SD
Gini coefficient	0.499	0.919	0.711	0.076
$\log_{10}$(PD)	2.862	4.113	3.524	0.218
Log_{10}(Income)	5.861	6.191	6.047	0.072
Shrinkage rate	1.514	40.214	13.092	7.165
Vacancy rate	6.479	50.710	16.313	5.798
$\log_{10}$(UA)	1.507	3.870	3.035	0.343
Moran's I	-0.133	0.228	0.004	0.027
Eccentricity	0.272	0.984	0.756	0.152
AWMSI	3.586	38.675	14.234	8.233
COMP	0.472	0.541	0.510	0.012
DI	1.811	52.028	43.443	11.373
PLADJ	75.990	98.533	86.714	5.063

From a geographical perspective (Figs. 3.3 and 3.7a), the mean values of the Gini coefficient, which represents UGS inequality, are higher in Hokkaido and Kansai, and there are large differences in UGS inequality among cities. This situation fully reflects the spatial heterogeneity of cities. Simultaneously, shrinking cities in Hokkaido face

more severe urban shrinkage (Figs. 3.4a and 3.7b) and vacant land phenomena (Figs. 3.4b and 3.7c). It is possible that most cities in Hokkaido are experiencing a long-term population contraction [86]. Kansai and Kanto, as the two most developed metropolitan areas in Japan, are higher in terms of population density (Figs. 3.4c and 3.7d) and per capita income (Figs. 3.4d and 3.7e) than other regions. In terms of centrality (Figs. 3.5a and 3.7f) and continuity (Figs. 3.6b and 3.7k), Japan's shrinking cities exhibit the morphological characteristics of polycentricity and high connectivity. It is related to the overall shrinking city policy in Japan, where most shrinking cities are moving toward polycentric, network-type cities [98,284]. The mean values of urban areas are essentially the same for all seven regions, but the difference in the urban area is larger for Hokkaido (Figs. 3.4c and 3.7l). In terms of patch compactness (Figs. 3.5d and 3.7i), the urban patches in the Tohoku and Hokkaido regions are looser overall, compared to the other regions. Eccentricity (Figs. 3.5b and 3.7g) and AWMSI (Figs. 3.5c and 3.7h) reveal significant variability among cities across the seven regions. Similarly, the degree of fragmentation of urban patches is very different between Kanto and Kansai (Figs. 3.6a and 3.7j). The cities in these two regions have experienced a high level of development over a long period of time, and thus, show great variability in their level and form of urbanization.

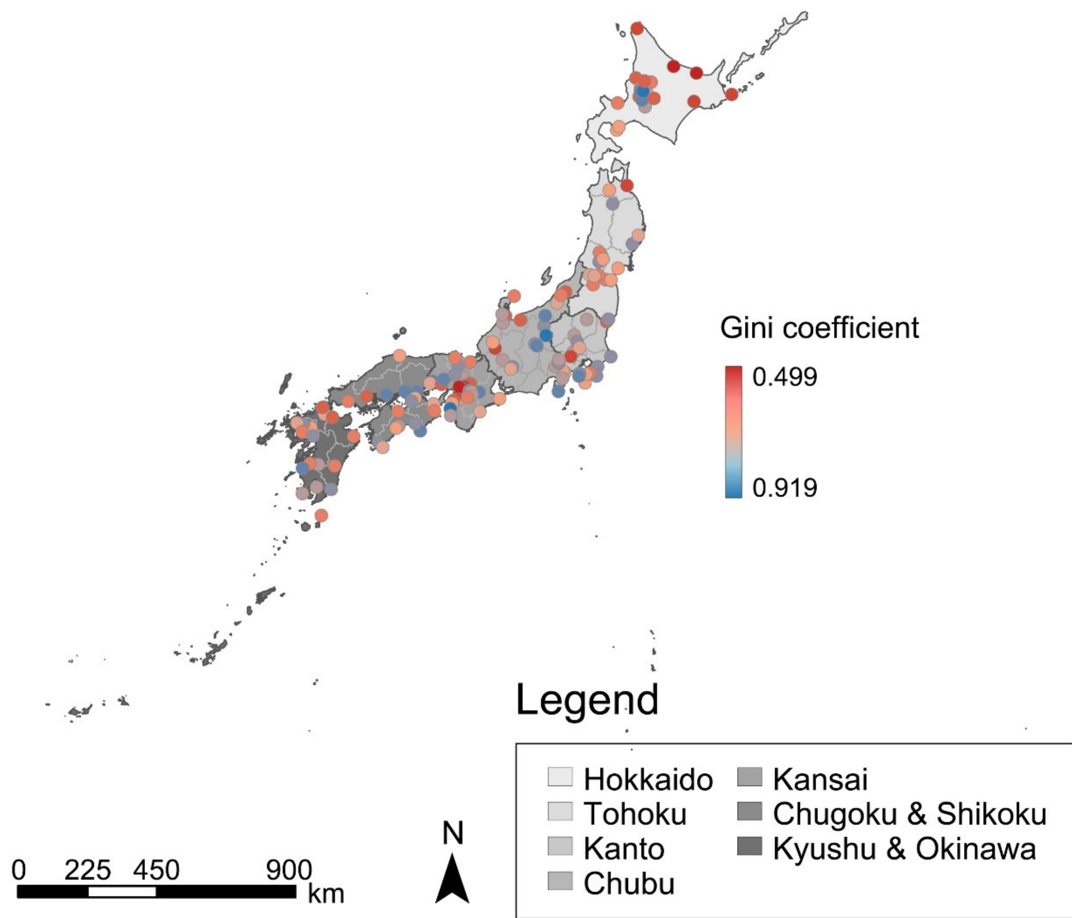

Fig. 3.3 Regional distribution characteristics of Gini coefficient

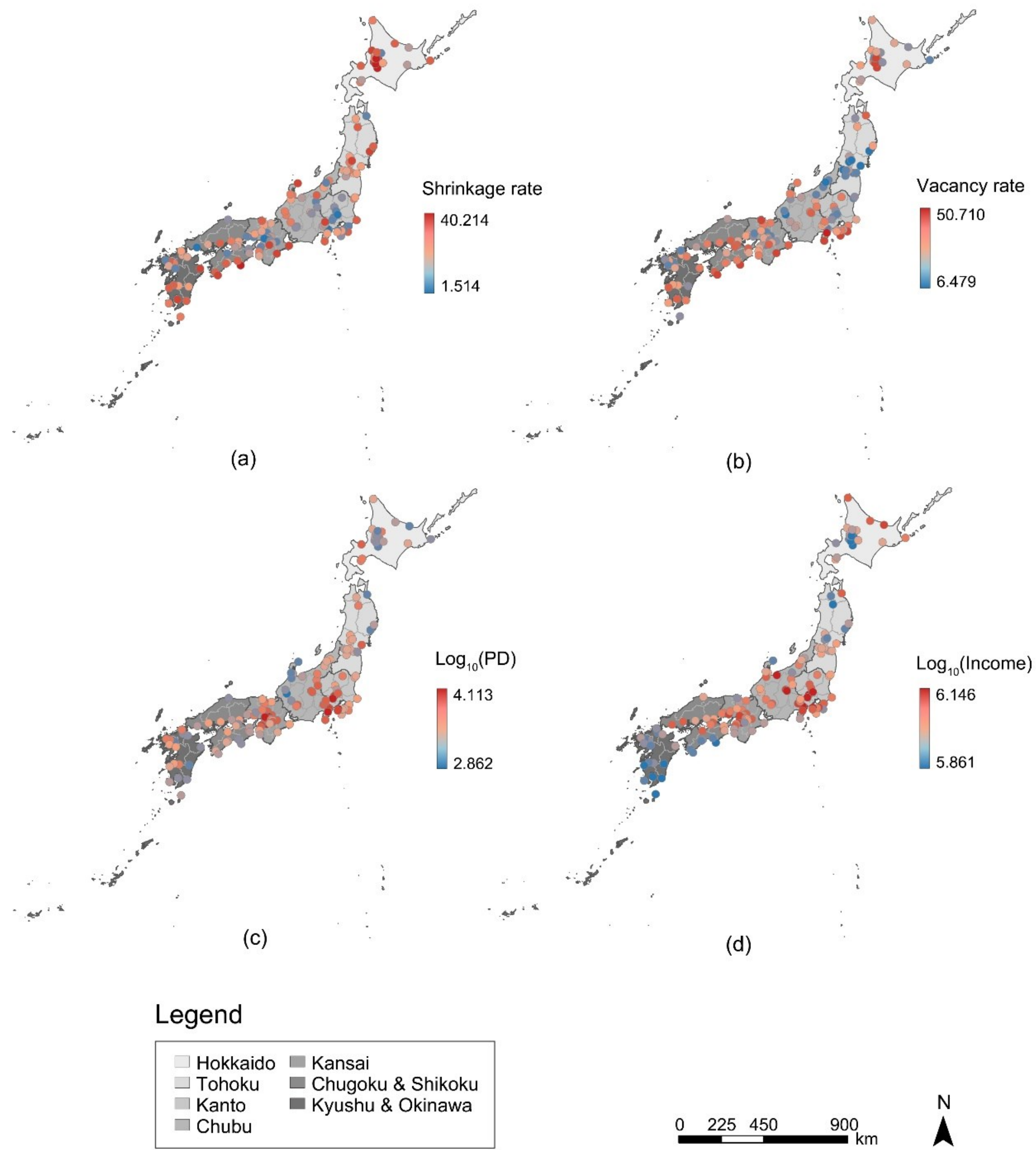

Fig. 3.4 Regional distribution characteristics of shrinking city characteristics variables: (a) Shrinkage rate; (b) Vacancy rate; (c) log10(PD); d) log10(Income)

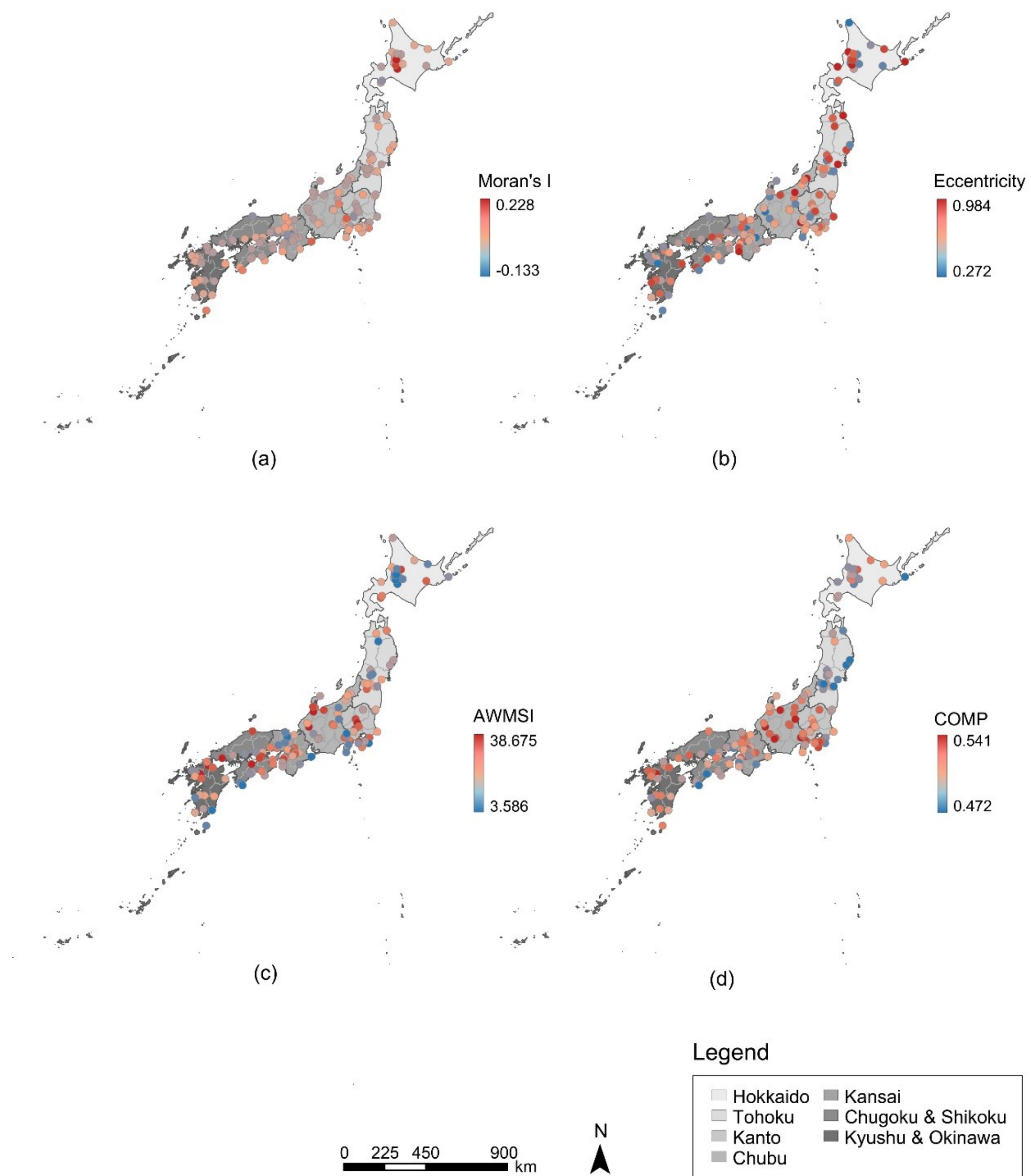

Fig. 3.5 Regional distribution characteristics of urban morphological indicators: (a) Moran's I; (b) Eccentricity; (c) AWMSI; (d) COMP; (e) DI; (f) PLADJ; (g) log10(UA)

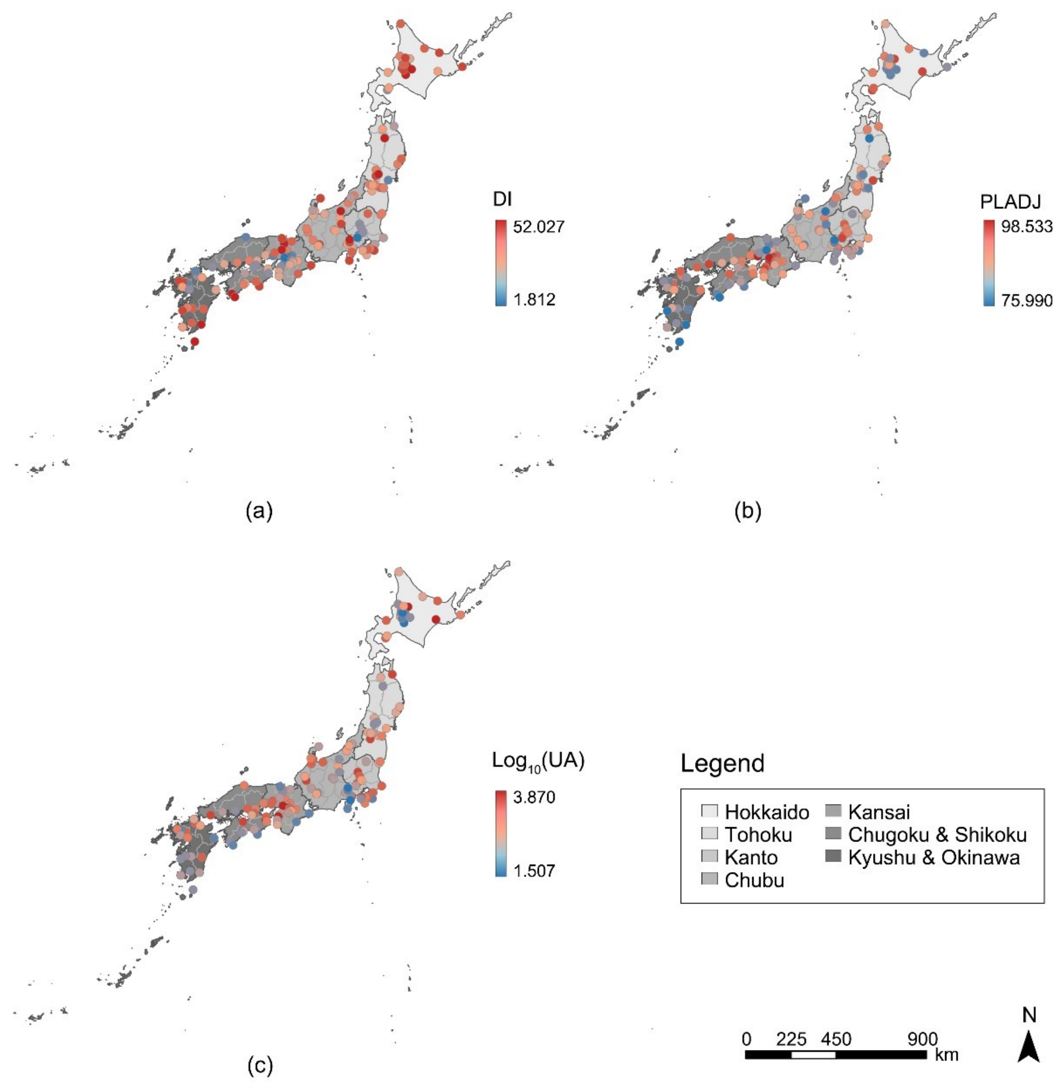

Fig. 3.6 Regional distribution characteristics of urban morphological indicators: (a) DI; (b) PLADJ; (c) log10(UA)

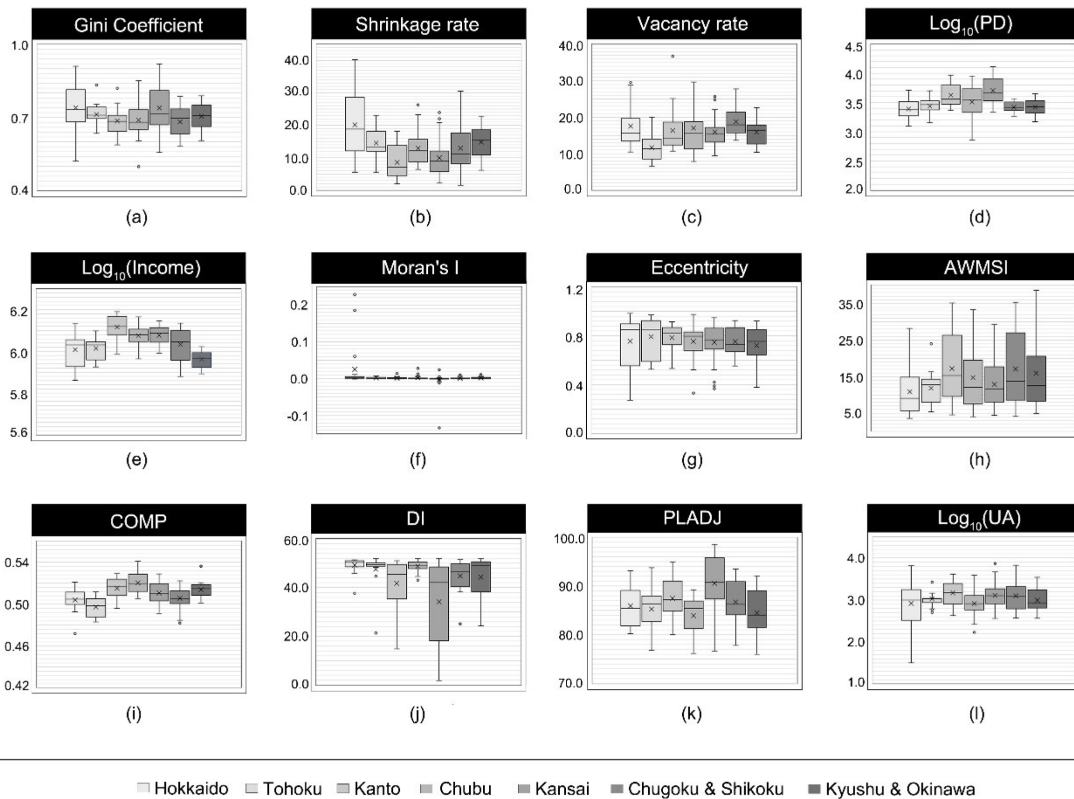

Fig. 3.7 Regional distribution characteristics of Gini coefficient and shrinking city characteristics variables: (a) Gini coefficient; (b) Shrinkage rate; (c) Vacancy rate; (d) log10(PD); (e) log10(Income); (f) Moran's I; (g) Eccentricity; (h) AWMSI; (i) COMP; (j) DI; (k) PLADJ; and (l) log10(UA)

3.2 OLS Regression Model

I first used OLS regression to determine if the model was suitable for GWR regression. Table 3.3 presents the results of the OLS regression. The model passed the F-test ($p = 0.000$), thus indicating that it was statistically significant at all test levels of $\alpha = 0.01$. The VIFs of all variables were lower than 5, which suggests that there is no multicollinearity between them. The model also possesses normally distributed residuals, as the K-S values are not significant. Overall, the model of this study can be

considered as a robust regression model.

Table 3.3 Results of OLS model

	Unstandardized Coefficients		Standardized Coefficients	t-value	p-value	VIF
	B	Std. Error	Beta			
Constant	-0.943	0.664	–	1.420	0.158	–
Vacancy rate	-0.001	0.001	-0.055	-0.747	0.456	1.339
Shrinkage rate	0.002	0.001	0.213	1.566	0.120	4.540
$\log_{10}$(Income)	0.217	0.108	0.205	2.017	0.046*	2.550
$\log_{10}$(PD)	-0.131	0.038	-0.376	-3.496	0.001**	2.843
Moran's I	-0.590	0.220	-0.211	-2.685	0.008**	1.514
Eccentricity	-0.022	0.033	-0.043	-0.651	0.516	1.074
AWMSI	-0.004	0.001	-0.394	-4.052	0.000**	2.321
COMP	0.655	0.468	0.103	1.402	0.163	1.322
DI	-0.003	0.001	-0.376	-3.355	0.001**	3.094
$\log_{10}$(UA)	0.050	0.027	0.227	1.848	0.067	3.695
PLADJ	0.006	0.002	0.367	2.964	0.004**	3.768
R^2	0.451					
Adj. R^2	0.406					
F	F (11,135) =10.063, p=0.000					

Dependent Variable: Gini coefficient

K-S=0.053, p=0.100

* p<0.05; ** p<0.01; *** p<0.001

The R^2 of the regression model is 0.451, thus indicating that the OLS model can explain 45.1% of the Gini coefficient. A higher Gini coefficient indicates higher UGS inequality. log10(Income) and PLADJ have a significant positive relationship on the Gini

coefficient. In contrast, AWMSI, DI, Moran's I, and log10(PD) have a significant negative effect on the Gini coefficient. Therefore, globally, income and continuity can have a significant negative effect on UGS inequality. In contrast, urban population, patch shape, urban centrality, and fragmentation can have a significant positive effect on UGS inequality. Furthermore, I observed the standardized coefficient Beta values and found the importance of the independent variables on the effect of the Gini coefficient. From highest to lowest, these are AWMSI; log10 (PD); DI; PLADJ; Moran's I; log10 (Income).

3.3 Comparison of GWR and OLS

The GWR model was used to explore the correlation between UGS equality and urban form indicators within different regions. First, a reasonable kernel bandwidth was determined using AICc. The results show that the optimal bandwidth is 105 (number of nearest neighbors=105) when the AICc value is the smallest. Second, I examined the standardized residuals of GWR. When the absolute value of the localized standardized residuals was greater than 2.5, it indicated that the predicted values of the GWR model were not locally reliable [285]. The absolute value of the standardized residual values is less than 2.5 for most of the regions, thus indicating that the GWR model was robust overall (Fig. 3.8b).

I used four indicators to verify the necessity of using the GWR model and the spatial significance of the variables' variation. If the goodness-of-fit of the GWR model is not improved over the OLS model, then the OLS model should be preferred [282]. As shown

in Table 3.4, the global R^2 of the GWR model ($R^2 = 0.600$) is significantly improved over the OLS model ($R^2 = 0.451$). The local R^2 of GWR ranges from 0.401 to 0.767, and the local R^2 of most regions is greater than the global R^2 of the OLS model. Only four cities have a lower local explanation than the global explanation of the OLS model (Fig. 3.8a). Moreover, the GWR model has a gradual increase in the explanation of UGS from southwest to northeast. AICc was used to measure the goodness-of-fit of the models, and when the difference in the AICc values of the models was greater than 3, it indicated a significant difference in the fit between the models [286]. The results show (Table 3.4) that the AICc values of the GWR model and the OLS model are -419.031 and -400.017, respectively, thus indicating that the GWR model has a better fit than the OLS model. In addition, Moran's I of the residuals of the OLS model reveals that the residuals of the OLS model have significant spatial autocorrelation. In contrast, the residuals of the GWR model tend to be spatially more randomly distributed. Finally, the F-test (F_1-test) of GWR was used to compare the regression results of OLS and GWR. The results showed that the F-value (F_1-value = 0.817) was statistically significant at the α=0.05 level, thus rejecting the null hypothesis that the GWR model did not improve the fit. Overall, the spatial variability of the model's variables is significant and requires the use of a GWR model to improve the model's goodness-of-fit.

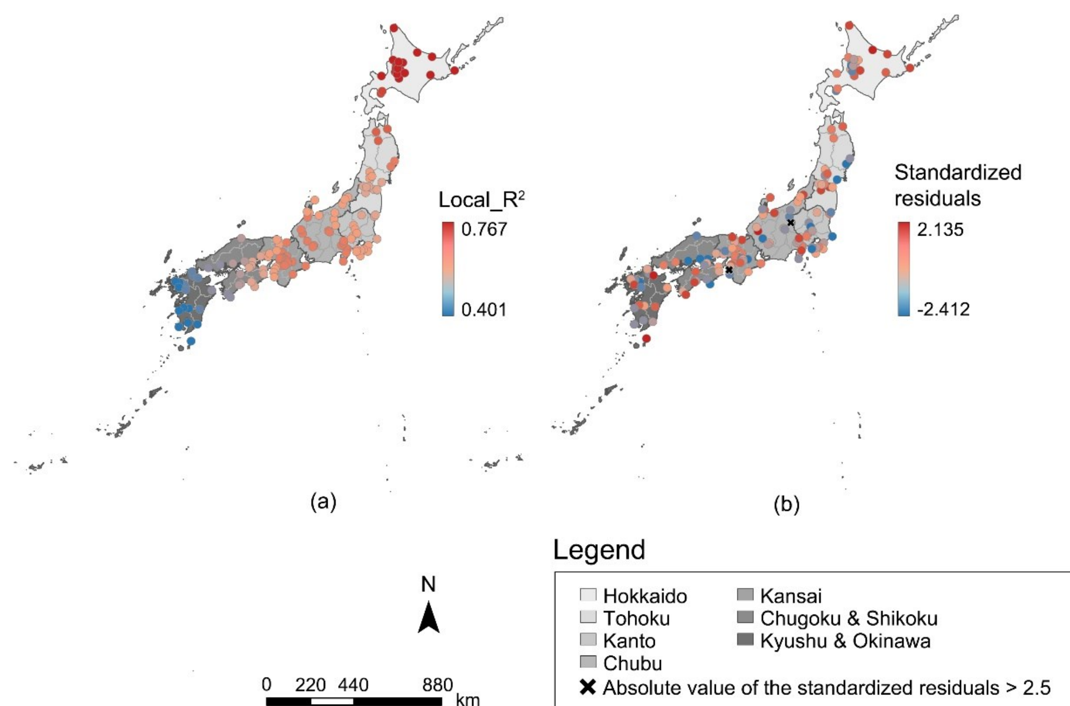

Fig. 3.8 Results of GWR model: (a) local R-squared; (b) standardized residuals

Table 3.4. Comparison of results between the OLS model and GWR model

	R^2	Adj. R^2	AIC	AICc	Moran's I	RSS	F_1-test
OLS	0.451	0.406	-402.754	-400.017	0.159**	0.475	
GWR	0.600	0.510	-452.900	-419.031	0.067	0.339	0.817*

* p<0.05; ** p<0.01

3.4 Relationship between the spatial variation of GWR regression coefficients

I used t-tests to determine the significance of the local parameter estimates (t-value > 1.96, or t-value < -1.96). Figures 3.9 and 3.10 show the local regression coefficients of the intercept, the characteristic indicators of shrinking cities and the urban form indicators, and their spatial variation relationships.

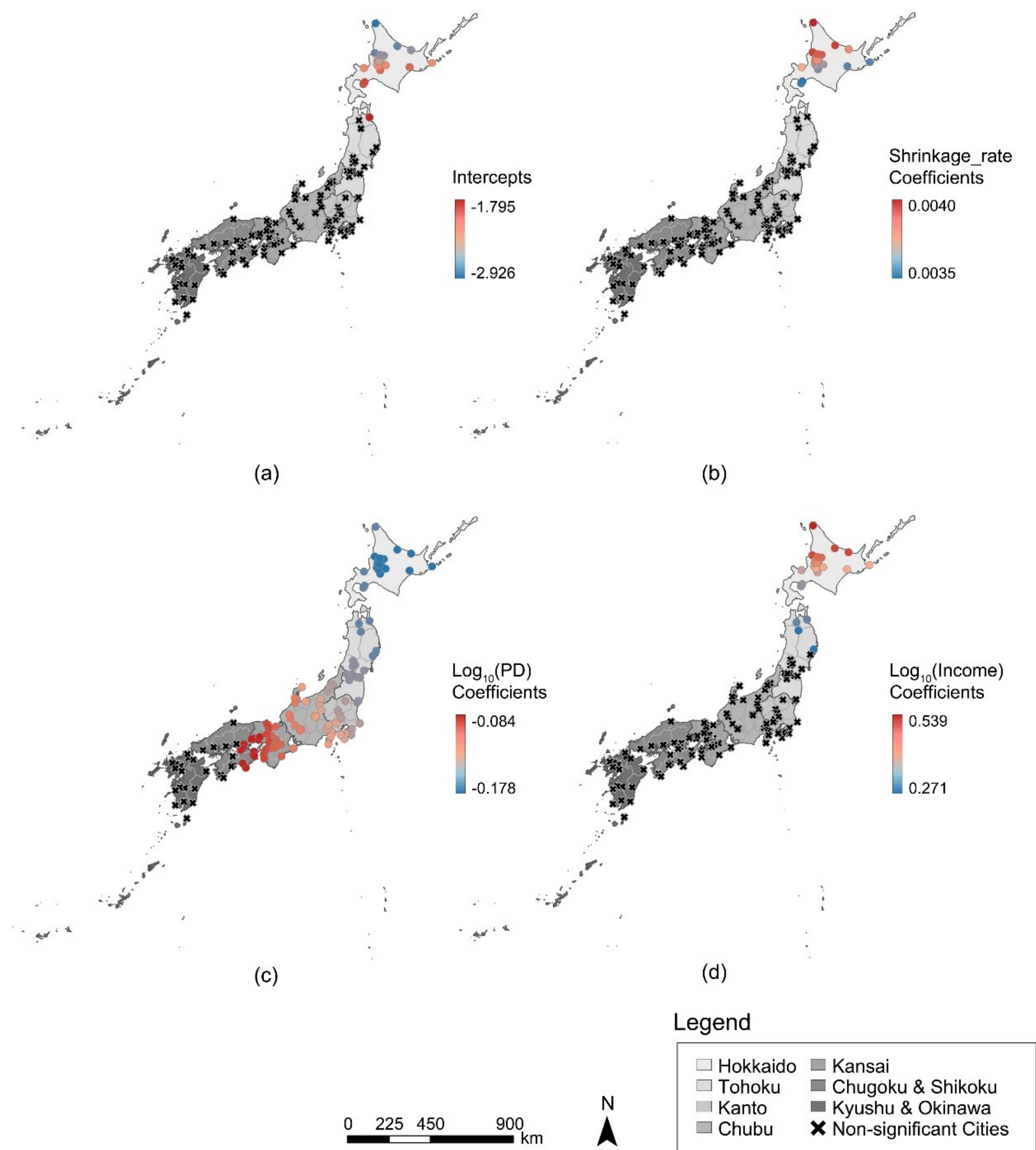

Fig. 3.9. Regression coefficients for intercept and shrinking cities' characteristic variables of the GWR model: (a) Intercept; (b) Shrinkage rate; (c) log10 (PD); (d) log10 (Income)

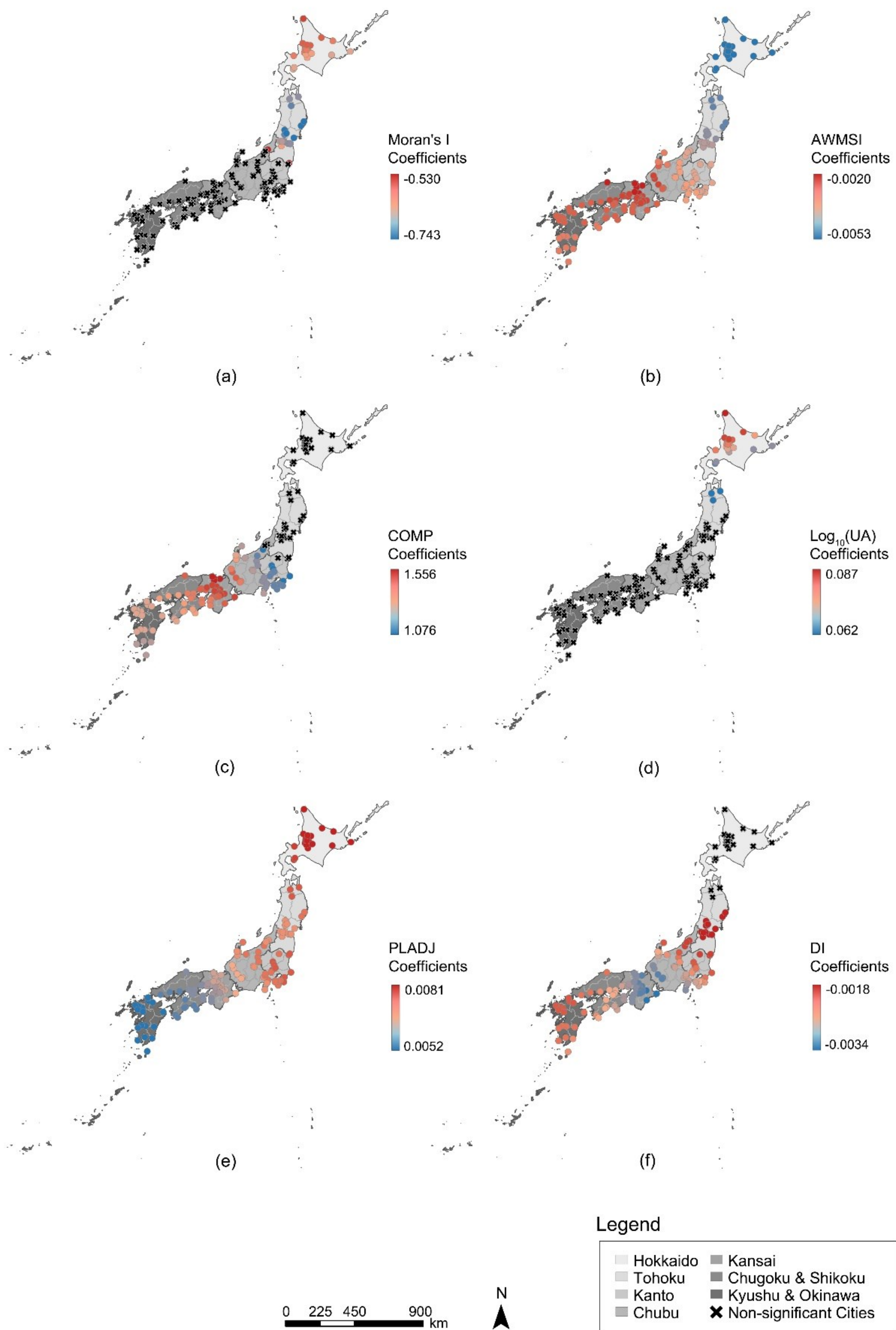

Fig. 3.10 Regression coefficients for the urban form indicator variables of the GWR

model: (a) Moran's I; (b) AWMSI; (c) COMP; (d) log10 (UA); (e) PLADJ; (f) DI

In all regions, the effect of Eccentricity on the Gini coefficient was not significant, thus indicating that the form of urban development cannot affect the UGS inequality. The effect of the vacancy rate on the Gini coefficient is also similarly insignificant. This result suggests that I have roughly eliminated the error introduced by the vacant land in shrinking cities on the measurement of UGS inequality [144].

Figure 3.9b shows that urban shrinkage has a significant positive effect on the Gini coefficient only in the Hokkaido region. A higher the rate of urban shrinkage in the Hokkaido region was associated with lower equality of UGS. In terms of population development, most cities in Hokkaido, the first cities in Japan to enter a high level of shrinkage since 1985, are experiencing long-term population shrinkage [86]. Compared to the high-density development in other regions of Japan, the Hokkaido region is sparsely populated and has the lowest population density in Japan [220]. Low-density urban development has led to a relative dispersion of housing. Large areas of vacant land and a gradually declining population can lead to the creation of many isolated dwellings, resulting in residential segregation [245]. The isolation between dwellings increases the difficulty of allocating social resources, and these areas are highly prone to unequal distribution of social resources, including UGSs [287,288]. Although cities in other regions are also experiencing urban shrinkage, there are fewer opportunities to create residential segregation due to high-density urban development. In the Hokkaido region, A higher urban shrinkage rate further reduces population density and undoubtedly increases the probability of residential segregation. Therefore, within the Hokkaido region, a higher

urban shrinkage rate implies a more serious problem of UGS equality. Similarly, the effect of UA on the Gini coefficient supports this inference (Fig. 3.10d). In the Hokkaido region alone, I found that the larger the UA, the more inequitable the distribution of UGS. Due to the development of low-density planarization of cities in the Hokkaido region, large sparsely populated areas not only increase the difficulty of allocating limited social resources, but also increase the risk of creating residential segregation during the population decline phase.

Only the cities in the Hokkaido region and four cities in the Tohoku region demonstrate that per capita income has a significant positive effect on the Gini coefficient (Fig. 3.9d). This means that the higher the economic level, the higher the level of UGS inequality in the cities of these regions. Hokkaido and Tohoku, the most prestigious agricultural production areas in Japan, have more developed agricultural economies. Among the cities in these regions, those with higher income levels are usually dominated by primary industries (e.g., Abashiri city, Mombertsu city), while those with lower incomes are dominated by secondary industries (e.g., Yubari city). Agricultural workers living on the periphery of densely inhabited districts (DIDs) in cities dominated by primary industries not only enjoy services from public green spaces from the city, but also have access to more farmland and natural UGSs. They enjoy far more ESs from the surrounding UGS than residents of urban centers. In contrast, in Hokkaido, shrinking cities with mainly secondary industries are usually mineral resource-based cities, and public housing units built around former industries form housing complexes that are evenly scattered throughout the city [289]. Most of these housing complexes are built in similar environments, thus creating a more even distribution of UGS.

Within five regions (except Kyushu & Okinawa and Chugoku & Shikoku), the population density in built-up areas has a significant negative effect on the Gini coefficient (Fig. 3.9c), which implies that a higher population density may have lower UGS inequality in cities. This result is consistent with previous findings, where metropolitan areas with compact populations may have lower UGS inequality [76]. Furthermore, the effect of this phenomenon is more positive in regions with lower population densities (Hokkaido and Tohoku). Lower population densities have a higher probability of producing isolated housing [245], thus leading to physical segregation of settlements. Therefore, in cities with lower population densities, more attention should be paid to the compactness of the urban population. However, a significant effect relationship of population density on the Gini coefficient was not observed in the Kyushu & Okinawa and Chugoku & Shikoku regions, and the effect relationship tended to be significant ($p < 0.1$). A possible explanation is the presence of strong influence points that affect the model fit, such as in Nakama city in the Kyushu region. Nakama city is the most densely populated shrinking city in the region, which still has a high Gini coefficient (Gini = 0.763). The Ongagawa river divides Nakama city into the eastern and western areas. On one hand, residences and businesses are concentrated mainly in the eastern area, which accounts for 90% of the population. On the other hand, in the western part of the city, 10% of the residents enjoy most of the farmland and parks [290]. This layout of the city is because of the coal mining industry and the first railway line (Chikuho-Honline); most of the population is concentrated along the railway line. The specificity of urban planning leads to a particularly serious problem of inequality in urban facilities. Another possible explanation is that minor differences in

population change may have little effect on the distribution of the UGS, as the cities in the two regions differ very little in terms of population density (Fig. 3.7d).

The compactness of the urban population does not represent the compactness of urban patches. The COMP represents the compactness of urban patches. In the OLS model, the effect of COMP on the UGS inequality is not significant, but in the GWR model, the more compact the urban patch is, the less conducive it is to the equal distribution of UGS. The effect of compactness of urban patches on the Gini coefficient is significant in five regions of Japan (except Hokkaido and Tohoku) and more positive in the Kyushu & Okinawa region (Fig. 3.10c). This situation may be related to the dominant industries in these regions. In Hokkaido and Tohoku, where cities dominated by primary industries are predominant [221], urban patches are predominantly residential, and the more concentrated residential patches do not affect the equal distribution of UGS. In contrast, cities dominated by secondary or tertiary industries have more industrial and commercial patches. The compact proximity of these patches to residential patches may lead to a decline in UGS and disparities in residential environments [291].

The centrality of urban patches is represented by the Moran's I of urban form indicator. The Moran's I of urban form has a significant negative effect on the Gini coefficient only in the Hokkaido and Tohoku regions (Fig. 3.10a). This result indicates that the more monocentric the city is in Hokkaido and Tohoku, the more the UGSs tend to be equitably distributed. This result differs from the findings of Xu et al. (2018a). They argue that polycentric cities in developing cities can distribute UGS better because they share more housing pressure than monocentric cities [76]. However, because of long-term

urban contraction, urban financial pressure gradually increases while housing pressure gradually decreases [292,293]. Consequently, sub-centers are often found to be restricted in development and construction, and even gradually decay and disappear [294]. In the Hokkaido and Tohoku regions, polycentric urban planning has resulted in sparser and more dispersed urban sub-centers due to lower population numbers and density. Although this is not a problem during the period of population growth, it is highly likely to lead to residential segregation in urban sub-centers as the population gradually declines, thus creating problems of UGS inequality.

DI is an indicator of the fragmentation of urban patches. In most regions (except Hokkaido), DI has a significant negative effect on the Gini coefficient and shows a more positive relationship in the Kansai and Chubu regions (Fig. 3.10f). Higher fragmentation of urban patches means that the mix of patches and forests may be higher. Therefore, their access to UGSs is greater, thus promoting an equal distribution of UGS. For the three cities in the Tohoku region and the cities in the Hokkaido region, there was no significant relationship between DI and the Gini coefficient. In these cities, although urban fragmentation increases residents' access to UGSs, fragmentation of urban patches further decreases the concentration of urban population distribution and may result in a polycentric development pattern. Considering the sparsely populated character of these cities, fragmented sub-centers may lead to residential segregation as the population decreases.

AWMSI and PLADJ are indicators of the shape and continuity of urban patches, respectively. In all regions, both indicators have a significant effect on the Gini

coefficient (Fig. 11b; Fig. 11e). Among them, AWMSI has a significant negative effect on the Gini coefficient, while PLADJ has a significant positive effect on the Gini coefficient. It indicates that the worse the continuity of urban patches, or the more complex the shape of urban patches, the lower the UGS inequality. The gradient of regression coefficients for both indicators gradually increases from southwest to northeast and shows the most positive effect in Hokkaido. Complex urban patches can increase the mix of UAs with UGSs [131]. Urban shrinkage seems to make urban patches more complex, as population decline generates many vacant plots. These vacant plots can further contribute to the equitable development of UGSs if they are converted into new UGSs [144]. It is because more vacant plots tend to be generated in more vulnerable communities [295]. Previous studies have concluded that green connectivity can effectively mitigate inequality in UGS and GI [141,296]. Higher urban patch continuity may lead to less connected UGSs, because urban patches block the development of UGS continuity, thus increasing its inequality. Paradoxically, higher continuity of urban patches often implies a more efficient urban transport system [135] that may enhance the accessibility of UGSs. Therefore, greenways and roadway greening seem particularly important, as they ensure greenspace accessibility while enhancing urban greenspace equality. In addition, studies have demonstrated that street greening is associated with residents' willingness to travel [297,298]; and enhances the well-being of UGSs [299].

3.5 Limitations and future directions

Despite the extensive analysis of the development of UGS inequality in shrinking cities in this study, it has some limitations. First, GWR is advantageous when dealing with

spatial autocorrelation. Compared with OLS, GWR is better in terms of goodness-of-fit. However, there are still factors that may affect model fitting: 1) the model still includes unknown omitted variables and 2) there may be non-monotonic influence relationships between predictor and explanatory variables. Future research should give more consideration to the potential factors affecting the UGS inequality and the nonlinear relationship between the distribution of UGS and urban form. Second, due to workload constraints, this study did not consider the quality of all UGSs in the city. This shortcoming may lead to measurement errors in UGS inequality, as UGS gentrification also affects its equitable development. Third, this study did not consider differences in ESs resulting from differences in UGS types. For example, although farmland is open and visible in Japan, it provides less cultural ESs than other UGS types. Future research could combine the quantity, quality, and ESs of UGS to explore the development patterns of UGS inequality more comprehensively. Finally, as this study focuses mainly on measuring UGS inequality in residents' daily lives, it uses the residential buffer as a reference for measuring UGS inequality. As I were constrained by the data, I did not consider the UGS inequality of residents in terms of work and mobility. Future studies could consider examine UGS inequality from the perspective of residents' mobile trips using mobile data.

4. Conclusion

Unlike previous investigations that discuss the UGS inequality, the focus of this study is on shrinking cities. Such cities exist not only in Japan but in many countries, so the exploration of UGS in shrinking cities should not be neglected. Moreover, this study not

only depicts the urban spatial forms of all Japanese cities that experience continuous contraction by establishing urban form indicators but also, for the first time, predicts the effects of urban form on the equitable distribution of UGS by OLS and GWR. The results establish that 1) the urban form of shrinking cities in Japan show an obvious non-smooth spatial relationship, and the majority of cities manifest a network-type development pattern; 2) In the Hokkaido region, higher urban shrinkage rates lead to worse UGS inequality; 3) In most cities, the denser the population, the lower the UGS inequality (except Chugoku & Shikoku, Kyushu & Okinawa areas); 4) AWMSI and PLADJ are the two most important urban morphological indicators affecting UGS inequality; the more complex or lower continuity of urban patches, the higher the UGS equality. 5) In the Hokkaido and Tohoku regions, the monocentric urban development pattern is more favorable to the UGS inequality distribution; 6) In the cities of Kanto; Chubu; Kansai; Chugoku & Shikoku, and Kyushu & Okinawa regions, the patch fragmentation is higher, or the patch is looser, and the UGS inequality is worsen.

This chapter reveals the potential relationship between urban form and UGS distribution, provides practical spatial development strategies for managers of shrinking cities, and helps promote sustainable UGS development in the context of urban shrinkage. Specifically, it will advise policymakers to steer the development of shrinking cities toward monocentric, complex, decentralized population compact cities and emphasize the importance of vacant land and roadway greening in shrinking cities. In addition, the results caution that policymakers should pay attention to the non-smooth relationships between different cities and that planning strategies for different cities should be focused on differently. Urban shrinkage exists in many countries, not only in

Japan, and understanding the inequality issues of urban shrinkage in different countries and finding solutions to equality issues together with national conditions can help cities develop more sustainably.

Chapter IV. UGS inequality based on morphological spatial patterns

1. Purpose of this chapter

The available evidence on the spatial structure and UGS inequality is still insufficient. Therefore, this study analyzes the impact of UGS structure on UGS inequality based on a survey study of Yokosuka City. It aims to focus on how Yokosuka City can conduct UGS planning more rationally and sustainably in the context of urban shrinkage. The specific objectives of this study are to.

1) analyze the spatial distribution characteristics of UGS inequality in the study area;

2) analyze the spatial structure and morphology of UGS;

3) examine the effects of MSPA classes on UGS inequality; and

4) provide knowledge for urban planning and design in the context of the current situation and development policies of shrinking cities in Japan.

2. Materials and methods

2.1 Study area

Yokosuka City is in the southeastern part of Kanagawa Prefecture, Japan, covering approximately 100.7 km^2 (Fig. 4.1). Japan is a mountainous island nation, with approximately 71% of the area comprising hilly terrain. Yokosuka is a typical hilly and

mountainous city in Japan.

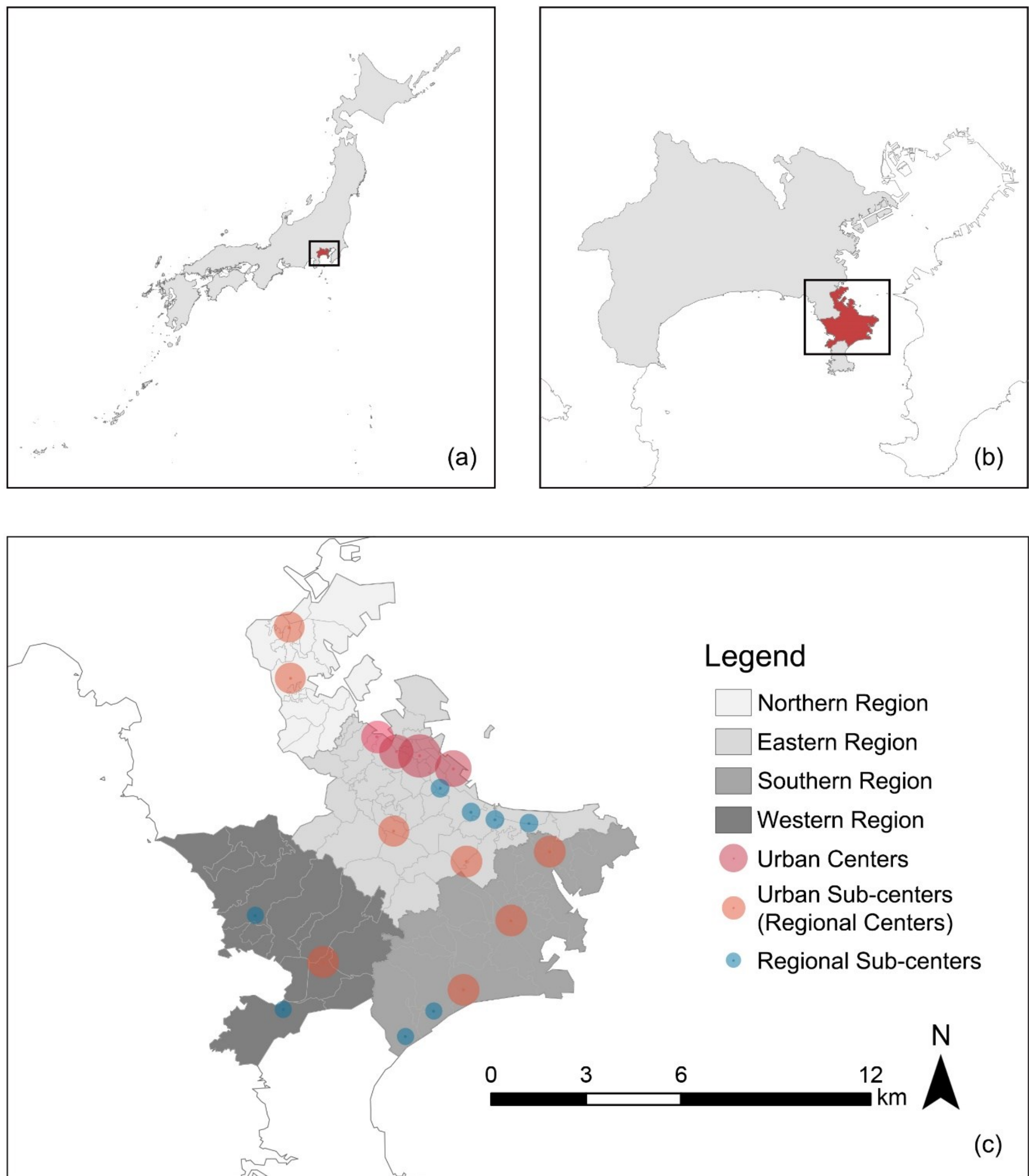

Fig. 4.1 Location of Yokosuka in Japan. (a) Location of Kanagawa Prefecture in Japan; (b) Location of Yokosuka in Kanagawa Prefecture; (c) Yokosuka City.

According to the 2015 census, the population of Yokosuka was 406,586, with a

population decrease of − 5.15% from 2000 to 2015 and a projected decrease of − 28.43% from 2015 to 2045 [255]. According to the net out-migration data of cities, towns, and villages published by the Ministry of Internal Affairs and Communications, from 2013 to 2018, Yokosuka ranked first in net out-migration in the Itto Sanken metropolitan area (one metropolis, three prefectures) which includes Tokyo, Kanagawa, Saitama, and Chiba prefectures (https://dashboard.e-stat.go.jp/dataSearch).

Yokosuka City is divided into four regions containing 112 Neighborhoods (Fig. 4.1), and urban plans are developed based on the socioeconomic and UGS statuses of the four regions [300]. To address the decreasing population, the City of Yokosuka has taken urgent measures. In March 2016, Yokosuka City developed a planning strategy to establish a network-based compact city [301]. According to the network-based development, Yokosuka has established three network center levels: urban center, urban sub-center (regional center), and regional sub-center. From an environmental policy perspective, a new Yokosuka City Green Basic Plan was established in 2016. In the future, Yokosuka City will aim to become a “green city” where various kinds of green plants are located close to each other, and to create a comfortable living environment in response to a declining population, fewer children, and an aging population.

Recent data show that the unemployment rate and income gap in Yokosuka City are widening and becoming progressively higher than average. This indicates that social inequality in Yokosuka City is gradually increasing. The widening unemployment rate and income gap may lead to housing segregation between the rich and the poor in Yokosuka City, resulting in a huge gap in living conditions among residents. Therefore,

it is necessary to explore UGS inequality in Yokosuka City.

Finally, Yokosuka City is a typical mountainous city in Japan that is dominated by natural UGS and is rich in natural UGS. The natural UGS morphology and spatial patterns here are more complex and diverse than in urban parks. Therefore, it is particularly important to explore the inequality of UGS in Yokosuka City and its relationship with the spatial pattern of UGS. This study is not only important for Yokosuka City, but also can provide valuable references and guidance for other shrinking cities in Japan that are dominated by natural UGSs.

2.2 Data collection and preparation

This study collected the 2015 population data (grid, 100 m) created by Nishizawa (2021) [254]. These data have higher precision than the 500 m grid census data as they are based on a high-quality land cover map from ortho-corrected multispectral SPOT6 satellite remote sensing imaging (October 9, 2015). The SPOT6 satellite remote sensing image has a spatial resolution of 6 m (pan-band 1.5 m). The SPOT6 images were first fused by Gram-Smith panchromatic sharpening algorithm, followed by radiometric calibration and atmospheric correction [302]. The satellite images were then divided into land cover maps (1.5 m × 1.5 m) with five land cover classes by support vector machine classifier: woodland, grassland, farmland, water, and built-up areas. In this chapter, the UGS uses the broad UGS definition of green space coverage. Considering the availability of UGS, I also acquired the land use map of Yokosuka City, from which I defined urban public spaces as “forest,” “natural land,” “public facility land,” “road

land,” and “public open space”. The land use map was overlaid with the land cover map to obtain all public green spaces, including all natural UGSs, UGSs affiliated with public facilities, road UGSs, and parks (Fig. 4.2).

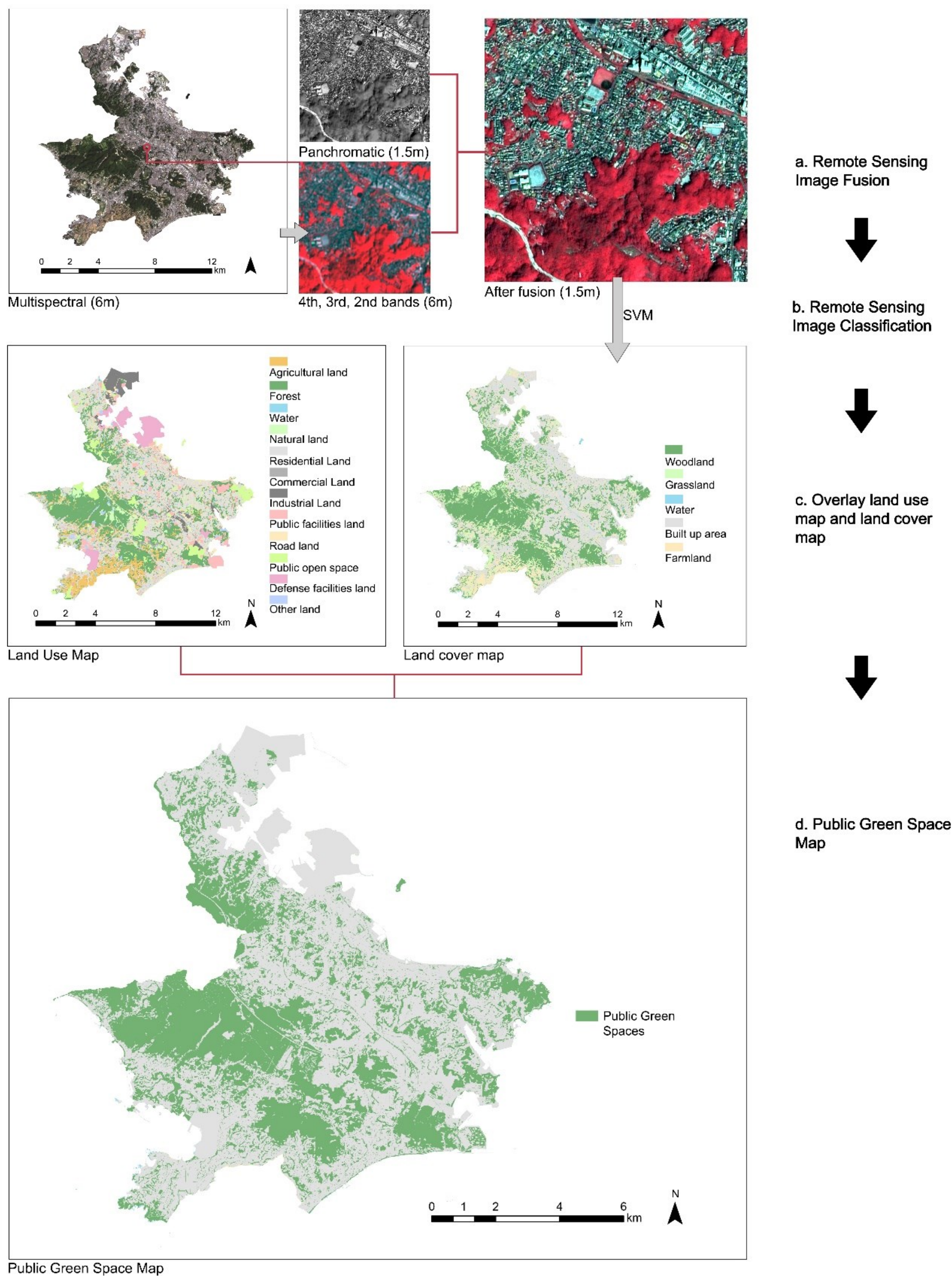

Fig. 4.2 Identification of UGSs in the study area.

2.3 Measuring UGS inequality

Considering the daily activities of the residents, I created a buffer zone of 500 m around each residential area, the maximum distance recommended for acquiring UGS and an appropriate distance for an average person to walk [303,304].

In this chapter UGS inequality measures the area of the UGS around the resident, measuring the subliminal benefits provided by the UGS, services that can be enjoyed passively without the resident having to visit. UGS inequality is created separately for all population grids in the neighborhood and quantifies the magnitude of the difference in UGS area per capita within all buffers to obtain an overall value. I used the Gini coefficient as an indicator to quantify UGS inequality. It can be divided into the following steps: 1) create 500 m buffers for all population grids in the neighborhood; 2) measure the area of UGS per capita in each buffer; and 3) use the Gini coefficient to quantify the difference in area per capita of UGS within all buffers and evaluate the UGS inequality.

Creating a separate Gini coefficient value for each neighborhood facilitates a visual description of the degree of inequality of the UGS within the neighborhood. It can be expressed as:

$$GINI = 1 - \sum_{i=1}^{n} \frac{P_i}{P}(G_{i-1}+G_i) \quad (4\text{–}1)$$

where P is the total population of the district, P_i is the total population of residential site i, and G_i is the cumulative total area of UGS within 500 m of residential site i.

2.4 Morphological spatial pattern analysis

MSPA is an effective method for studying the spatial pattern of UGS [141,305]. From the final green space map, I used UGS as the foreground and the other land use types as background. These data were converted to binary raster data in TIFF format with 2 M pixels in compliance with the upper limit of the software to ensure the most accurate analysis results using high precision images. The latest GuidosToolbox 3.0 was used to identify the morpho-spatial pattern of UGSs in Yokosuka [166]. I used eight domain-defined connectivity rules to measure the different connectivity of the eight pixels surrounding each pixel. I set the edge length to five pixels and the physical width of the edge to 10 m. I then derived seven non-overlapping classes of MSPA: core, edge, perforation, bridge, loop, branch, and islet (Table 4.1).

The proportion of the area covered by each MSPA category was calculated using the following equation:

$$P_i = S_i / S * 100 \tag{4–2}$$

where P_i represents the proportion of different MSPA classes in the buffer, S_i represents the area of different MSPA classes in the buffer, and S represents the total area of all MSPA classes in the buffer.

Table 4.1 Definition of MSPA classes.

MSPA classes	Definition [166]
Core	The area where the distance between the UGS pixel and the built-up area is longer than the set edge width (10 meters).

Perforation	The transition area between the core and the inner built-up area; the inner edge of the core.
Edge	The transition area between the core area and the outer built-up area; the outer edge of the core area.
Bridge	UGS pixels connecting at least two separated cores.
Loop	The core connects itself to the UGS pixel.
Branch	Pixels of UGS that extend from the core to the built-up area, but do not connect to other core areas.
Islet	Isolated pixels of UGS that are not connected to any other classes.

2.5 Classified into structural classes

Similar to Wang et al. (2019), I further describe the MSPA classes as structural types of UGSs based on the characteristics of the MSPA classes and the morphological characteristics of UGSs in Yokosuka City [141]. The seven classes and their geometric characteristics helped us analyze the morphological structure of UGSs and identify potential UGSs and park types based on the Japanese UGS classification. Seven MSPA classes were divided into seven structure classes (Fig. 4.3): polygon core (core), fragment (islet), outer boundary line (edge), inner boundary line (perforation), external connector (bridge), internal connector (loop), and partial connector (branch).

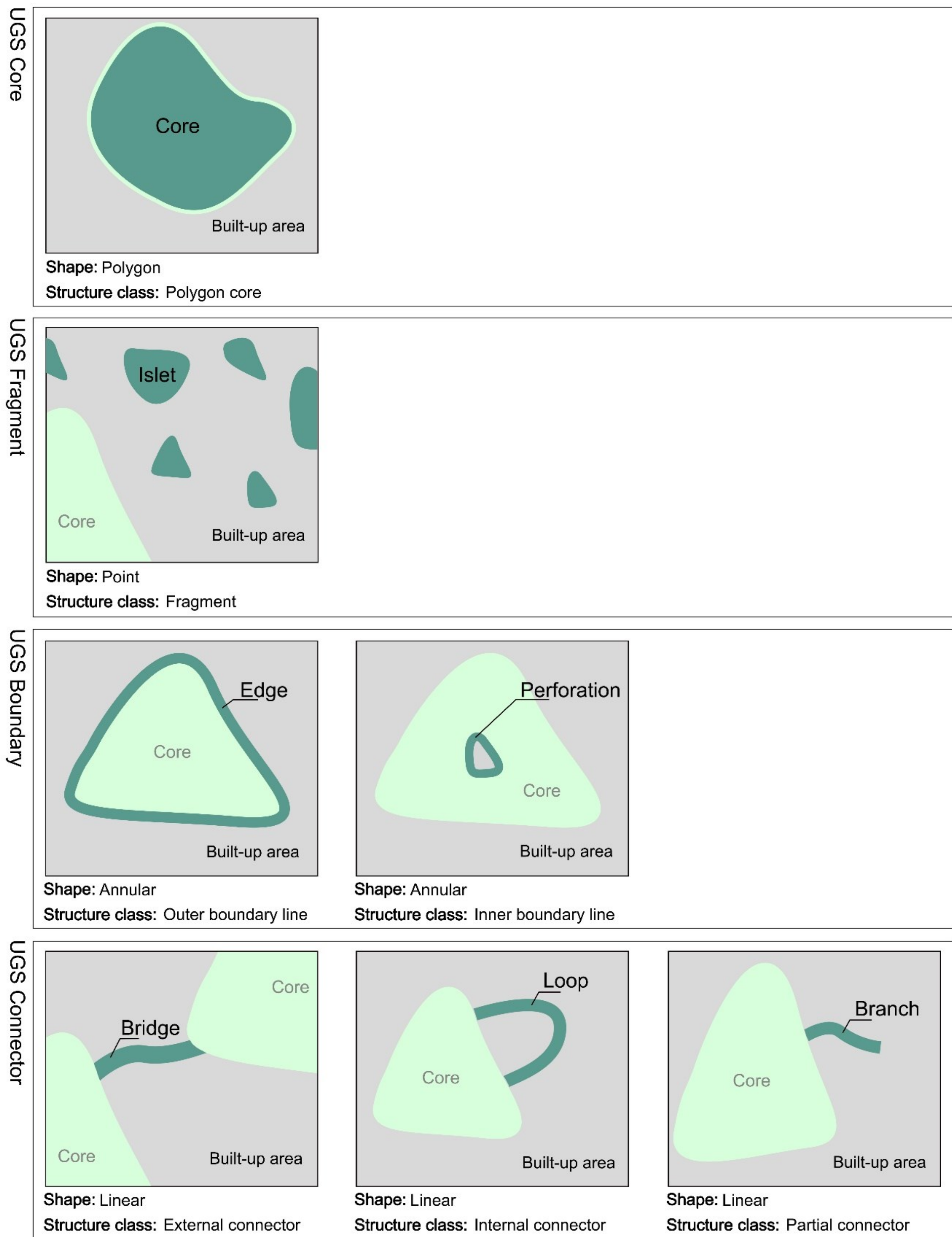

Fig. 4.3 MSPA classes converted into structure classes.

Cores are defined as polygonal cores, usually large UGSs in cities (e.g., forests,

integrated parks), that are core habitats for organisms and provide a large number of ESs to the city. A higher percentage of UGS cores represents a more complete UGS. Islets are isolated islands of fragmented UGS in the city, usually small UGSs, such as community gardens and street trees. Therefore, the higher the percentage of islets, the more fragmented the UGS is.

The perforation and the edge together form the boundary of the core UGS in the city, the geometry of which is a closed annulus of the UGS edge. Whereas the perforation is the inner boundary formed by the built-up area inside the core of the UGS, the edge is the outer boundary that represents the transition from the core of the UGS to the outer built-up area. These outer features typically share the same UGS type as the core but are more accessible than the core because they are closer to the built-up area. A higher proportion of penetrations and edges implies a more complex UGS pattern, as complex UGS leads to an increase in the length of the UGS boundary.

Bridges, loops, and branches usually present a linear geometry, representing connectors with different structural strengths. The bridge, as an external connector, is an important pathway that connects different large UGSs and permits the transformation of material energy between them. In contrast, the loop provides a self-cycling pathway for the UGS by connecting itself and can be seen as an internal connector of the UGS. The branch can be seen as a product of the further urbanization of the bridge and the loop. Compared to the bridge and loop, the branch provides less UGS connectivity but is an important pathway that connects the built-up area to the UGS core and is therefore classified as a partial connector. Connectors represent the connectivity of UGSs, usually

belt UGSs, such as road greening, greenways, and belt woodlands.

2.6 Socio-economic variables

Five socioeconomic variables were selected to describe the relationship between socioeconomics and UGS inequality in different neighborhoods in Yokosuka City: population growth rate, aging rate, proportion of children, population density, and average land price (Table 4.2). The population growth rate can indicate whether there is a population decline. The proportion of children and the proportion of older people is also an important indicator for Japanese cities, most of which are facing serious problems of childlessness and aging [306]. Population density can laterally reflect the distribution of the urban population and is an important indicator of UGS inequality [76]. The average land price can laterally reflect the economic status of neighborhood residents, and the distribution of UGS is more equitable in areas with better economic status [76].

Table 4.2 Descriptive statistics of socio-economic variables.

	Minimum	**Maximum**	**Mean**	**SD**
Growth rate (%)	-97.401	71.838	-1.512	25.406
Population density (N/km^2)	107.181	5346.135	1747.809	902.509
Elderly (% 65 years old and above)	0.197	47.791	26.012	10.160
Children (% 14 years old and below)	0.547	33.116	11.813	5.489
Land price (yen/m^2)	49734.984	528995.135	145278.970	87510.308

2.7 Statistical analysis

Neighborhood-level UGS entitlements are expressed as predictor variables through the Gini coefficient. The explanatory variables consisted of two categories: 1) the five socio-economic variables for neighborhood level; and 2) the percentage of MSPA classes within the neighborhood-level residential buffers. The neighborhood-level residential buffer is a dissolved buffer of all residential buffers within the neighborhood. Figure 4.4 shows the framework of the study and how the data were created.

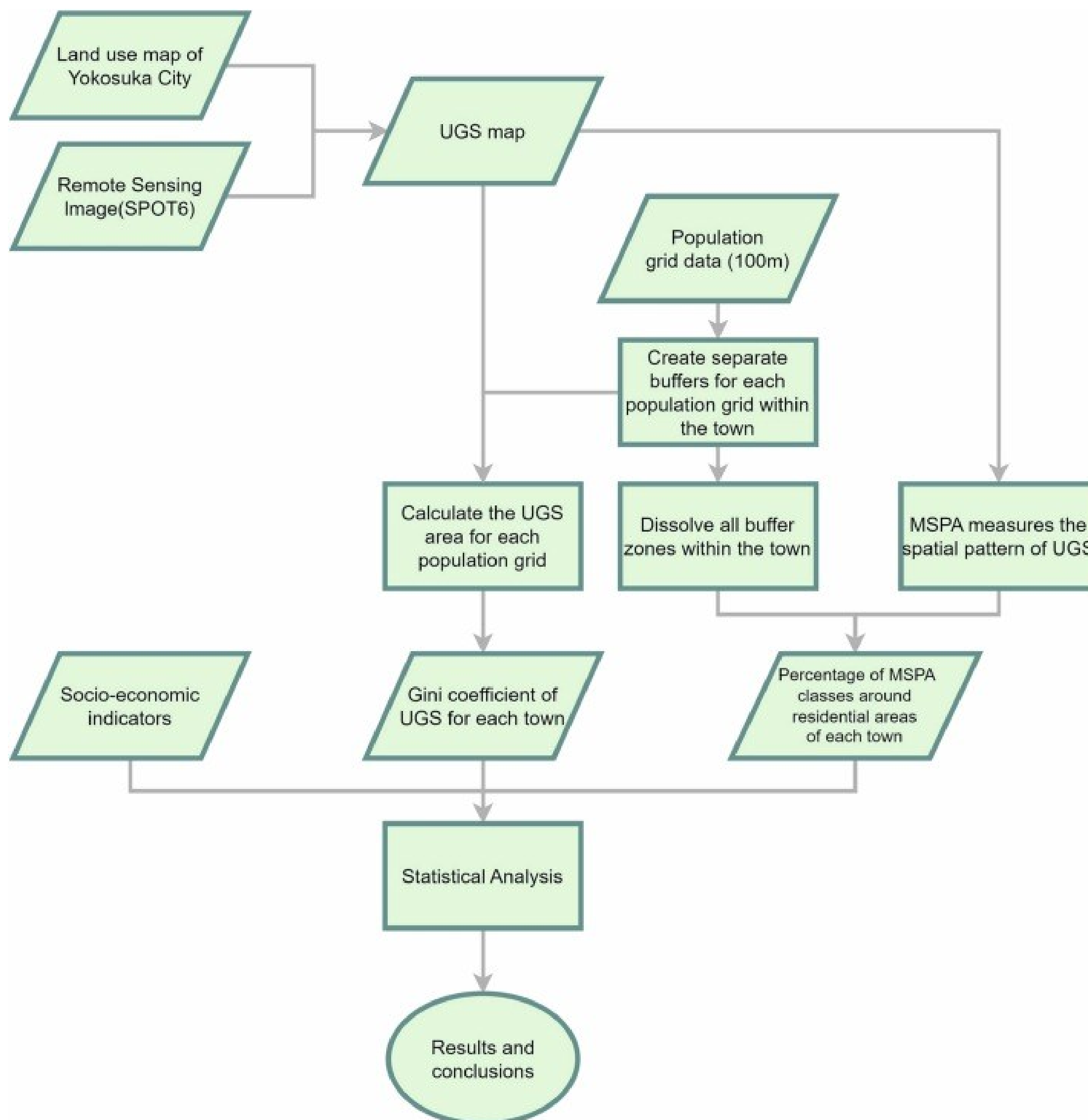

Fig. 4.4 Framework of the study.

I first measured differences in the Gini coefficient and the proportion of MSPA classes among the four regions of Yokosuka City using the nonparametric Kruskal-Wallis test and Dunn's post hoc test. Second, the variance inflation factor (VIF > 10) were used to determine if there was multicollinearity among the explanatory variables. Given multicollinearity, ridge regression was used instead of ordinary least squares (OLS), because multicollinearity can cause errors in the estimation of OLS models. Ridge

regression is a regularization method that provides a biased estimation of the data to improve the stability of the regression coefficients [307], which is suitable for fitting explanatory variables with multicollinearity. The estimation of the parameter k in ridge regression is crucial. It can be determined by ridge trace, whereby the value of k is optimal when it is stable [308].

3. Result

3.1 UGS inequality results

I measured the level of UGS inequality for each neighborhood in Yokosuka City using the Gini coefficient, excluding neighborhoods with less than two population data grids. Gini coefficients for neighborhoods in Yokosuka City ranged from 0.139 to 0.928. This implies that the distribution of UGS in neighborhoods in Yokosuka City varies widely from equality to inequality, and residents' access to UGS exposure varies widely by neighborhood.

According to the Kruskal-Wallis test and Dunn's post hoc test (Fig. 4.5), there was a statistically significant difference in the Gini coefficient between neighborhoods within the western and eastern regions ($p < 0.001$); the median Gini coefficient of neighborhoods in the western region was significantly higher than that of the eastern region, indicating that the inequality in UGS is more serious in the neighborhoods of the western region. The box plot in Fig. 4.5 shows that the western region had a highest average Gini coefficient, while the eastern region had the lowest average Gini

coefficient.

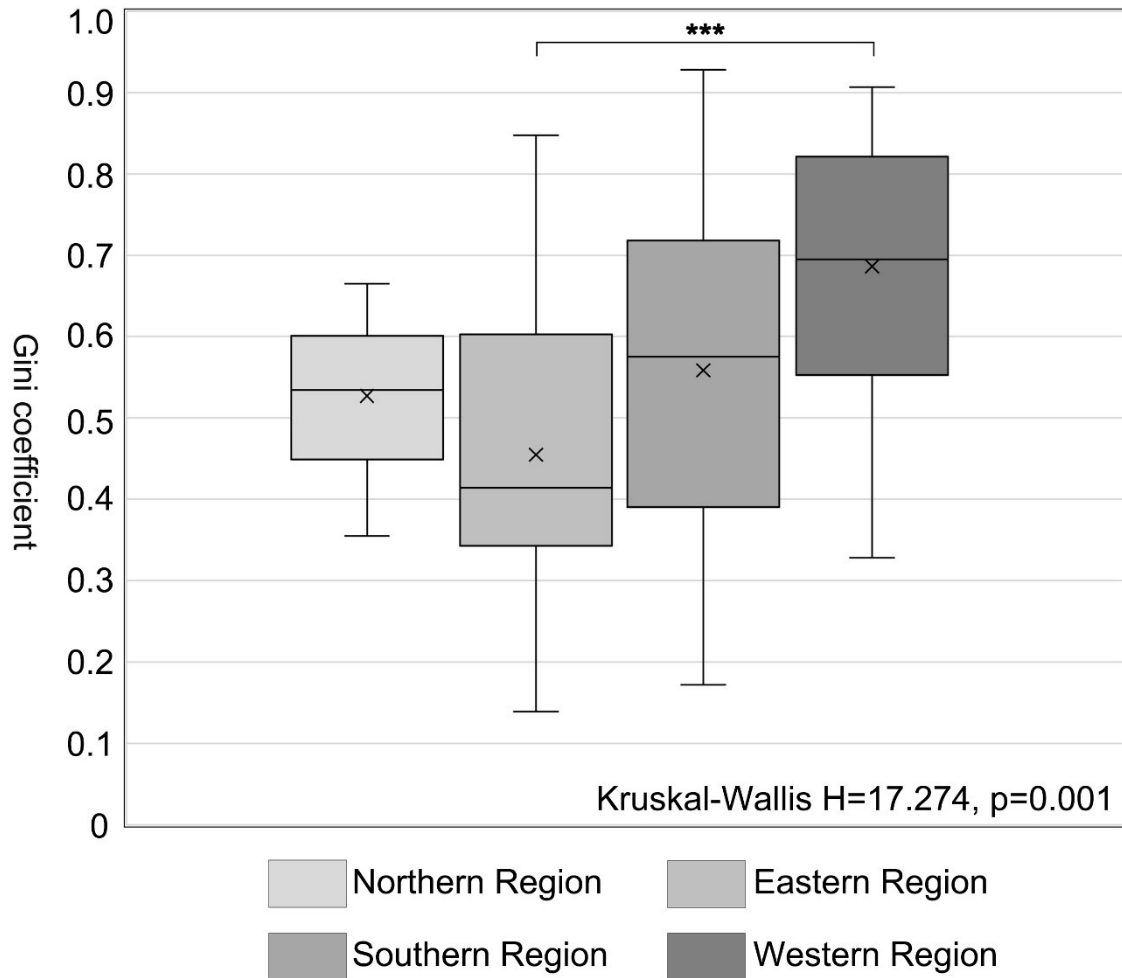

Fig. 4.5 Box plot of Gini coefficient for neighborhoods in Yokosuka City by region. Results of non-parametric Kruskal-Wallis test and post-hoc Dunn's test (*** adj. p < 0.001).

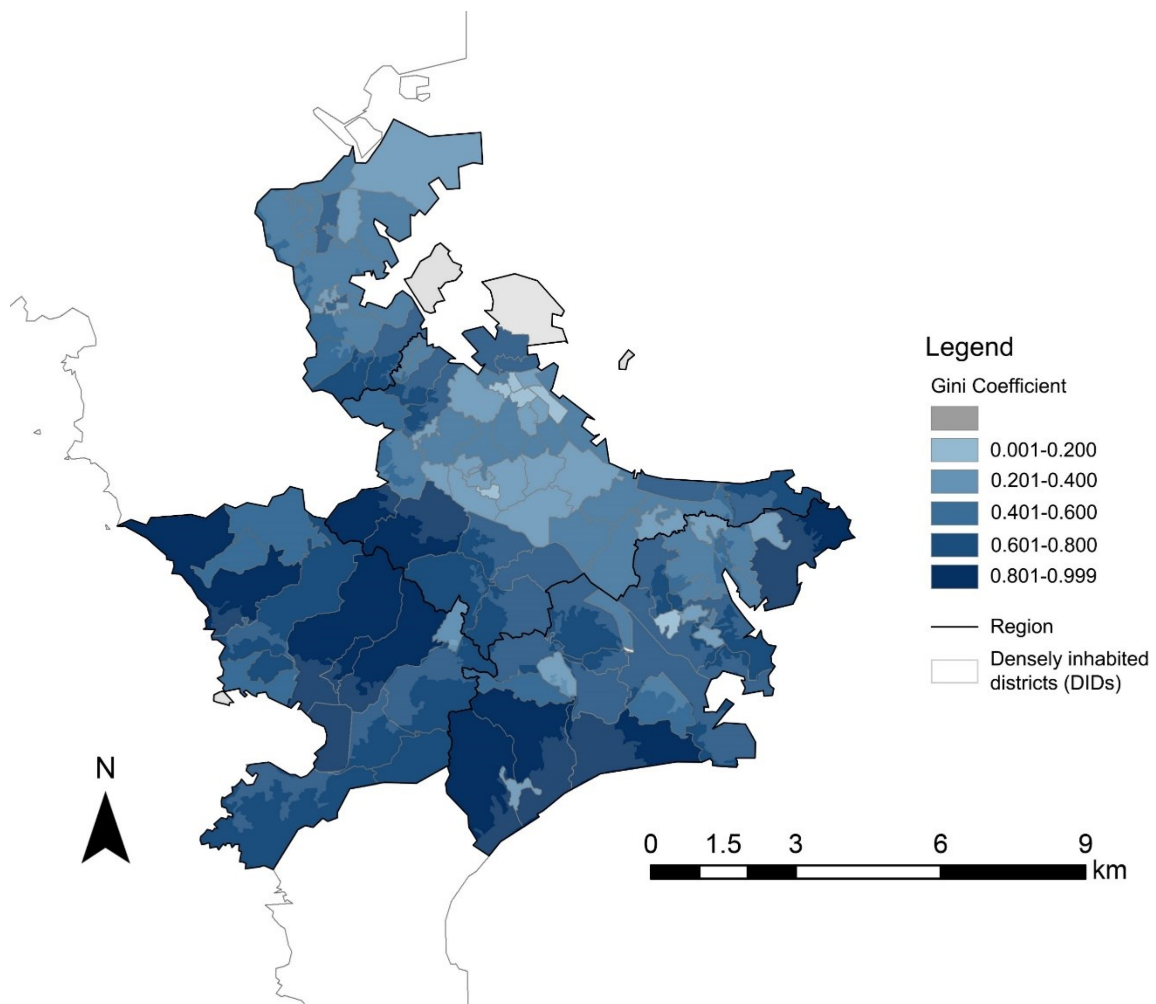

Fig. 4.6 Gini Coefficient of each neighborhood in Yokosuka City.

Figure 4.6 shows that neighborhoods located in the eastern urban centers had lower Gini coefficients, indicating that UGSs are more evenly distributed in neighborhoods located in urban centers. Most neighborhoods in the western region exhibited inequality or extremely inequality of UGS, while in the southern region, spatial heterogeneity, and spatial autocorrelation of equality distribution of UGS were found. An extremely inequality UGS distribution was found in some neighborhoods in the western and southern regions, most of which belonged to the urban and regional sub-centers in the Yokosuka City Network-type Compact City Plan.

3.2 Description of the spatial pattern of UGS based on MSPA

I analyzed the spatial pattern of UGSs in Yokosuka City using MSPA with edge widths of 10 m. Seven MSPA classes were generated (Fig. 4.7). The percentages of MSPA classes from highest to lowest were core (60.6%), edge (12.9%), bridge (8.8%), loop (6.6%), islet (5.9%), branch (3.6%), and perforation (1.5%).

Among the four regions of Yokosuka City (Fig. 4.7), the western region had a larger UGS area, while the northern region had a significantly lower UGS area than the other regions. The western region had a greater number of large UGSs, with core share 12.1%–18.8% higher than the other regions, and the lowest level of fragmentation of UGSs as the islet share was the smallest at 3.5%. Moreover, the western region had the lowest percentage of external connectors (bridges: 8.0%), internal connectors (loops: 4.7%), and partial connectors (branches: 2.7%) among the four regions, which indicates poor UGS connectivity. Contrastingly, the eastern region had the most fragmented UGSs (islets: 8.7%) but presented the best effectiveness regarding UGS connectivity due to having the highest percentage of bridges (10.6%), loops (8.3%), and branches (4.6%). The percentage of inner boundaries (perforation) of the core of UGSs was almost identical in all four areas. The proportion of outer boundaries (edge) from high to low was as follows: northern region (17.6%), eastern region (14.8%), southern region (14.2%), and western region (9.2%). The northern region had the most complicated UGS morphology, while the western region had a simpler UGS morphology.

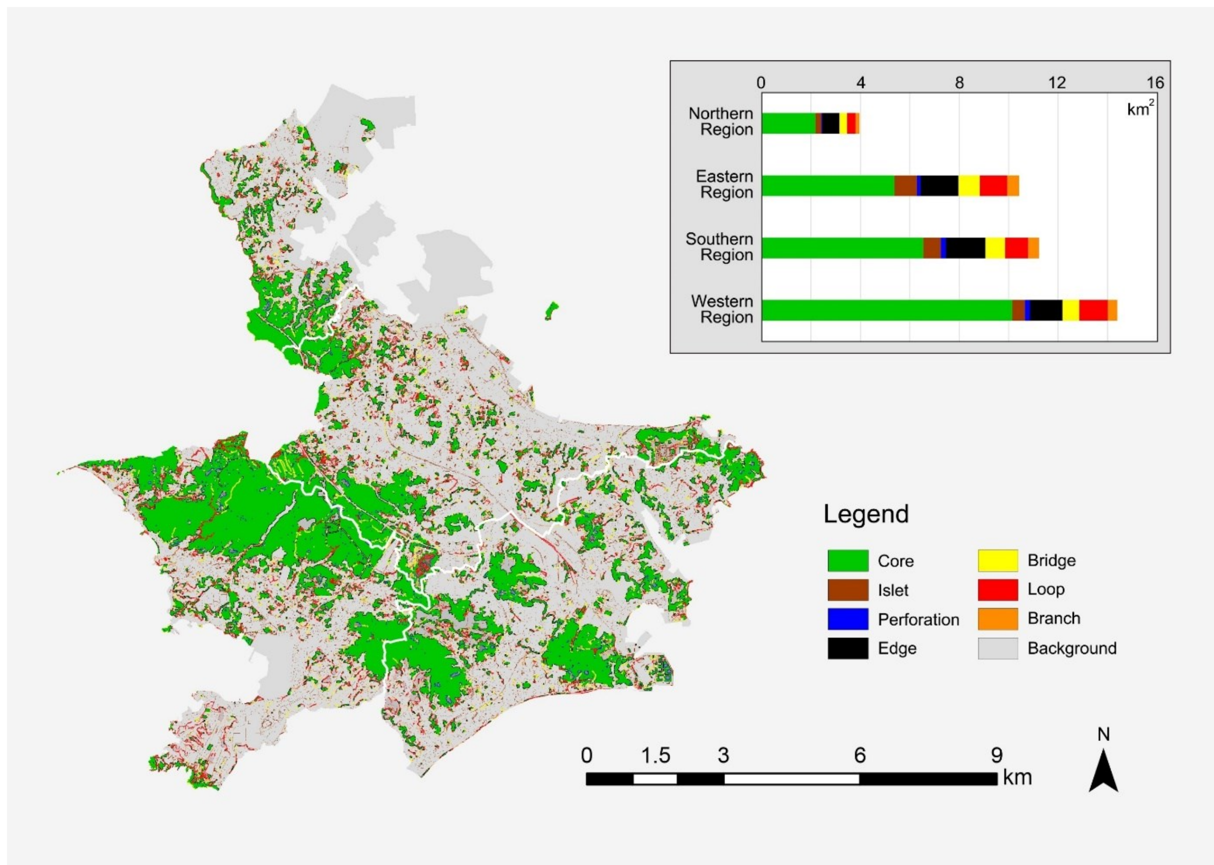

Fig. 4.7 Spatial pattern of UGS in Yokosuka City as identified by MSPA.

3.3 Differences in the proportion of MSPA classes around residences

I compared the differences in the percentage of MSPA grades around residences in the four regions. The results show (Table 4.3) that all MSPA classes differ between at least two regions. Dunn's post hoc test was used for a pairwise comparison of regions (Fig. 4.8).

Table 4.3 Results of Kruskal-Wallis test of the spatial pattern of UGSs around residential areas, between regions.

	Region (Median)	*H*	*p*

	Northern	Eastern	Southern	Western		
Core	38.936	33.537	54.618	59.938	27.561	<0.001***
Islet	7.183	13.558	6.729	4.886	23.06	<0.001***
Perforation	0.627	0.265	1.97	1.168	41.478	<0.001***
Edge	21.009	18.339	15.445	12.243	23.484	<0.001***
Loop	8.325	9.197	7.486	6.666	21.38	<0.001***
Bridge	14.478	12.302	9.487	10.539	15.328	0.002**
Branch	6.078	6.292	3.992	4.218	19.073	<0.001***

** $p < 0.01$; *** $p < 0.001$

Regarding UGS cores, there were statistically significant differences between neighborhoods in the southern-western and eastern regions. Compared to the eastern region, neighborhoods in the western and southern regions had a greater proportion of cores around residences. Regarding the percentage of islets, there was a significant difference between neighborhoods in the eastern region and all other regions. Neighborhoods in the eastern region had a higher percentage of fragmented UGS around their residences than did the other regions.

Regarding external UGS connectivity, the southern neighborhoods had less connectivity between UGSs around residences compared to the northern and eastern regions. Furthermore, neighborhoods in the eastern region had better internal UGS connectivity around residences. Finally, the percentage of partial connectors of UGSs around residential areas was higher in the eastern neighborhoods than in the southern neighborhoods.

In neighborhoods in the northern and eastern regions, the median percentage of

perforations around residences was significantly lower than in the southern region. In addition, the median percentage of perforations around residences in the eastern region was also significantly lower than that in the western region. In contrast, the median percentage of edges around residences was significantly higher in the northern region than in both the western and southern regions; the median percentage of edges around residences in the eastern region was only significantly higher than that in the western region. Overall, the percentage of UGS boundaries around residential areas was higher in the northern neighborhoods than in the other regions; this indicates that the UGS around residential areas were most complex in the northern neighborhoods.

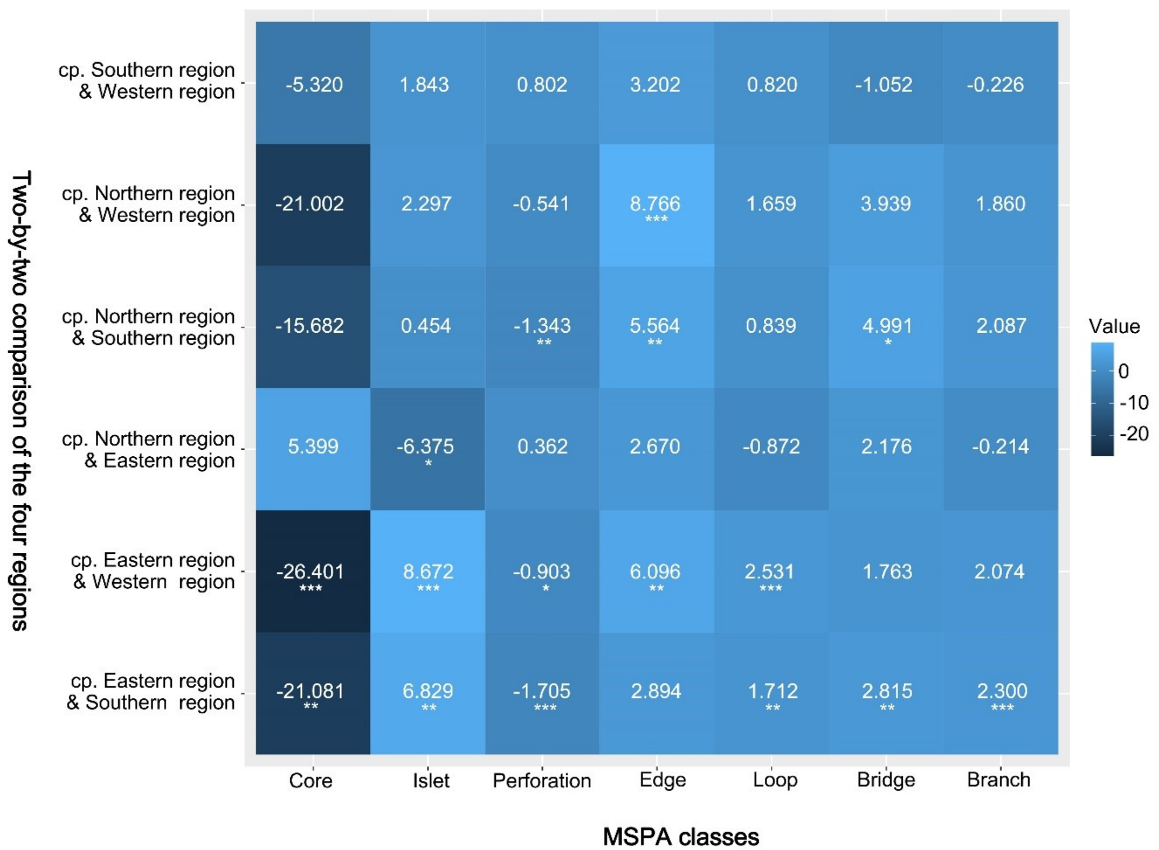

Fig. 4.8 Heat map of Dunn's test of spatial pattern of UGSs around residential areas between regions (cp.: Percentage comparison of MSPA classes between the two regions;

Numbers: median difference values of the percentage of MSPA class; * adj. p < 0.05, ** adj. p < 0.01, *** adj. p < 0.001).

3.4 Correlation between MSPA classes and UGS inequality

Given multicollinearity among the explanatory variables, I used ridge regression to analyze the relationship between the Gini coefficient and both socioeconomic indicators and MSPA classes. The ridge regression reduced the variance explained by the model to some extent in exchange for generating more reliable regression coefficients of the explanatory variables. The optimal *k* value of the model was 0.700 (Table 4.4), at which point the R^2 of the model was 0.444; that is, the socioeconomic variables and MSPA classes explained 44.4% of the variation in the Gini coefficient. The model was significant by F-test ($p < 0.001$), which implies that the ridge regression model was robust.

Table 4.4. Result of ridge regression model.

Categories	Variables	Coefficients	Standard error	p-value
Socioeconomic indicators	Content	0.722	0.047	<0.001***
	Land price	-0.111	0.04	0.007**
	Growth rate	0.008	0.048	0.863
	Children below 14 years of age	0.012	0.048	0.798
	Persons above 65 years of age	-0.085	0.039	0.033*
	Population density	-0.176	0.043	0.000***
	Core	0.069	0.015	<0.001***

	Islet	-0.076	0.034	0.028*
	Perforation	0.017	0.028	0.531
MSPA Classes	Edge	-0.078	0.036	0.035*
	Loop	-0.082	0.041	0.047*
	Bridge	-0.028	0.051	0.591
	Branch	-0.061	0.03	0.046*
R^2		0.444		
Adjusted R^2		0.370		
F		5.934***		
k		0.7		

Dependent variable: Gini Coefficient. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

A higher Gini coefficient implies a more unequal distribution of UGS. The results indicate that land price, proportion of elderly population, and population density are negatively associated with the Gini coefficient. Higher land prices, proportion of elderly population, and population density are associated with a more equal distribution of UGS. Additionally, there was no significant correlation between the population growth rate and the Gini coefficient, which implies that the increase or decrease of urban population in Yokosuka did not affect the equal distribution of UGS.

For the MSPA classes, there is a significant positive correlation of core to Gini coefficient. That is, that the higher the proportion of cores around the settlement, the more unequal the distribution of UGS in the neighborhood. However, islets, edges, loops, and branches have a significant negative correlation on the Gini coefficient, indicating that the higher the proportion of these classes around the settlement, the more equal the distribution of UGS.

After converting MSPA classes to structure classes, I find that the UGS core is positively correlated with Gini coefficient. Furthermore, UGS fragmentation, UGS boundary, internal connector, and partial connector are negatively correlated with Gini coefficient.

4. Discussion

4.1 Spatial distribution of UGS inequality

The study found that the eastern part of Yokosuka City has a more equal distribution of UGS. The Gini coefficient of neighborhoods in the western region is significantly higher than that of the eastern region. In the urban plan of Yokosuka City, the urban center is located in the eastern region, while the western region contains the urban sub-center, new neighborhoods, and suburban areas. There is an extremely inequality of UGS among urban and regional sub-centers in the southern and western regions.

Yokosuka City has developed over a long period into a polycentric network of urban centers, sub-centers (regional centers), and regional sub-centers. This development model has improved the commuting time of residents and thus the operational efficiency of the city [309], which in turn has generated more wealth for the city. However, Yokosuka City is facing urban shrinkage, which may continue. Under the influence of urban contraction, Yokosuka City is facing a long-term fiscal deficit problem [310], and it is difficult for the city to maintain a balanced relationship with polycentric development. The financial inclination and social resource input of the sub-center of the city may

subsequently decline, thus limiting the greenfield development of the sub-center. Meanwhile, the "Location Normalization Plan" policy of compact cities proposes to attract residents to live in densely inhabited districts (DIDs) by reducing the layout of infrastructure near suburban areas [301]. This may further trigger the disinvestment of UGS in sub-centers. Compared to suburban and rural areas, it is more difficult for sub-centers to acquire natural UGS; and compared to urban centers, sub-centers also lack community parks regarding quantity and quality. Thus, sub-center communities are at a disadvantage regarding access to natural UGS and community parks.

4.2 Correlation between socioeconomic indicators and UGS inequality

I measured the correlation of socioeconomic indicators on the UGS inequality in Yokosuka City. Investors are more willing to build UGS in these communities to meet the hedonic needs of the affluent [52]. The demand for UGS around residential areas by affluent communities leads to easier access to UGS [212,311]. Areas with a concentration of affluent people are well built with more evenly distributed UGSs among affluent communities. Although UGS inequality is lower within areas with high land prices, such a phenomenon may promote UGS gentrification [312].

Second, areas with higher proportions of the elderly are associated with equal UGS distribution. This result is consistent with previous studies, which found that such areas tend to have greater park access and more equal access to UGSs [76,101,212]. Older adults have higher attachment to UGSs than younger people do, as they prefer UGSs to other amenities [313,314]. Therefore, UGSs tend to be a priority for older adults when choosing

where to live. Conversely, young people usually prioritize areas close to workplaces or schools.

The inequality of UGSs was higher in regions with lower population density, a result consistent with that reported by Xu et al. (2018) [76]. It has also been claimed that decreasing population density in suburban areas is associated with lower accessibility to UGSs [101]. Compared to sprawling urban development patterns, compact cities reduce the physical spread of cities and increase their population density. Compact cities reduce the potential for green resource concentration in a few groups due to urban sprawl, but compact cities also imply greater supply and demand pressure on UGS. Because higher populations gather in urban areas. Simultaneously, it remains difficult for the government to prevent suburban sprawl due to land prices and the exclusivity of established communities [98]. This bottom-up outward expansion runs counter to the government's proposed compactness policy, resulting in the observed green inequality in urban sub-centers.

Additionally, I do not observe a significant correlation between increasing or decreasing urban population on UGS inequality. This suggests that in Yokosuka City, the current urban population shrinkage has not affected the equitable development of UGS; however, Yokosuka City is still in the early stages of urban contraction [86].

4.3 Correlation between MSPA classes and UGS inequality

The model shows that higher core percentages are associated with unequal UGS

distribution. From the perspective of policymakers, large UGSs in cities are usually assigned a broader range of services. This service area is usually based on accessibility by car rather than by foot. However, communities that are inaccessible by foot to the large UGS are considered to already have the same ESs as communities close to the large UGS, and therefore fewer community green spaces are set up (Fig 4.9). This phenomenon results in communities close to large UGSs receiving far more ESs than those that are inaccessible by walking. Second, areas with more UGSs are often suburban and rural, and the decline in population density and resulting physical separation between communities may also contribute to UGS inequality. However, from the perspective of ESs, cores are considered to be vital in reducing urban temperature [315] and particulate matter [316]; thus, they are a significant component of cities. Therefore, the approach of reducing the proportion of UGS cores to increase the equality of UGS is not desirable.

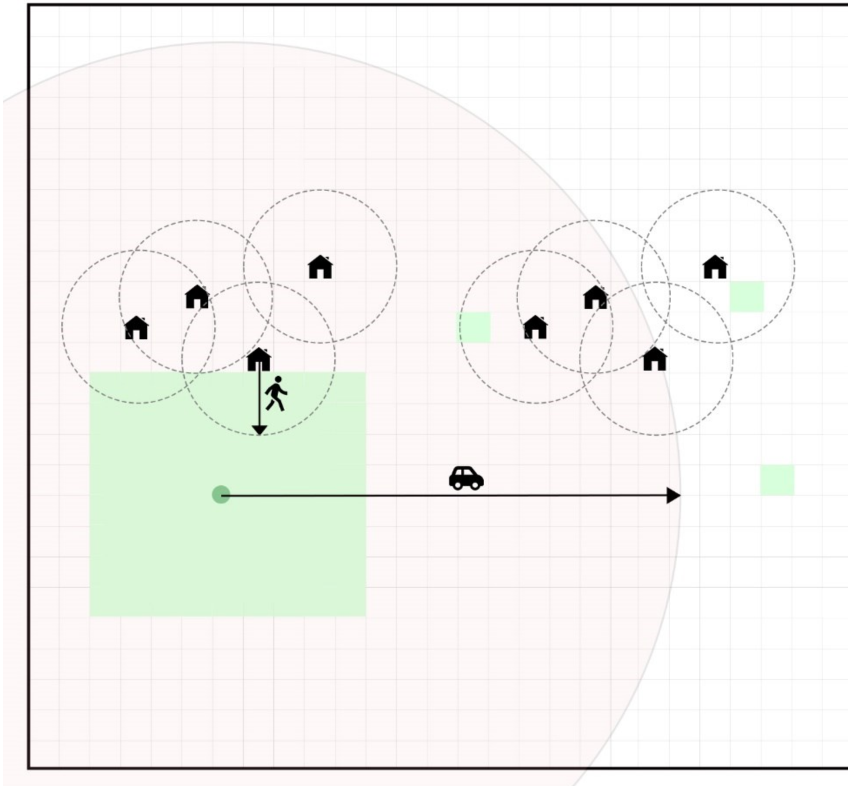

Fig. 4.9 Graphical representation of the relationship between UGS core and UGS inequality

Second, the lower the proportion of islets of UGS around residences, the lower the level of UGS inequality. Islets can be transformed into fragments in the UGS structure class, and the proportion of islets represents the degree of UGS fragmentation. The higher the degree of fragmentation of UGS, the more it is conducive to the equitable distribution of UGS. Fragmentation of UGS provides more green patches in built-up areas of the city, and although the distribution of green patches may be spatially autocorrelated, these patches are more evenly distributed and flexible in cities than are large UGSs (Fig. 4.10) [317]. In addition, islets contains most of the residential UGS (e.g., community gardens, neighborhood parks), which are closer to urban communities and have higher pedestrian accessibility [318]. Additionally, small UGSs are effective in preventing UGS

gentrification [319]. In recent years, research has recognized the important role of small UGSs in sustainable urban development, such as enhancing UGS accessibility [320], reducing the heat island effect [321], and maintaining the mental health of residents [161].

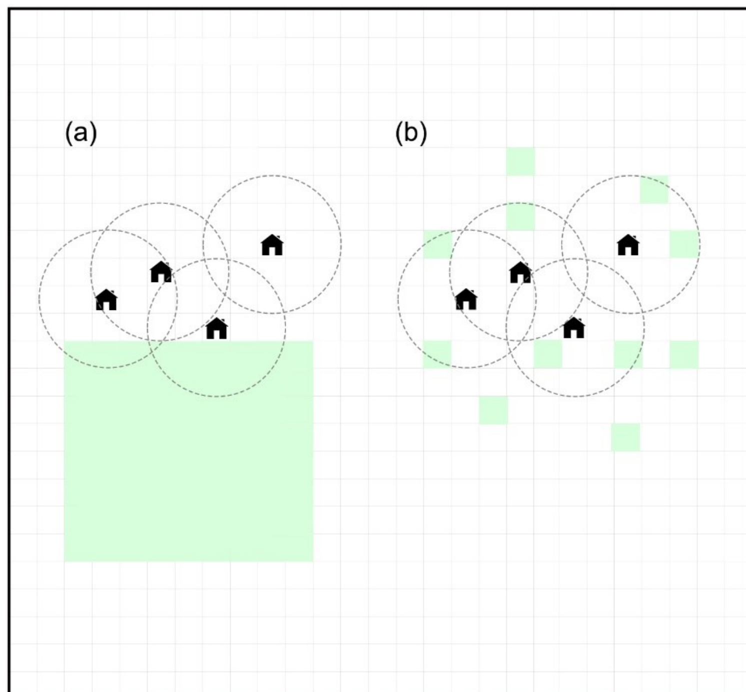

Fig. 4.10 Graphical representation of the relationship between UGS fragmentation and UGS inequality. a) simple rectangular UGS; b) fragmented UGS.

Furthermore, increasing the percentage of edges could mitigate the UGSs inequality. The edge is the outer boundary line of the UGS core and has higher accessibility. Meanwhile, the percentage of boundary lines can represent the complexity of large UGSs [322] because when the UGS form is more complex, the UGS edge length is longer. This means that enhancing the complexity of large UGS forms can mitigate the inequality of UGS. From a geometric morphological perspective, considering UGSs as urban geometric polygons, complex UGSs can increase the mixing of urban built-up

areas with greenery [131,323] and thus increase the possibility of approaching greenery in communities that would otherwise be far from large UGSs (Fig. 4.11). As inner boundary lines, the increased share of perforations can also increase UGS complexity. However, the perforation's effect on the UGS inequality was not significant. One possible explanation is that the internal built-up areas of large UGSs are usually plaza facilities within parks or constructed facilities within forests rather than communities. The increase in inner boundary lines may increase the complexity of the UGS but does not necessarily increase the potential of the community to approach the UGS.

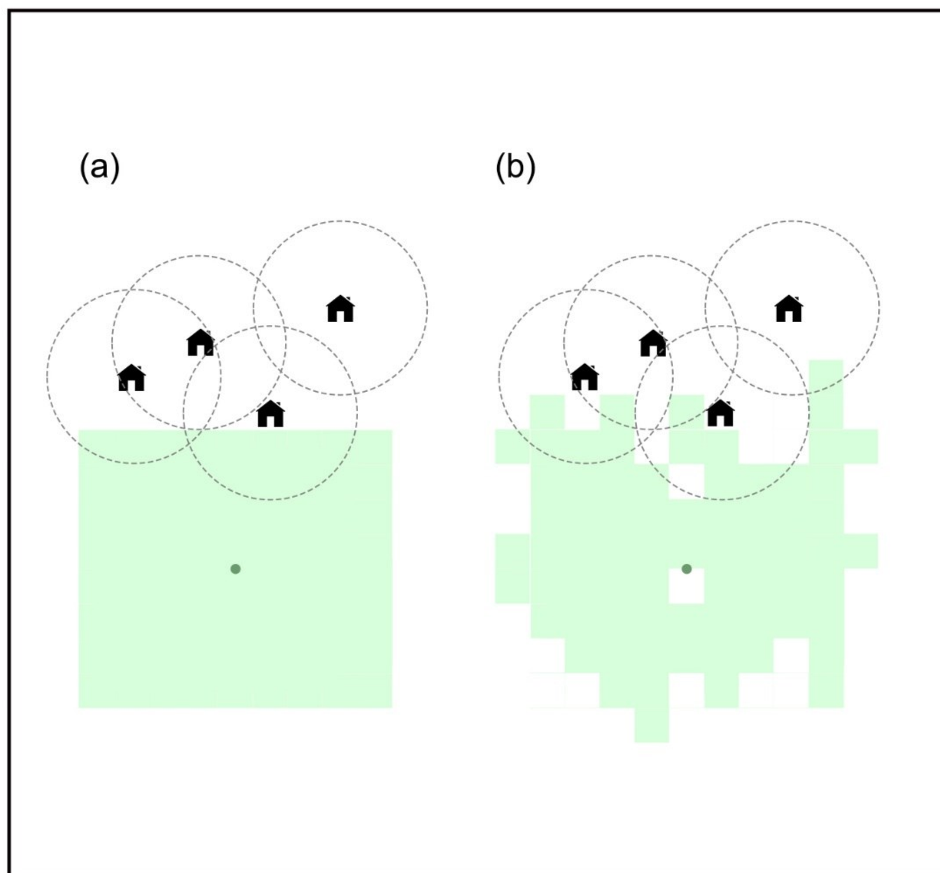

Fig. 4.11 Graphical representation of the correlation between UGS complexity and UGS inequality. a) simple rectangular UGS; b) complex polygonal UGS.

Among UGS connectors, internal connectors (loops) and partial connectors (branches) had a significant negative correlation with UGS inequality. Fig. 4.12 represents the effect of different linkers on the equal distribution of UGS. This result shows that the connectivity of UGS not only has ecological significance, but also helps to mitigate environmental inequalities. From one perspective, the complexity of UGSs is negatively correlated with UGS inequality; as the complexity of UGSs increases, narrower areas in UGSs may be transformed into different types of UGS connectors. From another perspective, the extension of connectors into the interior of settlements not only provides residents with a shared long edge [141] but also provides residents with green shortcuts to large UGSs (e.g., greenways, roadway greening). Some studies have found that street greenery is more likely to motivate urban residents to travel than urban parks [297,298]. Moreover, greenery on the way to parks provides more benefits to residents [299]. Unlike previous studies, bridges were not found to have a positive effect on the equal UGS distribution [141]. A possible explanation is that, unlike studies of community UGSs distribution, the current study focused more on public green spaces in cities. Unlike structures that extend into city's built-up areas (loops and branches), bridges are connectors that extend a large UGS into another large UGS. This extension is closer in location to the core of the UGS than to the residential area.

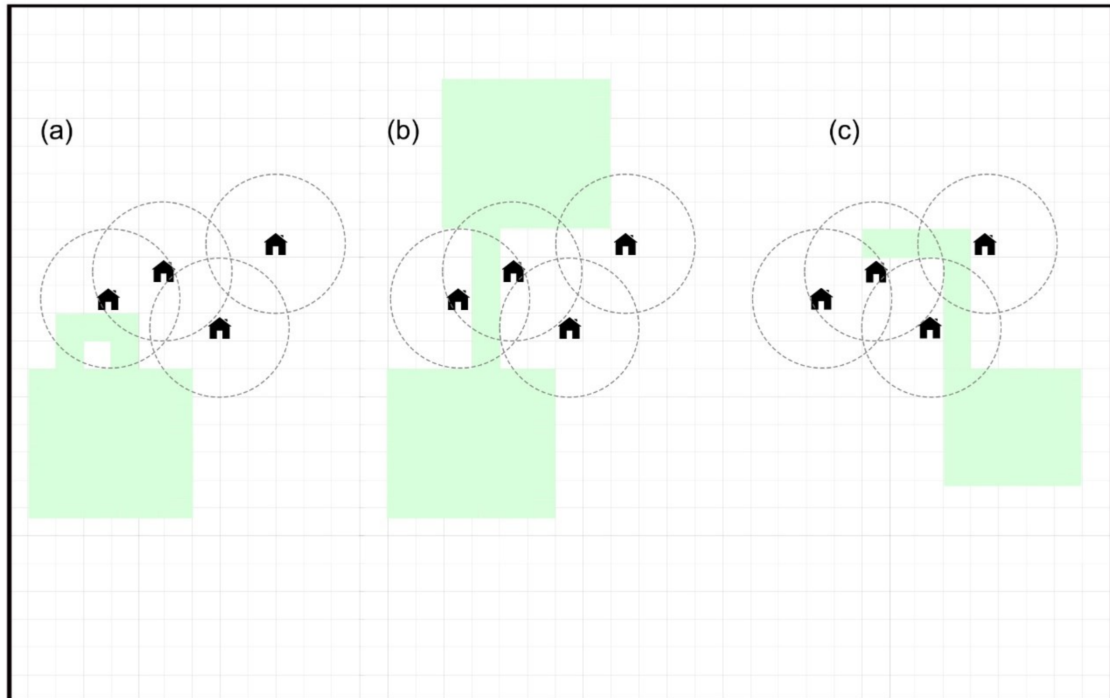

Fig. 4.12 Graphical representation of three UGS connectors correlated with UGS inequality. a) Internal connectors; b) external Connectors; and c) partial connectors.

4.4 Limitations and future directions

First, this was a cross-sectional investigation and thus may be subject to measurement errors due to unknown influences. Longitudinal studies should be considered to measure the dynamics of UGS inequality in shrinking cities. Second, MSPA with different edge widths affects the minimum scale of the core and thus the classification of MSPA classes [324]. Here, only MSPA with a 10 m edge width was considered, and the results are inevitably subject to some uncertainty. UGSs should be explored at multiple scales by setting multiple MSPA edge widths. Finally, the quality of UGSs was not considered in this study [144]. Different UGSs may have an unequal relationship with quality, affecting the ESs provided by UGSs and causing errors in the representations of UGS spatial

distribution inequality in shrinking cities [325]. A detailed quality evaluation system for UGSs must be developed, and different UGS types should be carefully classified and evaluated to ensure a more objective measurement of UGS inequality. Meanwhile, more consideration should be given to the future developmental trends of shrinking cities, and exploratory research on the equality of UGS using population projection data should be considered.

5. Conclusion

Similar to Yokosuka, many shrinking cities in Japan adhere to a policy of compact city development. However, fiscal constraints and land limitations mean that it is unrealistic for cities to simply increase UGS to achieve equitable UGS development. This chapter used MSPA to find the morphological structure of UGS that effectively promotes UGS equality to mitigate the costs required for the urban environment's sustainable development. The findings showed that 1) cores are detrimental to equal UGS distribution; 2) increasing the proportion of edges leads to an increase in UGS complexity, which mitigates UGS inequality; 3) an increase in islet proportion implies a higher degree of UGS fragmentation, which contributes to UGSs' equitable development; and 4) loops and branches are UGS connectors that extend into built-up areas, which enhance the structural connectivity of UGS and contribute to equal UGS distribution.

In addition, the chapter examines the relationship between socioeconomic indicators and the UGS inequality in shrinking cities. No effect of urban shrinkage on UGS

inequality was found in Yokosuka, although urban shrinkage leads to a decline in population and thus in population density. Compact city development strategies play an important role in maintaining equitable UGS development, but it is not known whether continued population decline will hinder such development in the future; thus, I recommend continuous monitoring of UGS inequality dynamics in shrinking cities.

This chapter reveals the effects of all MSPA classes on the equal distribution of UGS. Moreover, it further improves the framework of transforming MSPA classes into structure classes and explains the potential relationship between MSPA classes and the morphological structure of UGSs, providing an improved framework for future studies.

Chapter V. Rethinking UGS inequality based on demographic changes and preferences

1. Purpose of this chapter

In view of the changing demographic structure, in this chapter, I re-considered a key question: how can UGS planning, and accessibility be comprehensively reviewed to accommodate current and upcoming demographic changes? To respond to this important question, I set four specific research objectives: 1) Is it possible to develop a new methodology based on existing research methods that takes demographic changes into account more comprehensively? 2) Is the new methodology able to evaluate the accessibility of UGSs stably and accurately? 3) Is the new methodology effective in identifying differences and variations between UGS quality and different population groups? 4) Have governmental policies, based on the concept of urban planning policies adapting to demographic changes, promoted the equitable development of UGS resources?

Specifically, I developed the Floatable Supply and Demand Improved Two-Step Floating Catchment Area (FSD-2SFCA) method. Using a case study of Higashiosaka city, I first tested the robustness of the method by comparing the differences between the FSD-2SFCA method and existing methods for accessibility measurement. Second, the FSD-2SFCA method was utilized to measure the spatial change patterns of UGS accessibility for different population subgroups and different urban planning areas in the

context of population change (2020, 2040, and 2060) considering the park quality and demographic changes. Finally, based on the empirical results, appropriate recommendations are provided for urban planning policies formulated by the government.

2. Materials and methods

2.1 Study area

In this chapter, the study mainly considers environmental facilities in UGS and incorporates them into a new methodology for assessing UGS inequality. However, it is difficult to identify area boundary and internal environmental facilities in natural UGS, which makes it difficult to conduct the study with consideration of natural UGS. Considering time and efficiency, in this chapter I use a narrow definition of UGS that only includes urban parks in the scope of UGS. In general, urban parks are more deeply influenced by environmental facilities because they are more abundant. Because of this specificity, the choice of the study site is rigorous.

Japan is gradually stepping into a "super-aging society" and the demographic shift is posing a great challenge to the urban health of Japan [326]. Higashiosaka City is in Osaka Prefecture, Japan, and is designated by the Japanese government as a core city (Fig. 5.1). Higashiosaka City has a population of approximately 490,000 and a population density of approximately 8,138 persons/km^2. Since 2000, the population of Higashiosaka City is gradually declining, and the aging of the population is becoming

increasingly serious. It is expected that by 2060, the population of Higashiosaka City will decline to 350,000, with the proportion of older adults rising to 37% [327]. Higashiosaka City provides a very interesting case for the study, because urban demographic change (population decline, ageing and low birth rates) has become one of the most serious challenges facing Higashiosaka city [328].

In addition, Higashiosaka is a highly urbanized city. Compared to other cities, the city does not have diverse environmental zones such as hilly areas where farmlands and forests are distributed. Unlike Yokosuka City, which has abundant natural UGS in Chapter IV, Higashiosaka City represents those typical shrinking cities in Japan where parks are the main UGS resource. However, the total area of urban parks in Higashiosaka city, including city-planned parks, is 140.44 ha in the entire city area and 96.64 ha in the urbanized area. The per capita area of established urban parks is 2.8 m^2 in the citywide area and 1.9 m^2 in the urbanized area, indicating that the per capita park area is insufficient for both the citywide area and the urbanized area, and urgently needs to be further constructed and optimized.

Urban parks contain a wealth of environmental facilities, making them more responsive to the quality of environmental facilities and population preferences. Therefore, in the study of Higashiosaka city, I only considered the case of urban parks as UGS. The case study of Higashiosaka city enables a clearer illustration of how the quality of environmental facilities and population preferences affect UGS inequality in a shrinking city dominated by urban parks. Therefore, the results of the Higashiosaka case study can serve as a reference for more shrinking cities similar to Higashiosaka city that are highly

urbanized and lack abundant natural UGS.

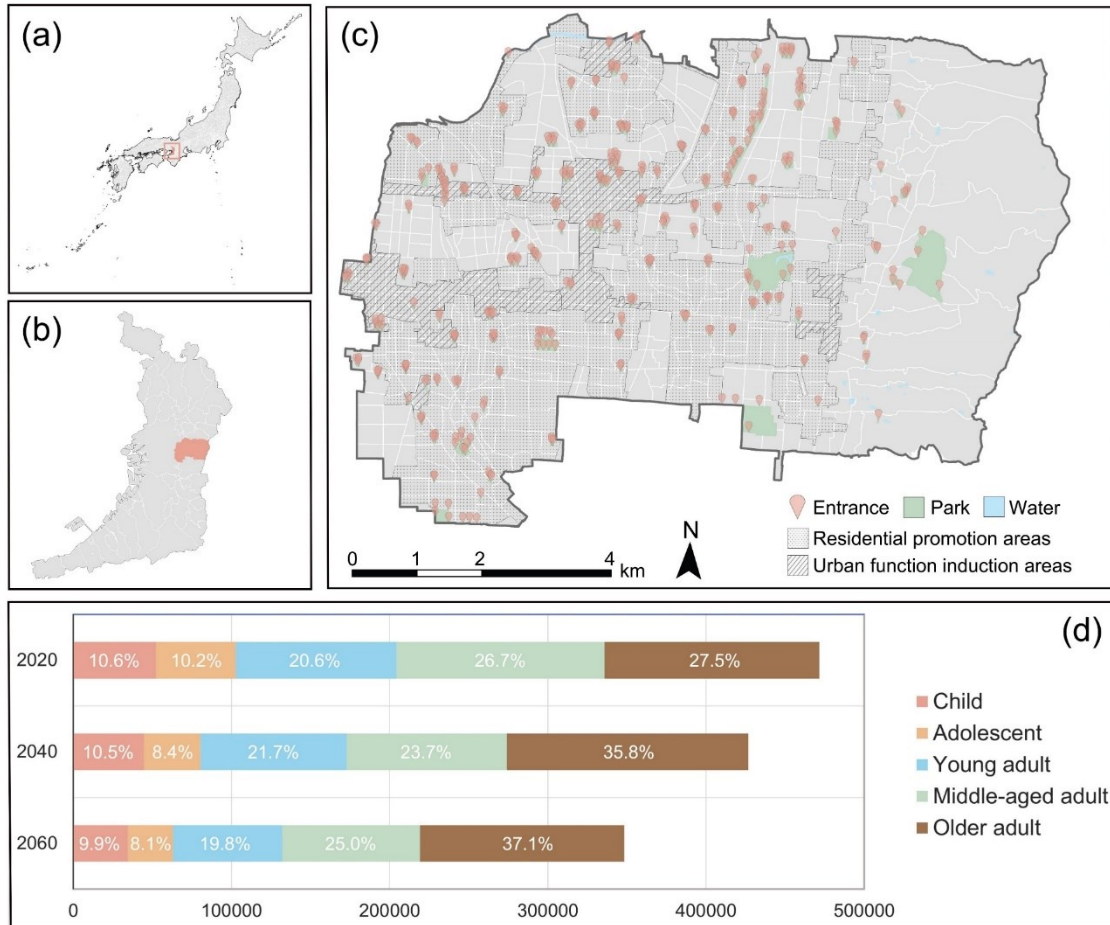

Fig. 5.1 Study area. a) Japan; b) Osaka prefecture; c) Higashiosaka City; d) Population change in Higashiosaka City

Faced with the challenge of a declining population, Higashiosaka City has proposed a planning goal of establishing a "compact city," aiming to concentrate urban resources to attract population migration to the core area of the city. The urban plan of Higashiosaka City divides urban areas into three main zones based on different purposes: urban function induction areas (UFIAs), residential promotion areas (RPAs), and other urban areas (OUAs) (Fig. 5.1c). UFIAs are equivalent to urban centers and are responsible for

major urban functions. RPAs are intended to encourage residents from other areas (e.g., suburbs) to move in to maintain the population density in the city's main urban area. The OUAs, including industrial and suburban settlements, are being developed for various purposes. The government does not encourage continued infrastructure development in OUAs.

2.2 Data collection and preparation

First, the case study included all identified urban planned urban parks and public green spaces in Higashiosaka City (n=115) [329]. I geolocated the entrances to all UGSs using Google Earth Pro; Figure 5.1c shows all UGSs' locations, boundaries, and entrances. Second, UGS quality data were collected from the assessment scores of six auditors, and preference weighting data for age groups were collected from a questionnaire survey involving Higashiosaka City residents. Third, the population data for 2020 were obtained from the census dataset [220]. Population projection data for 2040 and 2060 were obtained from population projections for Japan [330]. All population data were collected at the "chome" level, Japan's smallest census block. In addition, I collected polygonal data for densely inhabited districts (DIDs) in Higashiosaka City [331]. All population demand points are defined as the center of mass of the intersection of the census block and the DIDs polygon. Finally, road data were obtained from OpenStreetMap (OSM) [332]. All road networks were topologically corrected, and urban roads that do not allow pedestrian use, namely motorways, motorway links, and busways, were removed.

2.3 The FSD-2SFCA method

I propose the FSD-2SFCA method based on the existing 2SFCA method. Here, I consider the population age structure as an entry point and describe how the FSD-2SFCA method incorporates the preferences and travel abilities of different age groups into the model to calculate spatial accessibility.

2.3.1 Floatable supply improvements: a UGS attractiveness index based on population preferences

The traditional 2SFCA method typically uses UGS areas as the attractiveness index of UGSs. In contrast, in the FSD-2SFCA method, I introduce the preferences of different population subgroups as floatable variables in the model to further improve the UGS attractiveness index.

1) Quality scores for UGSs

A UGS quality assessment system should be established to measure the quality of UGSs. I conducted a pre-survey of ten UGSs in Higashiosaka city, combining previous UGS studies and the UGS environmental audit tool to finalize the UGS environmental assessment items (Table 5.1). Experts from urban planning and landscape architecture reviewed and commented on the items. Specifically, 23 items on environmental facilities were categorized into four domains: aesthetics (three items), amenities (seven items), recreational facilities (six items), and access/safety (eight items).

Table 5.1 Quality scoring table of UGSs

Domains	Items (N=23)	Response scales	Reasons	References
Aesthetics	Vegetation	Normalized Vegetation Index	Aesthetic elements of UGSs can influence residents' satisfaction with UGSs and reduce stress levels. Vegetation, water bodies, and sculptures are often recognized as key elements of the aesthetic experience in UGSs.	[68,179,333–337]
	Water features	Combine		
	Sculptures/Aesthetic features	Quantity		
Amenities	Seats	Quantity	Amenities relate to users' comfort and affect their time in the UGS. Basic amenities (e.g., seating restrooms) ensure the UGS is user-friendly.	[68,179,334,336–338]
	Water faucet	Quantity		
	Toilets	Quantity		
	Meeting facilities	Quantity		
	Shops	Quantity		
	Walking paths	Quantity		
	Shade	Quantity		
Recreational facilities	Picnic tables	Quantity	The UGS's recreational facilities provide residents with diverse opportunities to increase their physical activity and socialization. The variety of recreational facilities (e.g.,	[68,334,336,336,337,339,340]
	Nature experience facilities	Quantity		
	Children's playgrounds	Quantity		

	Sports facilities	Variety	sports facilities, picnic tables) meets the needs of a diverse population.	
	Barbeque	Service Capability		
	Pets	Service Capability		
Access/Safety	Slope	Slope	Safe, convenient access to UGSs promotes social inclusion and equality. Factors such as slope and accessibility affect UGS access for groups with different abilities. Monitors and lighting affect the safety of people using UGSs. Disaster prevention facilities uniquely influence Japanese UGSs, affecting people’s sense of safety and trust.	[68,334–337,341–343]
	Disaster prevention facilities	Quantity		
	Barrier-free	Coverage		
	Signage	Combine		
	Safe crossing aids	Quantity of 100m range		
	Lighting	Coverage		
	Monitors/Security guards	Quantity		

Table 5.2 Guidelines for scoring environmental facility items.

Scoring Method	Score		
	0	**1**	**2**
Quantity	No presence	Present in a few areas (1–2 places)	Present in most areas (≥3 places)
Combined quantity and quality	No presence	Poorly maintained or aesthetically unpleasant	Exceptionally maintained and aesthetically pleasing
Variety	No presence	1–2 kinds	More than or equal to 3 kinds
Service Capability	No service/no access	Only service space is available	Provide service facilities
Quantity of 100m range	No presence	Main entrance only	Almost all entrances
Coverage	No coverage	Coverage of a few areas	Coverage of most areas
Normalized Vegetation Index (NDVI)	[-1, 0]	(0, 0.5]	(0.5, 1]
Slope	Greater than 1:12 (4.76°)	1：12–1：16 (3.58°)	Less than 1:16 (3.58°)

Furthermore, I customized the response scales to fit the different items and used a three-point scale for all the UGS environmental assessment items (Table 5.2). The quantity depends on the number of items in the UGS, such as toilets and children's facilities. A score of 0 was given if the item was not present in the UGS, a score of 1 if it was present in a few areas (1–2 places), and a score of 2 if it was present in most areas (≥3

places).

Safe crossing aids were assessed using specific quantities. Specifically, the presence or absence of safe crossing aids (e.g., crosswalks) within 100 m of the UGS entrance was measured. There were 0 points for no safe crossing aids, 1 point for the main entrance only, and 2 points for most entrances (>66.6%).

Similarly, variety refers to the richness of items carried in the UGS, such as sports facilities. A score of 2 was assigned when the type of sport carried was greater than or equal to 3. For example, if only tennis courts are present in the UGS, a score of 1 is given; if tennis courts, baseball fields, and fitness equipment are present, a score of 2 is given.

The combination of quantity and quality depends on the aesthetic or maintenance level of environmental facilities. For example, a sign that is in disrepair is scored as 1, whereas a well-maintained sign is scored as 2.

Service capacity is a judgment of whether a UGS provides the service of an item. For example, 0 means that pets are not allowed in the UGS; 1 means that pets are allowed in the UGS, but no dog park is available; and 2 means that a dog park is available in the UGS.

Coverage is a judgment of the percentage of area served by an item. For example, a score of 1 was given when adequate lighting existed in only a small part of the UGS,

and a score of 2 was given when a large part of the UGS was covered.

The normalized vegetation index (NDVI) is an evaluation criterion that responds to vegetation cover and growth status and is widely used in the study of UGSs [333,344]. The NDVI takes values ranging from -1 to 1. When NDVI is less than or equal to 0, there is water, clouds, or built-up area in the site; when NDVI is greater than 0, the site is covered by vegetation. The larger the value, the better are the vegetation growth conditions and coverage. Therefore, NDVI is scored as 0 for less than or equal to 0, 1 for less than or equal to 0.5, and 2 for greater than 0.5. The NDVI values for the UGS were calculated from the average NDVI values for March, June, September, and December 2020 based on Google Earth Engine.

I refer to the Americans with Disabilities Act (ADA) definition of ramp access for people with disabilities [345]. The ADA states that the limit for ramps is 1:12 when people with disabilities can travel without the assistance of bystanders. 1:16 is the extreme slope at which people with disabilities can travel normally. I defined the maximum slope of the 100-m buffer zone of the UGS to measure UGS access. The slope data were obtained from the National Land Dataset of Japan (https://nlftp.mlit.go.jp/ksj/index.html). Here, vegetation and slope were converted from geographic data to absolute values; the remaining items were assessed manually using a desktop audit and field research.

Based on the methodology for UGS audits proposed by Edwards et al. (2013) and Lee (2022), six trained landscape architecture students audited UGSs in Higashiosaka City

from January to April 2023 using a combination of desktop and field audits [68,346]. All auditors independently audited all city UGSs in the study area (n=115). I used Fleiss' kappa to measure the consistency of assessments among multiple auditors [347]. The results showed that the Kappa statistic was greater than 0.4 for all items (Table 5.3), and the consistency of the assessments among auditors was acceptable [348,349]. Figure 5.2 shows the average of the quality ratings for each UGS.

Table 5.3 Kappa coefficients for environmental facilities items

Items	**Kappa**	**Items**	**Kappa**
Vegetation	–	Children's playgrounds	0.614
Water features	0.876	Sports facilities	0.745
Sculptures/Aesthetic features	0.733	Barbeque	0.831
Seats	0.674	Pets	0.905
Water Faucet	0.581	Slope	–
Toilets	0.947	Disaster prevention facilities	0.758
Meeting facilities	0.789	Barrier-free	0.566
Shops	0.824	Signage	0.621
Walking paths	0.725	Safe crossing aids	0.750
Shade	0.823	Lighting	0.618
Picnic tables	0.893	Monitors/Security guards	0.865
Nature experience facilities	0.753		

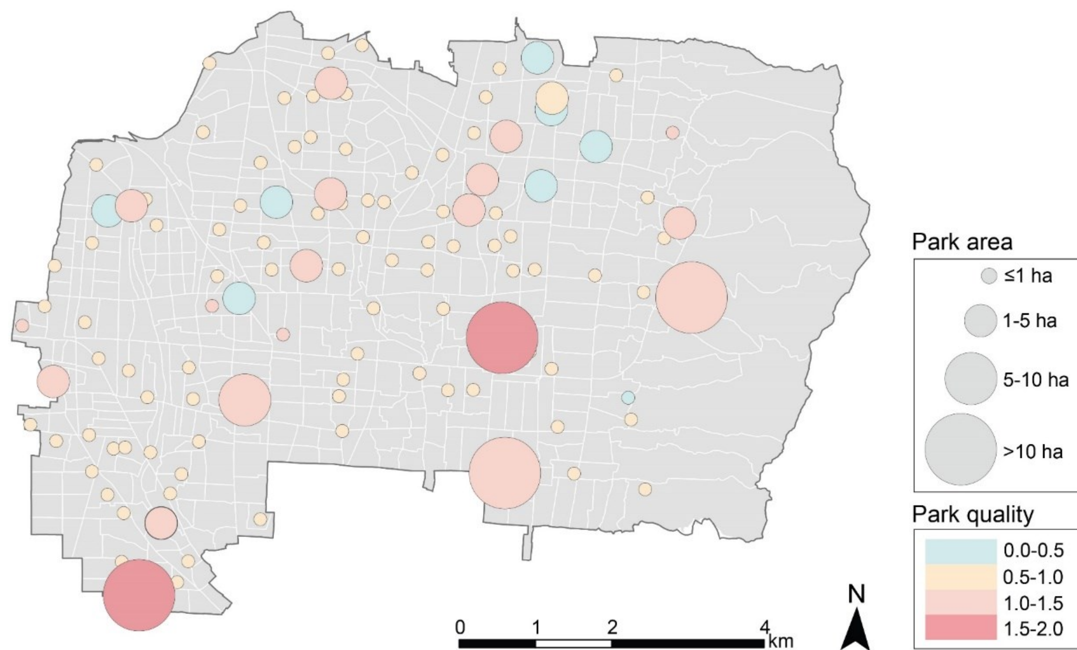

Fig. 5.2 UGS quality and area in Higashiosaka City

2) Weighting based on the preferences of different populations

There are significant differences in the preferences of different age groups for environmental facilities in UGSs. Therefore, it is necessary to consider the preferences of different age groups when assessing UGS quality. Based on the definition of age groups in Healthy Japan 21, I divided the population as follows: children (0−14 years), adolescents (15−24 years), young adults (25−44 years), middle-aged adults (45−64 years), and older adults (65 years or older) [350]. However, children under six years old are not included in the survey because of their lack of ability to perform controls [351]. To understand the preferences of different age groups for environmental facilities in UGSs, I conducted a web-based questionnaire survey involving Higashiosaka City residents via the Freeasy Questionnaire Inc. (https://freeasy24.research-plus.net/) platform after obtaining permission from the local Ethics Review Board. Freeasy Questionnaire Inc. is

a professional online questionnaire service company with more than 13 million registered users in Japan. A questionnaire survey was conducted in two ways. First, Freeasy sent a questionnaire request to all users who lived in Higashiosaka City and were 15 years old or older (Freeasy requires all users to be 15 years old or older). After obtaining informed consent from the participants, they were allowed to complete the questionnaire online. Second, for children under 15 years of age, a pre-questionnaire was distributed to people with children living in Higashi-Osaka City (except for adult users who had already completed the questionnaire), totaling 5,000 pre-questionnaires. Only users who met the following conditions were included in the formal survey: 1) children in the household were aged between 6 and 14 years old (Children under 6 years old were not included in the survey because of their lack of ability to perform controls [351]; Therefore, the preference results for 0 to14 year olds were obtained by surveying 6 to 14 year olds.); and 2) both the child and the guardian agreed to the child completing the questionnaire in the presence of their guardian. A total of 1032 users met these conditions. For cost reasons, I randomly sent formal survey invitations to 400 of these users. In the first question of the formal survey, I stated that “The purpose of this survey is to understand the preferences of children between the ages of 6 and 14 years old for UGS amenities. If you are aware of the above and would like to participate in this survey, please have your child take the lead in answering the following questions without providing your subjective opinion.” Only users who chose “Agree” were entered into the formal survey. Finally, a total of 307 users completed all the survey questions. In addition, I used text and pictures in the formal survey and labeled complex text with pronunciation to ensure that children could complete the questionnaire on their own to the greatest extent possible, and that parents only played an auxiliary role (e.g.,

helping to read) in the survey. Finally, I used Freeasy questionnaire cleaning service and all questionnaires with unusual response times, the same IP address, and unnatural responses were excluded. In total, 1,705 valid questionnaires were collected, covering all age groups: children (n=307), adolescents (n=313), young adults (n=337), middle-aged adults (n=362), and older adults (n=386). All groups passed the Cronbach's α test (>0.8; Table 5.4).

Table 5.4 Results of alpha reliability test

Age	**N**	**Cronbach's α**
Child (0–14 years old)	307	0.869
Adolescent (15–24 years old)	313	0.907
Young adult (25–44years old)	337	0.872
Middle-aged adult (45–64 years old)	362	0.878
Older adult (above 65 years old)	386	0.845
Total	1705	0.875

The survey questionnaire consisted of two parts: 1) demographic characteristics (Table 5.5) and 2) a preference survey for UGS environmental facilities. A five-point Likert scale was used for the UGS environmental facilities preference survey. Residents' preference weights for UGS environmental facilities were obtained using the following formula:

$$\beta_{mf} = \frac{\lambda_{mf}}{\sum_{\theta \in F}(\lambda_{m\theta})} \tag{5.1}$$

where β_{mf} represents the weight of population subgroup m on environmental facility f; λ_{mf} represents the mean value of population subgroup m's ratings on environmental facility f; and $\lambda_{m\theta}$ represents the mean value of population subgroup

m's ratings on the θth facility in the set F of environmental facilities. Fig. 5.3 shows the preference weights of different age groups for UGS environmental facilities.

Table 5.5 Demographic characteristics of the sample

Attributes	Category	Frequency	Percentage (%)
Age	Child (0–14 years old)	307	18.0
	Adolescent (15–24 years old)	313	18.4
	Young adult (25–44years old)	337	19.8
	Middle-aged adult (45–64 years old)	362	21.2
	Older adult (above 65 years old)	386	22.6
Gender	Male	879	51.6
	Female	826	48.4
Marital status	Married	741	43.5
	Unmarried or divorced/widowed	964	56.5
Children	Yes	680	39.9
	No	1025	60.1
Occupation	Student	505	29.6
	Civil servants	22	1.3
	Manager/executive	20	1.2
	Physicians/medical personnel	25	1.5
	Company employee	404	23.7
	Freelancer	75	4.4
	Part-time job	170	10.0
	Housewife	160	9.4
	Unemployed	289	17.0
	Other	35	2.1
Annual Household Income (JYP)	Less than 2 million	282	16.5
	2 to 5 million	674	39.5
	5 to 10 million	600	35.2

10 to 15 million	100	5.9
15 to 20 million	21	1.2
Above 20 million	28	1.6

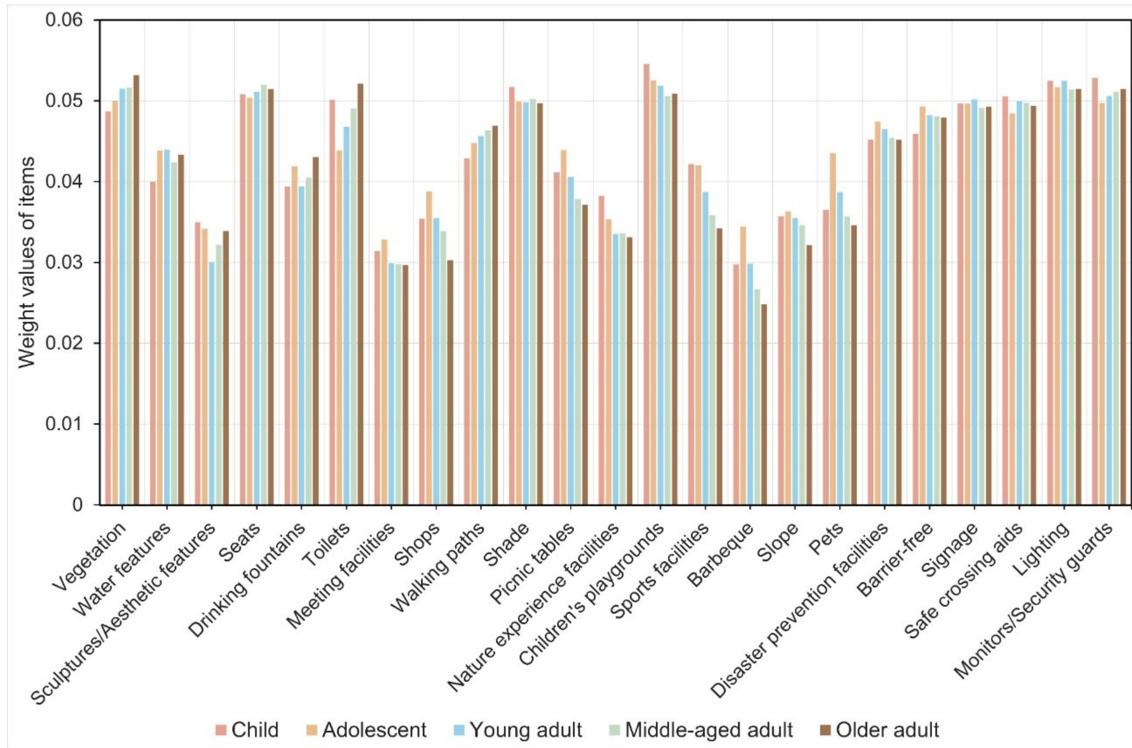

Fig. 5.3 Preference weights of different age groups for UGS environmental facilities

In the FSD-2SFCA method, the attractiveness of a UGS is not limited to the value of the UGS area (S_j^A) or the quality-weighted area score ($S_j^A \times q_j$), but rather, a floatable quality-weighted area score is implemented based on the preferences of different age groups. This improvement better describes the heterogeneity of the UGSs in terms of supply and provides the basis for calculating the floatable choice probabilities. Specifically, it is expressed as

$$S_{mj} = S_j^A \times \sum_{f \in F} \left(q_{if} \times \beta_{mf} \right) \tag{5–2}$$

where S_{mj} is the attractiveness index of UGS j to population subgroup m; S_j^A is the

area of UGS j; q_{jf} is the quality score of environmental facility f in UGS j; and β_{mf} represents the weight of population subgroup m on environmental facility f.

2.3.2 Floatable demand improvement: choice probabilities of UGSs for different populations

The traditional 2SFCA method ignores the competitive relationship between UGSs when calculating population demand [201]. I introduced the Huff model to capture differences in attractiveness among UGSs, which characterizes the competitive relationship between UGSs by modifying residents' choice weights. However, the traditional Huff model assumes that residents have the same travel abilities and environmental preferences, meaning that all residents within demand point i have the same choice probability for a nearby UGS j [182]. Therefore, I further improved the Huff model to refine the estimation of population demand by introducing floating variables for the ability to travel and the environmental preferences of different population subgroups.

First, spatial accessibility, as defined by the 2SFCA method, was calculated based on specified travel costs [198]. Because there are gaps in the travel abilities of different age groups, the thresholds for different age groups also vary. In this study, I used a travel time of approximately 15 min to measure suitable walking distances based on the walking speeds of different age groups [188] (Table 5.6).

Table 5.6 Walking speed and travel distance for different age groups

Age	Walking speed (m/min)		Walking distance (m)
	Mean	**SD**	
Children (0–14 years)	64.1	12.6	1000
Adolescents (15–24 years)	79.3	13.7	1100
Young adults (25–44 years)	79.5	13.5	1200
Middle-aged adults (45–64 years)	72.4	12.8	1200
Older adults (65 years or older)	59.2	8.5	900

Note: The walking speed for each age group is based on the results derived from Kunio's (1975) study.

Second, I used the Huff model to quantify the probability of choosing available UGSs for different age groups. A Gaussian function was used to represent the travel resistance of each age group, and residents' UGS attractiveness decreased as the walking distance increased [352]. This probability is expressed as:

$$Prob_{mij} = \frac{S_{mj} d_{ij} G(d_{ij}, d_m)}{\sum_{k \in \{d_{ij} \leqslant d_m\}} S_{mj} d_{ij} G(d_{ij}, d_m)} \quad (5\text{–}3)$$

$$G(d_{ij}, d_m) \begin{cases} \frac{e^{-\frac{1}{2}\left(\frac{d_{kj}}{d_m}\right)^2} - e^{-\frac{1}{2}}}{1 - e^{-\frac{1}{2}}}, & d_{ij} \leqslant d_m \\ 0, & d_{ij} > d_m \end{cases} \quad (5\text{–}4)$$

where $Prob_{mij}$ is the choice probability of population subgroup m in demand point i for UGS j; S_{mj} is the attractiveness index of UGS j for population subgroup m; d_{ij} is the distance between demand point i and UGS j; d_m is the travel distance threshold for population subgroup m; and G is the Gaussian decay function.

2.3.3 Spatial accessibility of UGSs

Following the 2SFCA method, the supply–demand ratio (SDR) of UGS j needs to be calculated before calculating the spatial accessibility of the demand point. The 2SFCA and SD-2SFCA methods establish a single-threshold catchment for UGS j to calculate the ratio of the UGS attractiveness index to the sum of weighted population demand.

However, in the FSD-2SFCA method, I must establish multiple travel threshold catchments for UGS j to cover different age groups. A further challenge is that the attractiveness index of UGS j is different for the population subgroups within each demand point. Therefore, I used the following equation to overcome this challenge:

$$R_j = 1/\sum_{m \in M} \left(\frac{\sum_{k \in \{d_{kj} \leqslant d_m\}} Prob_{mkj} P_{km} G(d_{kj}, d_m)}{S_{mj}} \right) \quad (5\text{–}5)$$

where R_j is the SDR of UGS j; P_{km} is population subgroup m at demand point k within the catchment coverage; $Prob_{mkj}$ is the choice probability of population subgroup m within demand point k for UGS j; and M is the set of all population subgroups m.

Because UGS attractiveness indices are not the same for different population subgroups, the traditional method of calculating SDRs is not applicable. Unlike the previous direct calculation of SDR from the perspective of UGS j, the FSD-2SFCA method calculates the demand–supply ratio (DSR) of population m to UGS j by considering it from the perspective of population subgroup m within the catchment area of UGS j. Then, the SDR for UGS j is found by calculating the inverse of the sum of the DSRs for

subpopulation m within the UGS j catchment area.

Next, I established the matching catchment area for population subgroup m within demand point i. The SDRs of all UGSs within the catchment were weighted and summed based on the distance decay function and choice probabilities to estimate the accessibility index A_{im} for subpopulation m within demand point i as follows:

$$A_{im} = \sum_{l \in \{d_{ij} \leqslant d_m\}} Prob_{mil} G(d_{il}, d_m) R_l \quad (5–6)$$

where $Prob_{mil}$ is the choice probability of UGS l by subpopulation m within demand point i; and R_l is the SDR of UGS l.

Finally, accessibility index A_i of demand point i can be expressed as the sum of the accessibility indices weighted by the population subgroups m within demand point i:

$$A_i = \sum_{m \in M} \frac{P_{im}}{P_i} A_{im} \quad (5–7)$$

where P_{im} is the population of subgroup m within demand point i; and P_i is the total population of demand point i.

2.4 Scenario construction and assessment

Three different scenarios were used to evaluate and compare UGS accessibility as measured by the various methods. These scenarios aimed to test the robustness of the FSD-2SFCA method by comparing the differences between existing and new methods (Fig. 5.4). The scenarios based on the measurements of the different methods are presented as follows.

2.4.1 Scenario I: Traditional Gaussian-based 2SFCA method

In this scenario, I applied the traditional Gaussian-based 2SFCA method to evaluate the accessibility of UGSs in Higashiosaka city. The method defines the UGS attractiveness index as a score based on the UGS area and considers only the decaying effect of distance on UGS attractiveness. The catchment area threshold was determined based on an average 15-minute walking distance for residents.

Step 1: Create a service catchment area with travel thresholds for UGS j. Search for all populations within the catchment area and calculate the ratio of UGS area to population (R_j), as follows:

$$R_j = \frac{S_j^A}{\sum_{k \in \{d_{kj} \leqslant d_0\}} P_k G(d_{kj}, d_0)} \tag{5–8}$$

where d_{kj} is the distance between demand point k and UGS j; P_k is the population of demand point k ($d_{kj} \leqslant d_0$); S_j^A is the area of UGS j; G is the distance decay function, in this case a Gaussian decay function. The Gaussian decay function was calculated as follows:

$$G(d_{kj}, d_0) = \begin{cases} \frac{e^{-\frac{1}{2}\left(\frac{d_{kj}}{d_0}\right)^2} - e^{-\frac{1}{2}}}{1 - e^{-\frac{1}{2}}}, & d_{kj} \leqslant d_0 \\ 0, & d_{kj} > d_0 \end{cases} \tag{5–9}$$

Step 2: Establish a catchment area for demand point i, search for the supply to demand ratio (R_l) of UGS l within the catchment area, assign weights using a Gaussian decay function, and sum all UGSs within the threshold to obtain the accessibility index of demand point i.

$$A_i = \sum_{l \in \{d_{ij} \leqslant d_0\}} G(d_{il}, d_0) R_l \quad (5\text{–}10)$$

where A_i is the accessibility index of demand point l; the higher the value, the better the accessibility.

2.4.2 Scenario II: The SD-2SFCA method

In Scenario II, I included the effect of UGS environmental facilities on UGS attractiveness based on the traditional 2SFCA method and considered the competitive relationship between UGSs by introducing the Huff model. This scenario was tested using the same distance thresholds as in Scenario I.

First, the attractiveness factor S_j of the UGS was improved by considering the quality and area of UGS j.

$$S_j = S_j^A \times q_j \quad (5\text{–}11)$$

where S_j^A is the area of UGS j and q_j is the environmental facility quality index of UGS j.

Second, the Huff model was introduced to consider residents' choice of UGSs within the catchment area and to express the competition between UGSs. The Huff model is expressed as follows:

$$Prob_{ij} = \frac{S_j d_{ij} G(d_{ij}, d_0)}{\sum_{k \in \{d_{ij} \leqslant d_0\}} S_j d_{ij} G(d_{ij}, d_0)} \quad (5\text{–}12)$$

where $Prob_{ij}$ is the probability that residents of demand point i choose UGS j; S_j is the attractiveness index of UGS j; d_{ij} is the distance between demand point i and UGS j; and G is the distance decay function (in this case, a Gaussian decay function).

The Gaussian decay function is calculated as follows:

$$G(d_{ij}, d_0) = \begin{cases} \frac{e^{-\frac{1}{2}\left(\frac{d_{ij}}{d_0}\right)^2} - e^{-\frac{1}{2}}}{1-e^{-\frac{1}{2}}}, d_{ij} \leqslant d_0 \\ 0 \quad , d_{ij} > d_0 \end{cases} \quad (5\text{–}13)$$

Following the 2SFCA method, all populations within the catchment area are searched in combination with the Huff model. The ratio of attractiveness to population (R_j) was calculated using the weighting of the Gaussian function and selection probability as follows:

$$R_j = \frac{S_j}{\sum_{k\in\{d_{kj}\leqslant d_0\}} P_k G(d_{kj}, d_0) Prob_{kj}} \quad (5\text{–}14)$$

where d_{kj} is the distance between demand point k and UGS j; P_k is the population of demand point k ($d_{kj} \leqslant d_0$); S_j is the attractiveness index of UGS j; $Prob_{kj}$ is the probability of selection of UGS j by the population at demand point k.

Finally, a catchment area was established for the demand point i. The supply to demand ratio (R_l) of UGS l within the catchment area was determined, and the accessibility index of demand point i was obtained by summing all UGSs within the threshold by assigning weights through a Gaussian decay function and selection probability:

$$A_i = \sum_{l\in\{d_{ij}\leqslant d_0\}} G(d_{il}, d_0) Prob_{il} R_j \quad (5\text{–}15)$$

where the accessibility index of demand point i of A_i, the higher the value, the better the accessibility.

2.4.3 Scenario III: The FSD-2SFCA method

Based on Scenario II, different age groups' preferences and travel abilities were further

considered. Therefore, supply and demand were floatable for different age groups.

In this study, I used a combination of 2000, 2020, and 2060 demographic data (including population size and structure) to project potential future UGS accessibility issues within urban areas. I also evaluated the strengths and weaknesses of the methods used in different scenarios through horizontal and vertical comparisons. Notably, the 2040 and 2060 UGS accessibility measurements are based on no new UGSs built after 2020. Under this assumption, the number and distribution of city UGSs will remain constant, and the accessibility projections only consider the impacts of population change (population size and structure) on UGS accessibility, allowing for easy identification of areas where existing UGS construction is weak under future demographic trends, allowing for forward-looking UGS construction. This assumption does not predict a halt in new UGS development in the future but rather furnishes a baseline scenario to assist urban planners and policymakers in understanding the challenges UGS accessibility would encounter if no actions were taken.

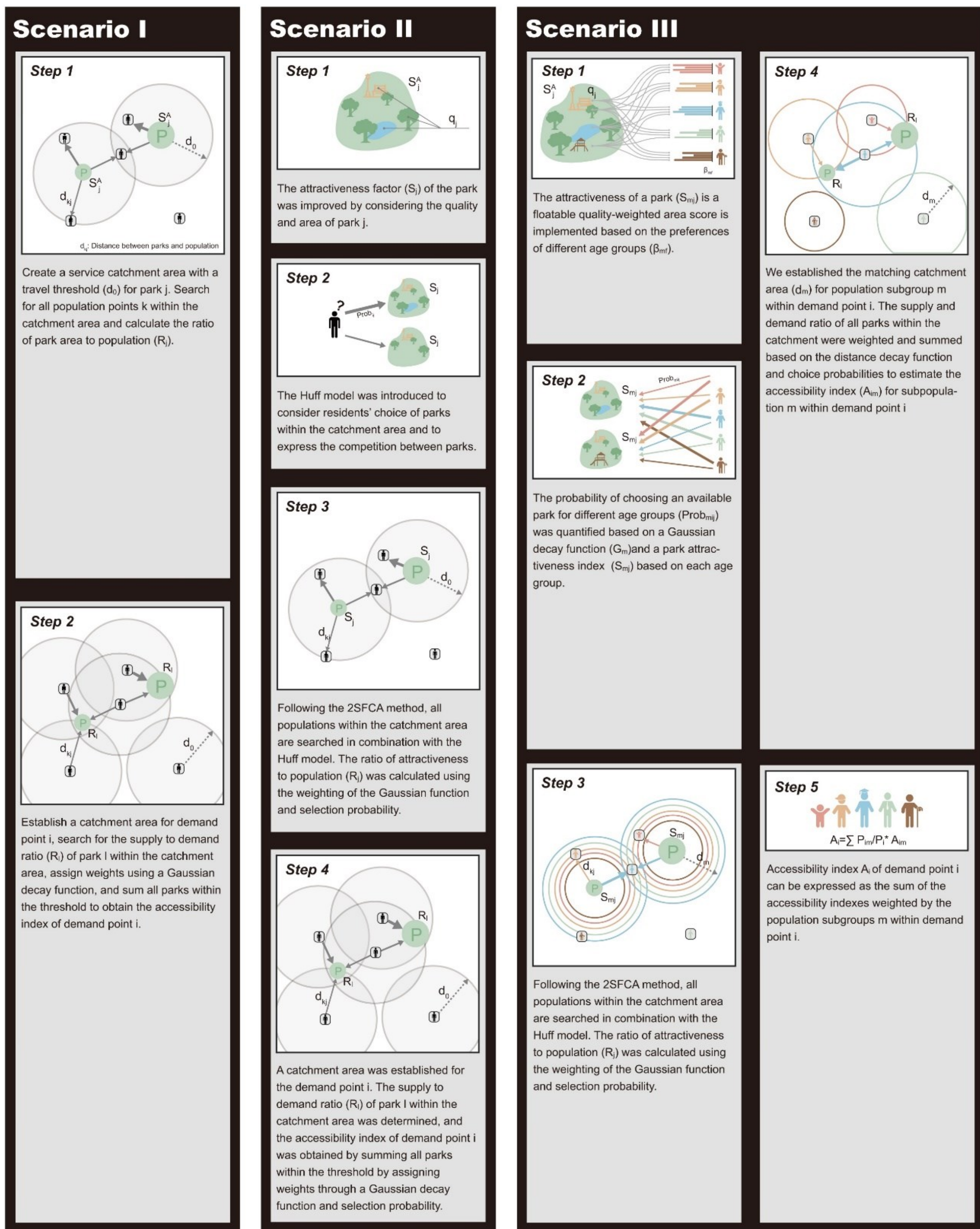

Fig. 5.4 Schematic diagram of the specific steps of the methods used in the three scenarios

2.5 Spatial patterns of UGS accessibility

The bivariate global and local Moran's I (bi-LISA) is used to measure the spatial relationship between park accessibility and population demand [201]. The bi-LISA formula is as follows:

$$I_{xy}^{a} = Z_{x}^{a} \sum_{j} W_{ab} Z_{y}^{b} \quad (1)$$

where Z_{x}^{a} is the population demand for block a; Z_{y}^{b} is the supply of park accessibility to its neighboring block b; and W_{ab} is a spatial weight matrix based on a first-order queen adjacency matrix. The bi-LISA identifies spatial associations between variables through four types of spatial clustering: high-high (HH), low-low (LL), high-low (HL), and low-high (LH) [353]. HH represents the high value clustering of population demand with the surrounding UGS accessibility supply; LL is the low value clustering of population demand with the surrounding UGS accessibility supply; LH represents the spatial clustering of lower population demand with the surrounding higher UGS accessibility supply, which implies "overserved"; HL represents the spatial clustering of higher population demand with the surrounding lower UGS accessibility supply, which implies " underserved ".

2.6 Measuring UGS inequality

In this chapter, UGS inequality measures inequality in UGS services, considers the quality of UGS, and measures differences in the proactive service provided by UGS, a service that requires residents to actively travel to UGS. The Gini coefficient was originally used to calculate residential income inequality [213]. In this study, I use the Gini

coefficient to further measure inequality in UGS accessibility. The Gini coefficient can be expressed as the area between the line of absolute equality and the observed Lorenz curve divided by the area between the line of absolute equality and the line of absolute inequality [219]. The formula is:

$$Gini = 1 - \sum_{i=1}^{n} \frac{P_i}{P} \left(\alpha_{i_{-1}} + \alpha_i\right) \quad (2)$$

where P_i is the population demand for the ith block, P is the total population demand for all blocks, and A_i is the cumulative UGS accessibility at the ith demand point. The Gini coefficient ranges from 0 to 1, with larger values being more inequitable.

3. Results

3.1 UGS accessibility for three scenarios

In response to the second research objective, I constructed three different scenarios to evaluate and compare UGS accessibility as measured by various methods. Since the accessibility index was calculated based on different methods, z-score normalization of the accessibility index for different scenarios was conducted to enhance the comparability between different methods. A comparison of the three scenarios showed differences in the spatial distribution of accessibility across scenarios (Fig. 5.5). First, there were significantly more blocks in Scenario I with an accessibility index greater than the mean (z-score > 0) than in Scenarios II and III, particularly in the central region. Conversely, in the central region, there were significantly fewer blocks in Scenario I with an accessibility index greater than one standard deviation (z-score > 1) than in Scenarios II and III. Second, blocks with accessibility indices greater than four

standard deviations (z-score > 4) in Scenario III were the most numerous of all the scenarios (e.g., east-central and south-central regions), implying that there are relatively more blocks in Scenario III with accessibility indices well above the mean.

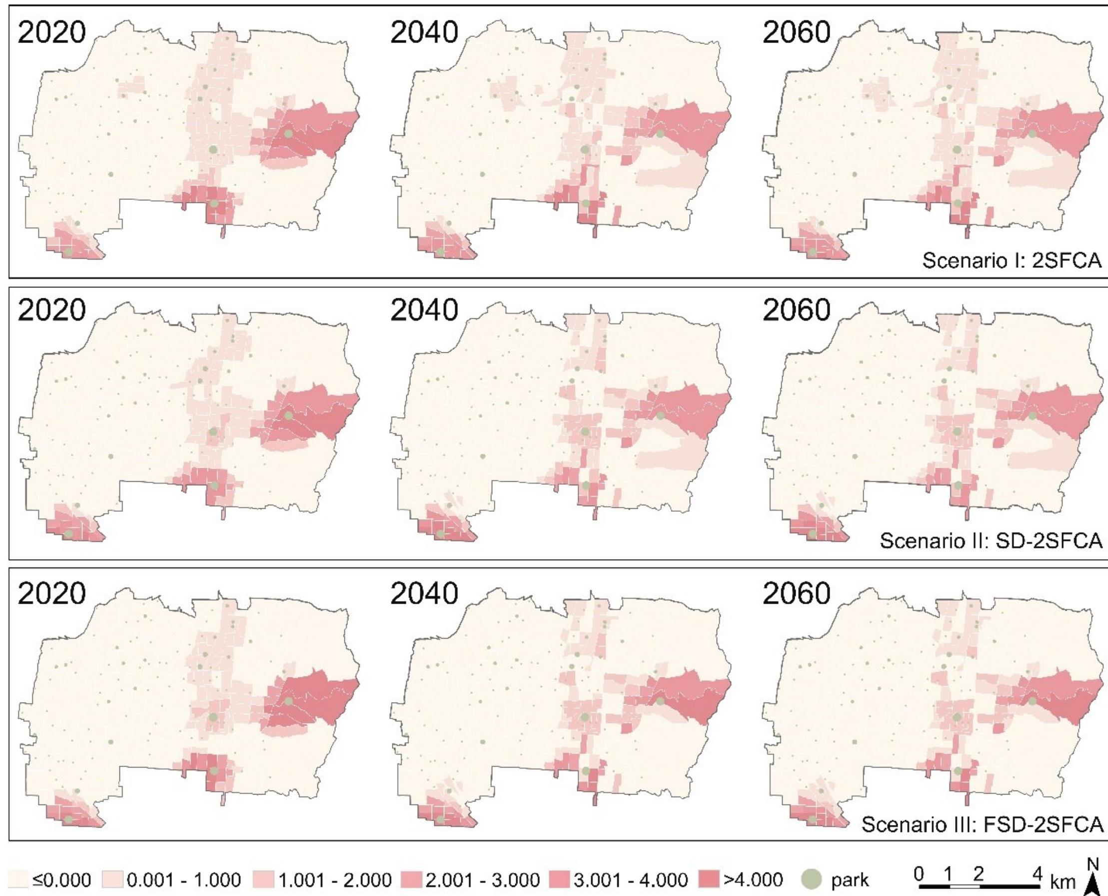

Fig. 5.5 Spatial pattern of UGS accessibility in the three scenarios

Table 5.7 presents the variation in the accessibility index across the scenarios. Similar to the results shown in Fig. 5.5, Scenario III identified more underserved blocks and populations in all years. Moreover, the coefficient of variation for Scenario III was the largest of all the scenarios, implying that UGS accessibility for Scenario III was the most discrete at the block level.

Table 5.7 Statistical variability for the three scenarios

Years	Underserved blocks (N=500)			Underserved populations			Coefficient of variation (CV)		
	Scenario I	Scenario II	Scenario III	Scenario I	Scenario II	Scenario III	Scenario I	Scenario II	Scenario III
2020	386	400	405	379567	390921	395841	1.702	1.843	2.001
2040	390	409	413	321157	333248	336835	1.648	1.829	1.976
2060	391	409	412	262146	272259	275030	1.661	1.849	2.003

Note: Underserved blocks are defined as those that are smaller than the mean value of the accessibility index.

Finally, the Gini coefficient reveals inequities in UGS accessibility across the three scenarios (Fig. 5.6). First, the accessibility inequality trends over time are approximately the same for the three scenarios, implying that all three scenarios possess good stability. Second, the measured Gini coefficients under the three scenarios ranged from low to high: Scenario I, II, and III. Among them, Scenario III, measured using the FSD-2SFCA method, showed the highest sensitivity. Therefore, addressing the second research question, the findings confirm the reliability of the FSD-2SFCA method in measuring UGS accessibility. Overall, addressing the second research question, the findings confirm the reliability of the FSD-2SFCA method in measuring UGS accessibility.

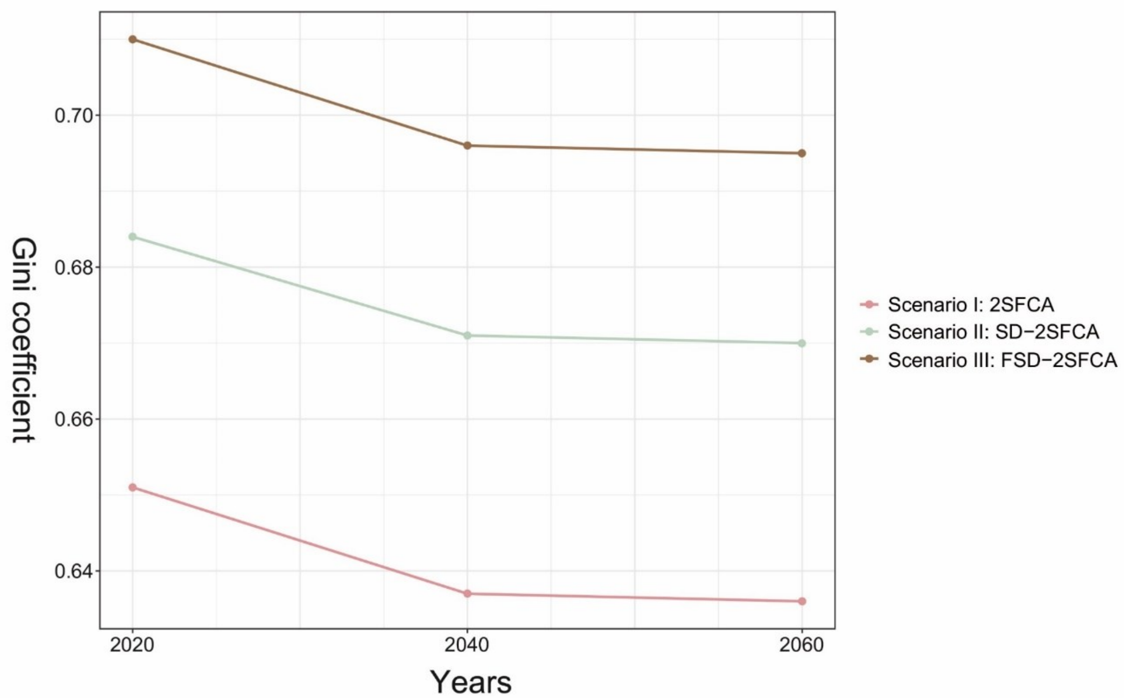

Fig. 5.6 Gini coefficients for UGS accessibility for the three scenarios

3.2 UGS accessibility supply-demand mismatch

3.2.1 UGS accessibility supply for different age groups

I applied the FSD-2SFCA method to analyze differences and changes in UGS accessibility across age groups in response to the third research question. The findings reveal significant differences in the spatial patterns of UGS accessibility for different age groups, especially in the central part of the city (Fig. 5.7). Fewer blocks had higher UGS accessibility indices for older adults and children than for other age groups, such as in the north-central and south-central areas of the city. The ranking of UGS accessibility means based on age group was as follows: adolescents > young adults > middle-aged adults > children > older adults (Fig. 5.8). UGS accessibility increased for different age groups as the year increased but decreased in some blocks in the central

and east-central parts of the city.

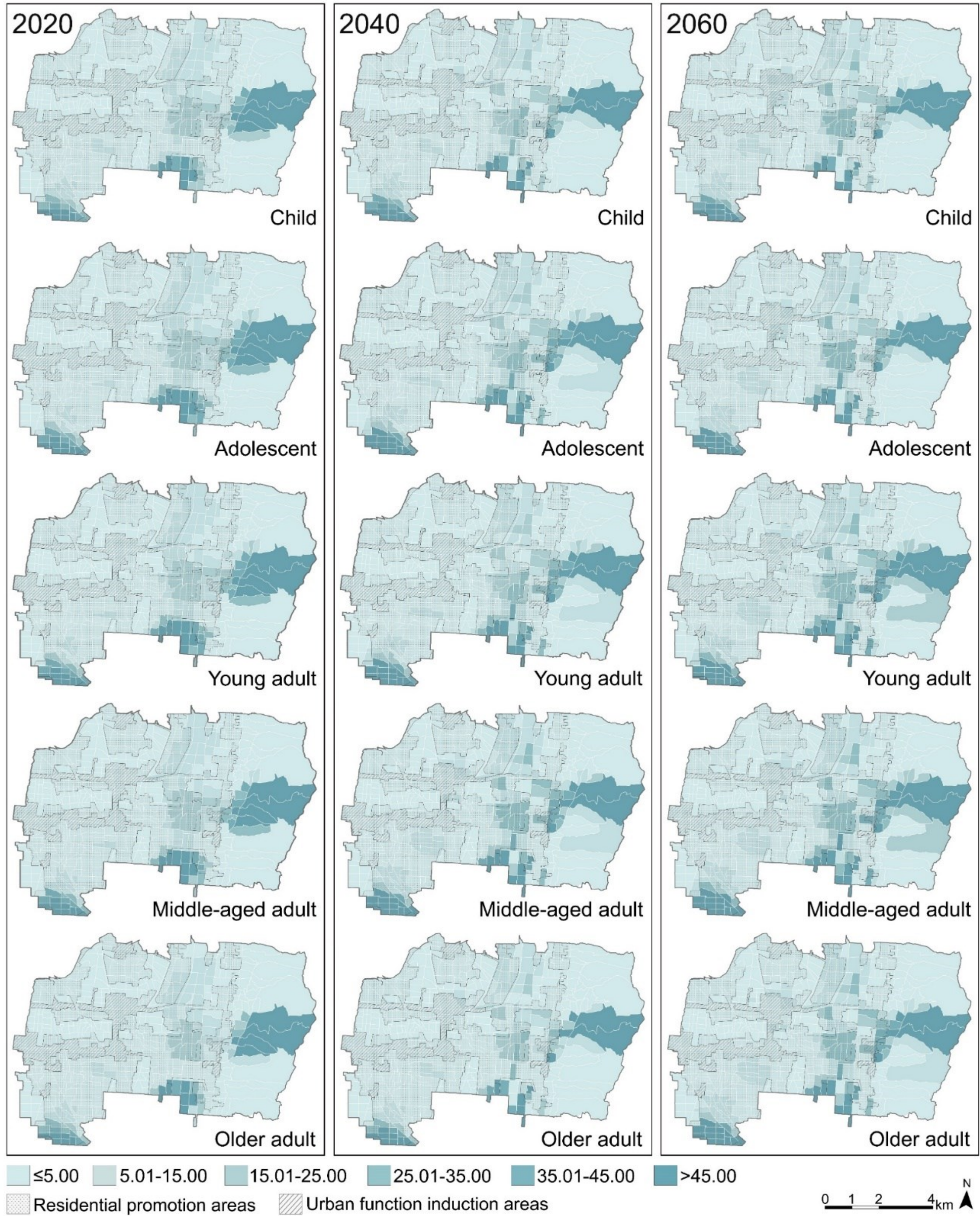

Fig. 5.7 UGS accessibility index maps for different age groups

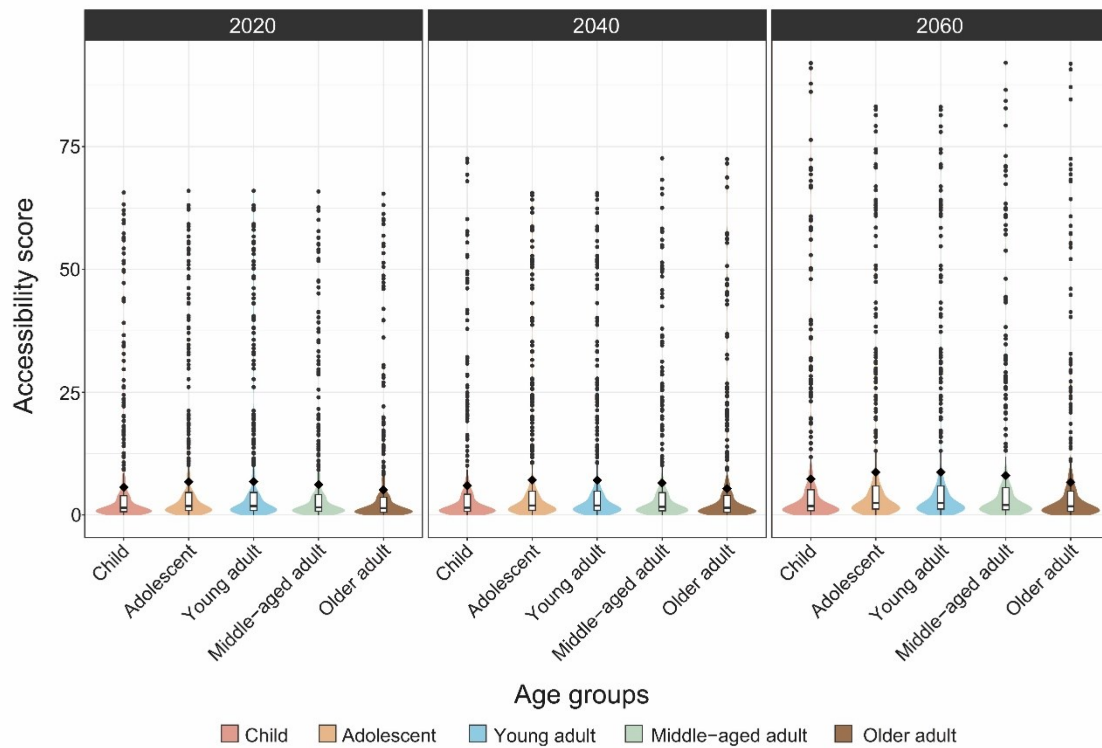

Fig. 5.8 UGS accessibility index by age group

The bi-LISA map further reveals the spatial pattern of demographic demand and UGS accessibility supply for different age groups (Fig 5.9). Although the Global Moran's I showed a positive spatial correlation between population demand and UGS accessibility for different age groups (Table 5.8), there were still areas of anomalous supply and demand services. In the west, northeast, and southeast, UGSs were "underserved" (HL clusters) for all age groups; however, the spatial patterns of the different age groups were slightly different. For example, in the UFIAs, there were more "underserved" blocks for other age groups than for older adults and children. UGSs were "overserved" (LH cluster) for all age groups in the city's southwestern, south-central, and east-central parts. However, older adults had the fewest "overserved" blocks, which increased over time.

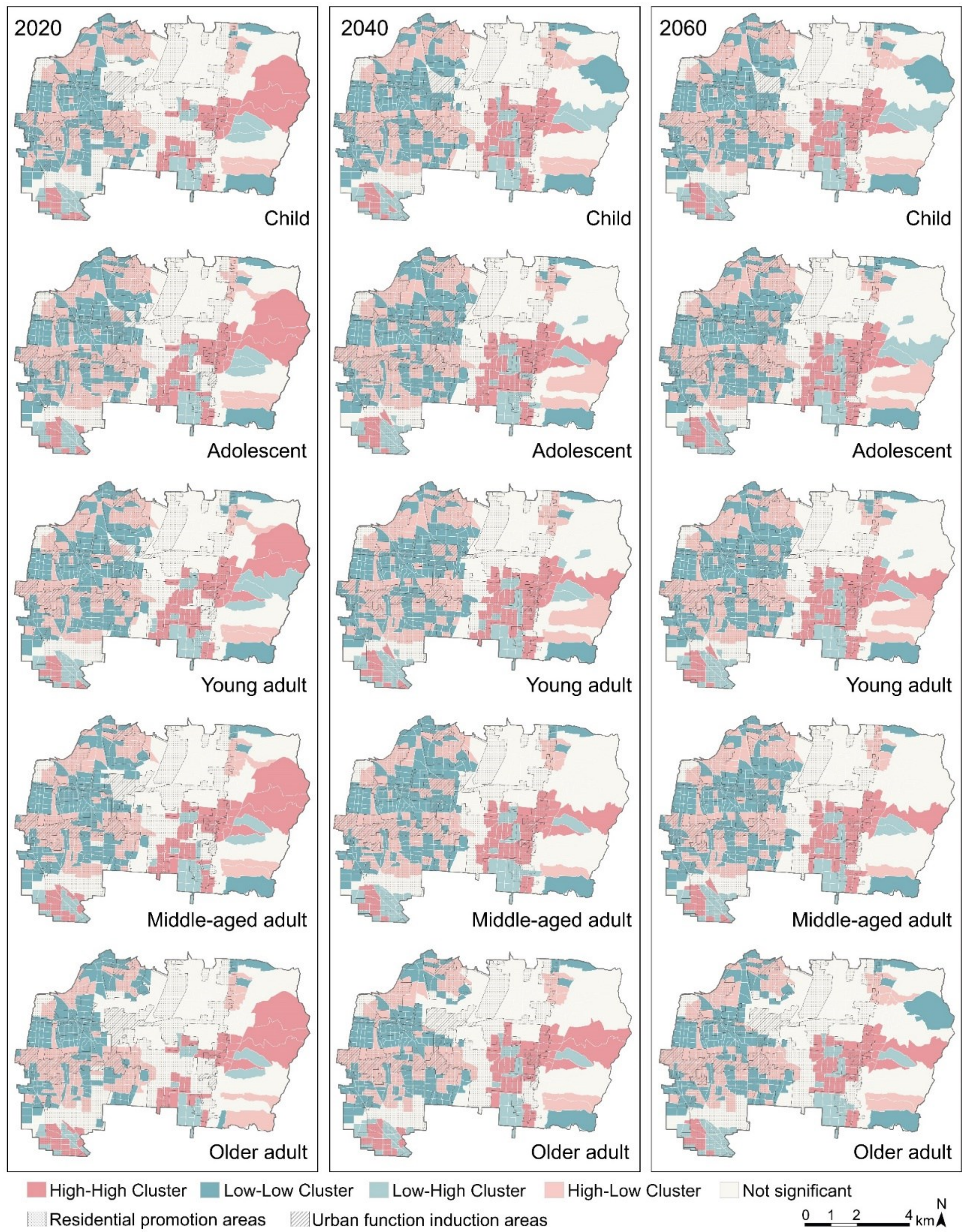

Fig. 5.9 Bi-LISA maps of UGS accessibility supply and demand for different age groups

Table 5.8 Results for bivariate global Moran's I

Years	Y	X	Moran's I	p-value
2020	Total accessibility	Total population	0.043	0.001
	Accessibility for children	Child population	0.031	0.005
	Accessibility for adolescents	Adolescent population	0.040	0.001
	Accessibility for young adults	Young adult population	0.020	0.033
	Accessibility for middle-aged adults	Middle-aged adult population	0.058	0.001
	Accessibility for older adults	Older adult population	0.055	0.001
2040	Total accessibility	Total population	0.045	0.002
	Accessibility for children	Child population	0.043	0.002
	Accessibility for adolescents	Adolescent population	0.049	0.001
	Accessibility for young adults	Young adult population	0.063	0.001
	Accessibility for middle-aged adults	Middle-aged adult population	0.018	0.028
	Accessibility for older adults	Older adult population	0.041	0.001
2060	Total accessibility	Total population	0.040	0.001
	Accessibility for children	Child population	0.039	0.001
	Accessibility for adolescents	Adolescent population	0.047	0.001
	Accessibility for young adults	Young adult population	0.059	0.001
	Accessibility for middle-aged adults	Middle-aged adult population	0.053	0.001
	Accessibility for older adults	Older adult population	0.187	0.026

Fig. 5.10 further reveals blocks with mismatched supply and demand for UGS accessibility due to population structure changes between 2020 and 2060. I found that blocks with a rising proportion of older adults but declining accessibility were the most prevalent and concentrated in the city's central and southeastern parts. This means that while demand for UGSs for older adults has increased in these blocks, the supply of

UGS accessibility has declined, potentially leading to further service scarcity. In contrast, blocks with declining population percentages but rising accessibility were most prevalent among adolescents. This implies that UGS services are growing despite the declining needs of the adolescent population, potentially leading to further over-servicing. Children, young adults, and middle-aged adults had a more random block distribution of UGS accessibility supply-demand mismatches resulting from demographic change. However, it is still evident that the eastern part of the city for children, young adults, and older adults shows a clear trend of tight supply and demand.

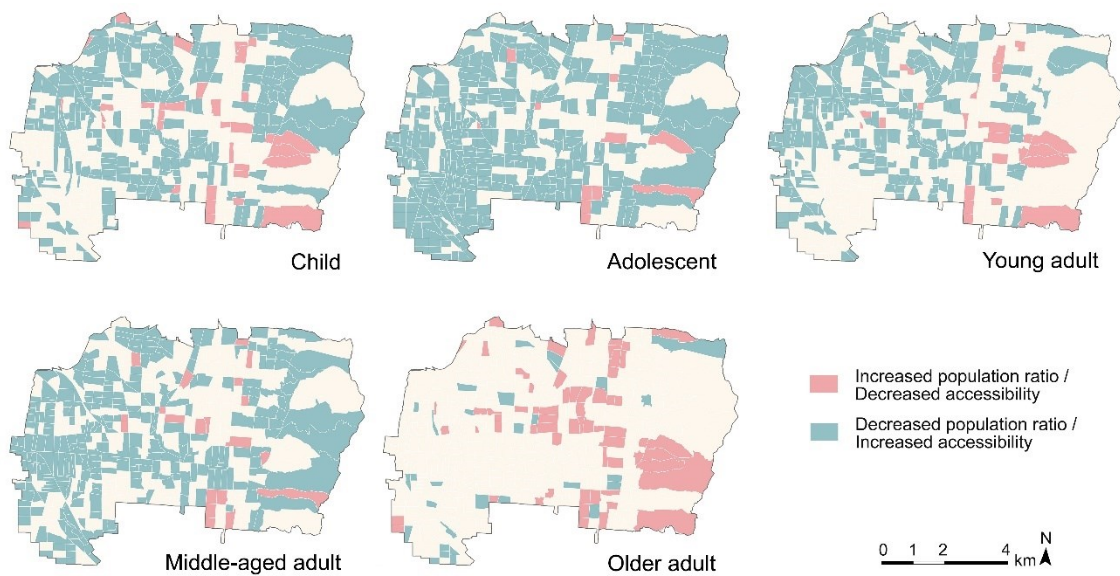

Fig. 5.10 Mismatches between supply and demand for services resulting from population structure changes and accessibility changes (red color indicates blocks with positive age-specific population percentage growth but negative accessibility growth between 2020 and 2060; blue color indicates blocks with negative age-specific population percentage growth but positive accessibility growth between 2020 and 2060.)

Finally, the Gini coefficient indicates inequality in UGS for different age groups (Fig.

5.11). The results showed that UGS accessibility was most inequitable for older adults. Children and young adults showed a very different trend from the remaining age groups in that the Gini coefficient first declined and then increased. Meanwhile, unlike older and middle-aged adults, the rate of decline in the Gini coefficient for young adults increased over time. By 2060, UGS inequality were greater for older adults, followed by children, middle-aged adults, young adults, and adolescents, in descending order.

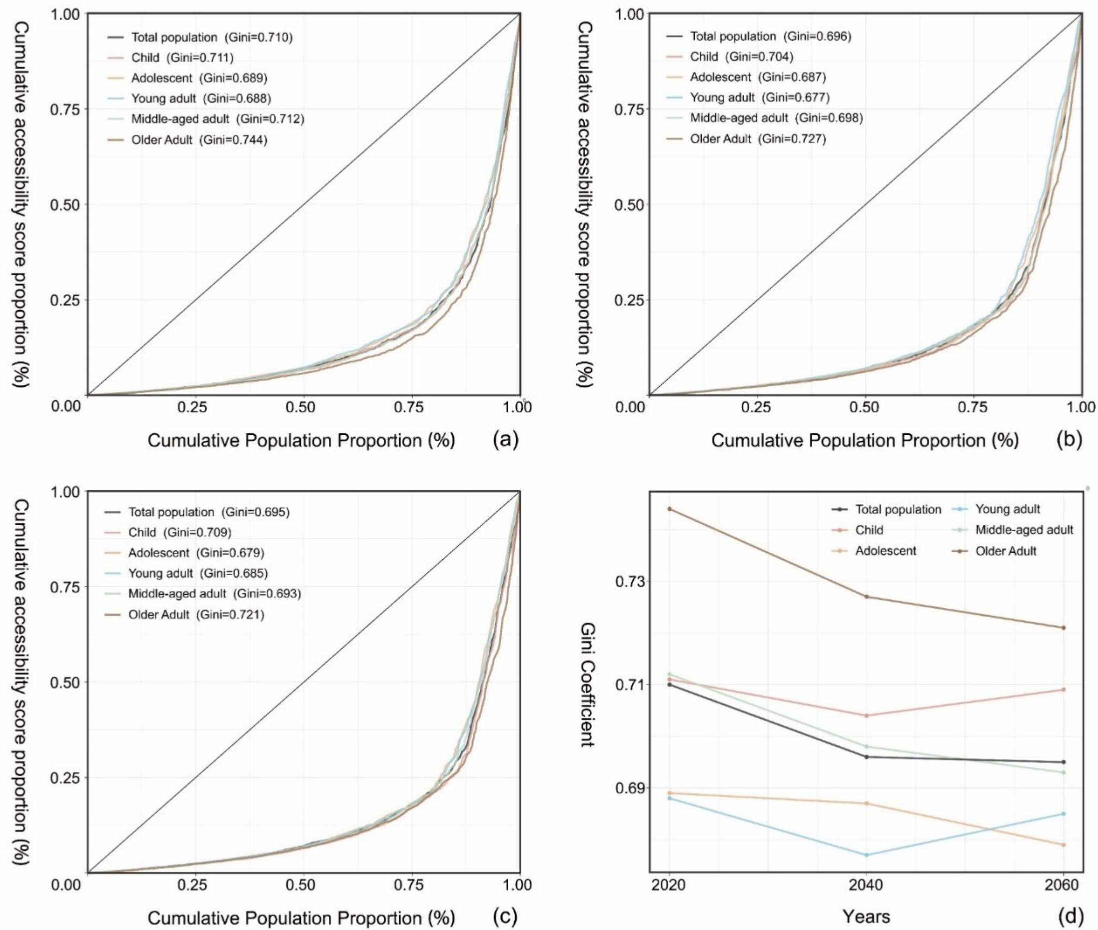

Fig. 5.11 Inequality in UGS for different age groups. a) Gini coefficient in 2020; b) Gini coefficient in 2040; c) Gini coefficient in 2040; and d) Gini coefficient trends

3.2.2 Differences in the UGS accessibility supply between urban planning zones

In exploring the fourth research question, I conducted a detailed analysis of UGS accessibility in different urban planning areas in Higashiosaka City. These planning areas are intended to respond to urban population decline and aging, assuming different urban functions in the context of demographic change. I found that UGS accessibility was higher in the central and east-central areas than in the western areas (Fig. 5.12a). The UGS accessibility at the block level increased yearly, but the spatial pattern appeared more scattered. UGS accessibility was consistently low within the UFIAs compared to the RPAs and OUAs (Fig. 5.13).

The bivariate Global Moran's I showed a positive spatial correlation between UGS accessibility and population for years (Table 5.8). The HL clusters (service scarcity) in the Bi-LISA map were concentrated in the RPAs and UFIAs in the western part of the city and, to a lesser extent, in the OUAs in the northeastern and southeastern parts of the city (Fig. 5.12b). The number of "underserved" blocks increased slightly over time. Conversely, LH clusters (overserved) were concentrated in the southwestern and south-central parts of the city, dominated by RPAs and OUAs.

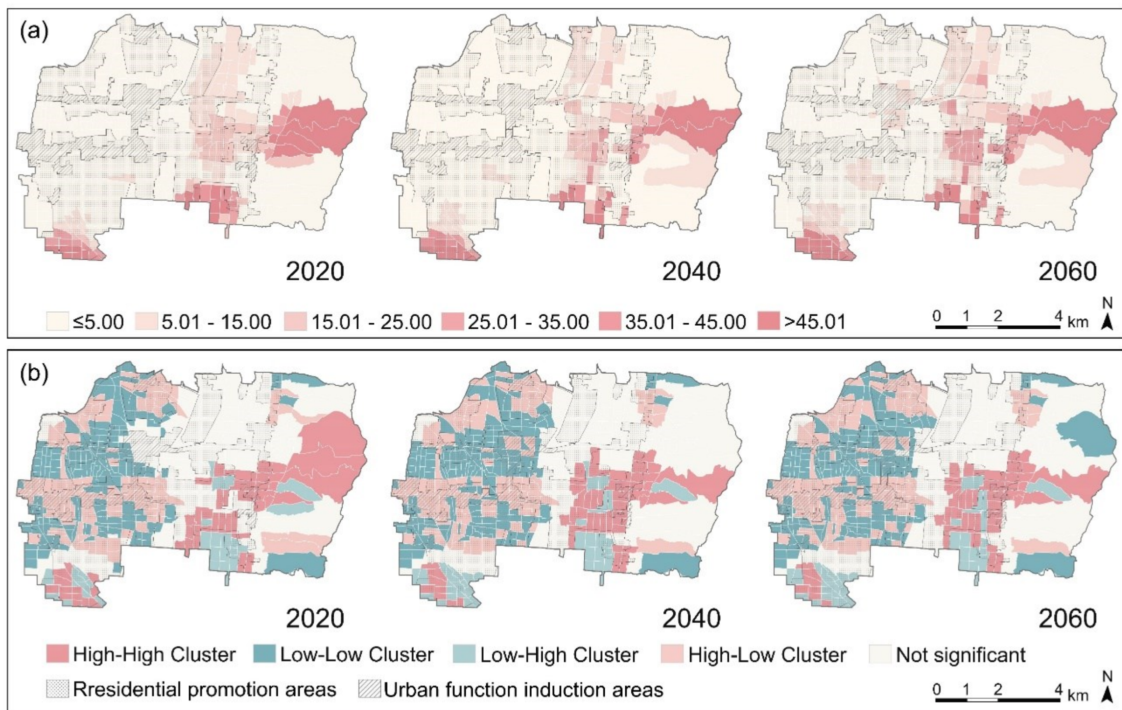

Fig. 5.12 Spatial distribution of UGS accessibility supply in Higashiosaka City. a) Accessibility index maps, b) Bi-LISA maps.

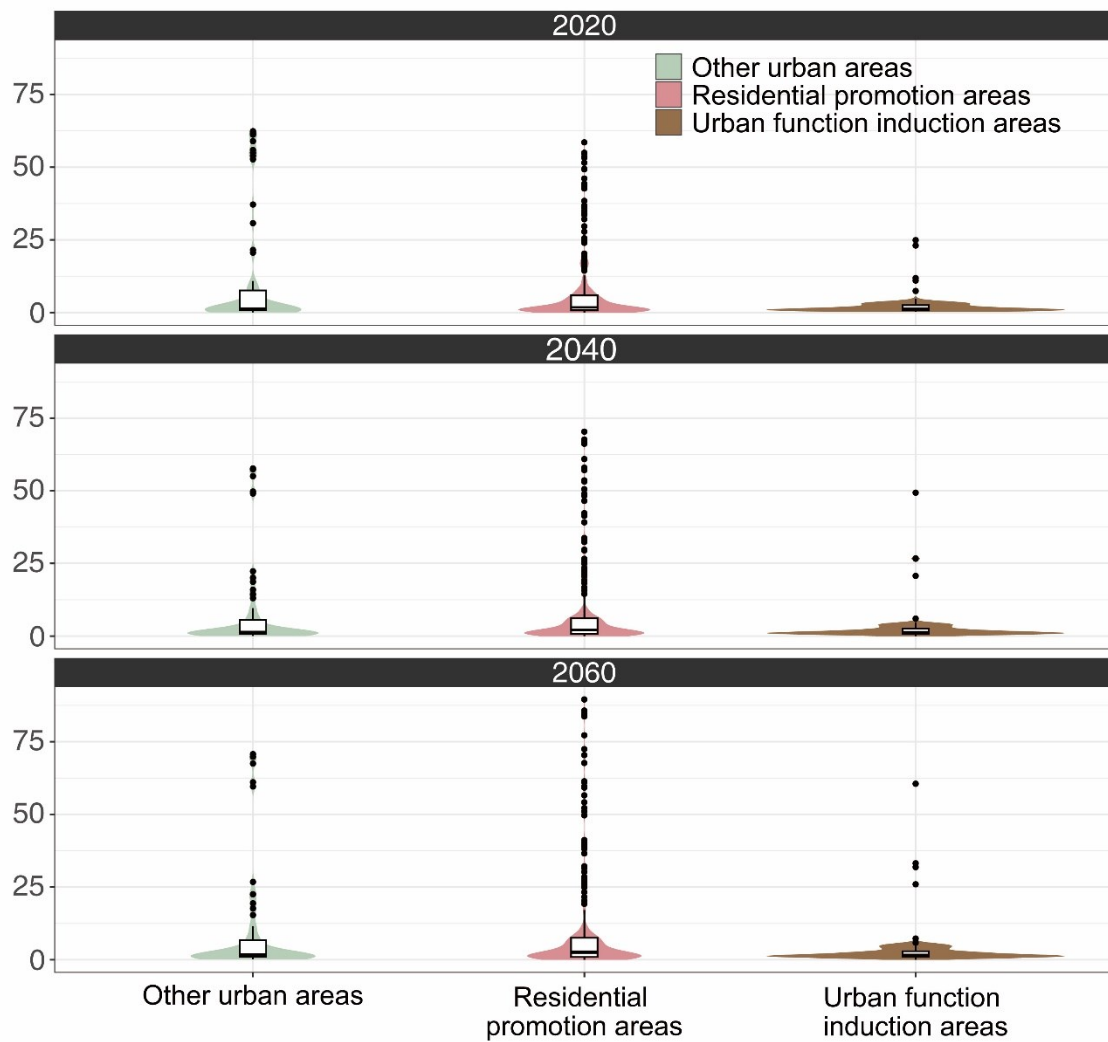

Fig. 5.13 UGS accessibility index by urban planning zone

The Gini coefficient further reveals the inequality in UGS supply in different urban areas (Fig. 5.14). The results showed that inequality in UGS was the lowest among the UFIAs. By contrast, OUAs, dominated by industrial and suburban residential areas, had the highest degree of inequality in UGS. UGS inequality in the UFIAs tended to increase as the years changed. In contrast, there was little change in the degree of inequality in UGS in the RPAs and OUAs.

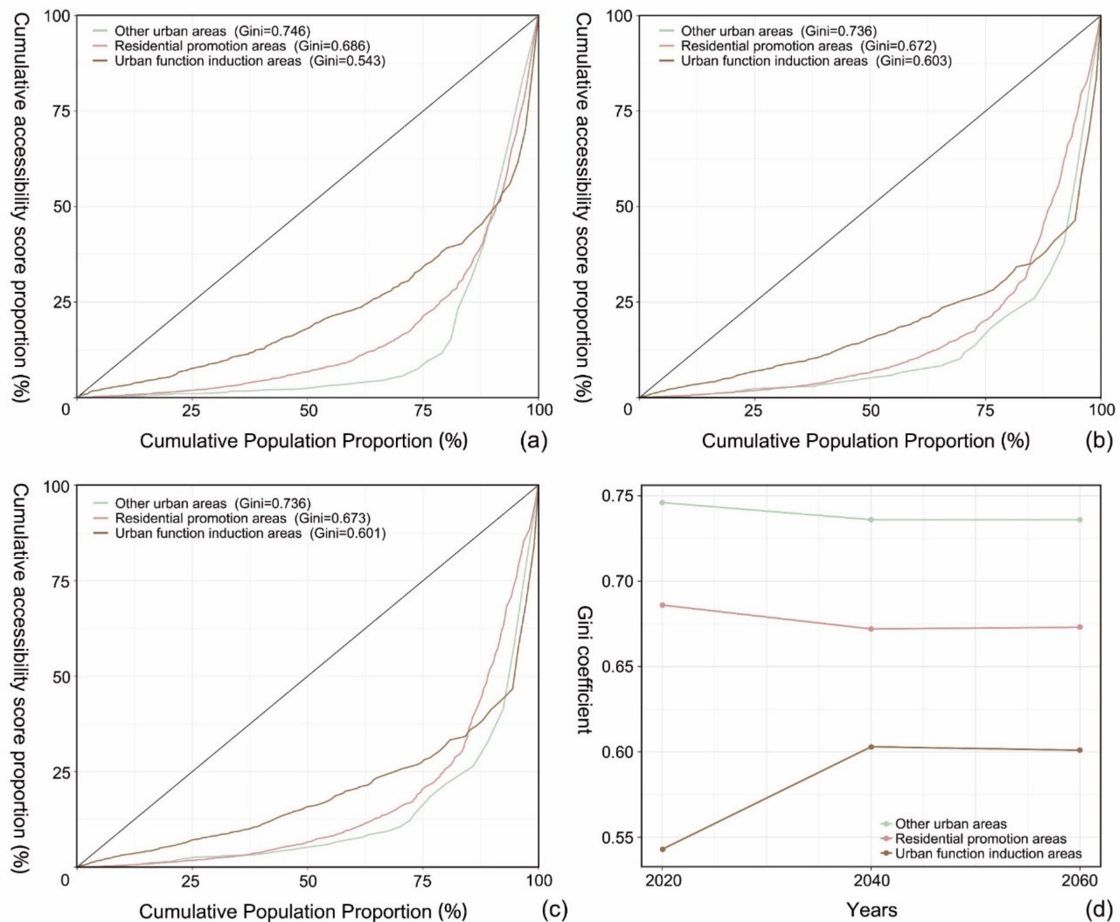

Fig. 5.14 UGS inequality in different urban areas. a) Gini coefficient in 2020; b) Gini coefficient in 2040; c) Gini coefficient in 2040; and d) Gini coefficient trends

4. Discussion

4.1 Rethinking UGS planning under demographic change: implications for Higashiosaka City

Utilizing the FSD-2SFCA method, the research delves into UGS accessibility from the perspective of population structure, focusing on the distribution of different age groups within urban areas and their combined impact on the provision of UGS accessibility. This population structure-based analysis thoroughly accounts for the diversity of age

structures among neighborhoods and is closely tied to urban planning policies, addressing how to optimize UGS distribution on a macro level, enhance overall accessibility, and balance the needs among different age populations.

In contrast to analyses that focus solely on a single age factor aimed at satisfying the current needs of specific groups, an age-based population structure analysis places a greater emphasis on the necessity for long-term and comprehensive planning. It considers overall social structural changes, such as trends in population aging or youthfulness, and their long-term impacts on UGS systems. This approach provides an important perspective for the development of more forward-looking and inclusive urban planning policies, ensuring that UGS systems can adapt to the evolution of the social fabric and meet the needs of all age groups.

The case study reveals that the mismatch between supply and demand of UGS accessibility between blocks shows a significant change in different age groups. The proportion of young population in Higashiosaka City is expected to decrease considerably over the next 40 years due to population decline and lower birth rates. This will lead to a gradual surplus of UGS accessibility services for the adolescent groups in Higashiosaka City. In contrast, the shortage of UGS accessibility services for older adults will worsen due to the gradual growth of this population. While UGS inequality for older adults have decreased over time, they are consistently the most severe among all age groups. Consistent with previous findings, Sikorska et al. (2020) found that older adults were the most disadvantaged regarding access to public UGSs [354]. This phenomenon is a “wake-up call” for future urban planning in Japan. In the face of aging

and childlessness, Higashiosaka City should pay more attention to the impact of demographic changes on the accessibility of UGSs, particularly for older adults.

The results show that for older adults, vegetation, seats, and toilets in the UGS are the ultimate desired of all environmental facilities. This result is not the same as previous studies. Bjerke et al. (2006) claimed that older adults have a lower preference for dense vegetation in parks [355]. Another study found a significant positive correlation between the quantity and quality of greenery and the number of older adults using parks [356], while Van Puyvelde et al. (2023) reported that older adults preferred ample rest areas and natural elements [357]. The reason for this phenomenon may be related to geographical and cultural differences. In addition, another study from Hong Kong had similar findings to ours and found that older adults preferred amenities such as seats, public toilets, and other convenience facilities [358]. By improving the environmental quality of UGSs in the neighborhood of older adults may encourage more frequent visits by older adults [357].

Meanwhile, it is important to note that while UGS inequality weakened over the years for most age groups, UGS inequality for children and youth showed a different trend of weakening followed by growth. Depending on trends related to aging and childless families, some blocks may experience an imbalance in their age structure [330]. The study predicts that the proportion of children, young adults, and older adults in some neighborhoods in the eastern part of Higashiosaka City will increase significantly over the next 40 years, yet UGS accessibility services will decline significantly. While the eastern part of the city is not entirely part of the core area, it is served by several large

UGSs. These well-facilitated UGSs are crucial in attracting residents, particularly the older adult population. Studies have shown that older people generally prefer UGSs, so these UGSs may be a key factor in their relocation choices [314]. Conversely, neighborhoods in the urban core may appear more exclusive because of the compact city development strategy and Japan's unique housing inheritance system [98]. This trend particularly affects young families, who may face additional challenges when seeking to relocate to the core. Young families often opt for more randomized migration to more marginal urban areas [98]. This migration trend may lead to an increase in young adult and child populations in the eastern region. Thus, the increased tension between supply and demand for UGS accessibility in the eastern region for specific demographics.

In response to population decline, Higashiosaka City's compact city strategy maintains population density in the urban center through UFIAs and RPAs. However, the reality often contradicts expectations. The analysis shows that among all the urban planning areas, the UFIA and the RPA have experienced the most significant population decline. In addition, the supply of UGS accessibility within the UFIA remains low and increasingly inequitable. Previous studies have found that the lower the population density, the more the inequalities in UGS [244]. Meanwhile, within UFIA, neighborhoods with lower UGS accessibility indices experienced greater population declines, leading to a further increase in the inequality in UGS supply within the area. UGS inequalities were consistently worse in OUAs (e.g., industrial areas and suburban settlements) than in UFIAs and RPAs, with a slight change noted over time. This could be attributed to the OUA having the lowest population density of all the urban planning zones, with some residences being developed adjacent to industrial land, resulting in a severe

residential–industrial mix in Higashiosaka [359]. In addition, most of the existing large UGSs were built near suburban residential areas, creating a noticeable gap between mixed–industrial residential neighborhoods and suburban residences, particularly in the east-central and northeastern parts of the city. Although the government has invested significant resources in RPAs to attract residents, owing to the exclusivity of established neighborhoods, immigrants may have difficulty relocating to RPAs [98]. Reduced investment in the OUA and the continued migration of new residents make it difficult to mitigate the inequitable distribution of the area and may even lead to more severe residential segregation.

4.2 Advantages of the FSD-2SFCA method

This study proposes a floatable spatial accessibility model for estimating UGS accessibility. This approach differs from previous models in several distinct ways. First, previous methods have only used UGS or facility-weighted areas to reflect UGS attractiveness [193,352]. However, this ignores the preferences of population subgroups for environmental facilities in UGSs. Based on a multidimensional quality assessment of UGSs, the model developed in the study further considers the preferences of population subgroups for environmental facilities and can quantify UGS attractiveness for different populations more precisely. Second, previous methods have tended to use only a single travel distance to measure UGS accessibility for residents [179,182], ignoring the disparity in travel ability between populations [187]. The method sets the corresponding travel thresholds based on the travel ability of different populations, avoiding measurement bias due to disparities in travel ability. Finally, the traditional Huff model represents

competing scenarios for UGS visits by calculating the choice probability of residents within the demand point for each UGS in the catchment [201]. The visit probability for a given UGS is the same for all residents within the demand point. However, the UGS visit probability should differ for different populations within the catchment area because of population preferences and travel abilities. The FSD-2SFCA method takes into account UGS choice probabilities of different populations by further improving the Huff model. Therefore, in this method, the catchment area, UGS attractiveness, and choice probability of residents are floatable variables.

The FSD-2SFCA method has several advantages: 1) it mitigates the overestimation of UGS accessibility by previous methods and is also more sensitive to the equitable distribution of UGS accessibility; 2) as a flexible measurement method, it allows for a variety of demographic considerations; and 3) it can quickly calculate the total value of spatial accessibility while obtaining individual spatial accessibility values for each population subgroup, which facilitates thinking about specific population subgroups individually.

In this study, I use age structure as an example to elaborate the operational procedures of the FSD-2SFCA method. However, the application of the FSD-2SFCA method is not limited to the analysis of age structure; researchers can perform targeted demographic analysis by replacing the age group in the case with other demographic variables (e.g., gender, disability). In addition, the applicability of the FSD-2SFCA method extends to the prediction of other urban infrastructures, although this may require that the service items and user preferences of the infrastructures be adjusted accordingly to suit different

assessment needs. Further, the FSD-2SFCA method supports more fine-grained adjustments to improve its sensitivity, such as by increasing the number of items assessed for UGS environment facilities or by setting specialized distance decay functions for different population subgroups. I believe that the FSD-2SFCA method is highly adaptable and replicable and can be applied to a wide range of relevant research areas with appropriate adjustments.

4.3 Limitations and future directions

Although the proposed methodology introduces important advantages in the context of demographic change, several limitations remain. First, the UGS quality assessment only covered some environmental facility items (n = 23) for ease of implementation, which is not an exhaustive list [179,193]. Second, most of the environmental facility items considered only the number of facilities, ignoring the maintenance and aesthetics of UGSs, which can influence residents' access to UGSs [62,67]. However, the model allows for improved accuracy by incorporating more environmental facilities items, and UGS accessibility can be assessed in the future using a more complete UGS quality scoring system.

Third, I only focused on UGS accessibility for different age groups and did not consider other demographic factors (e.g., gender, race). Moreover, I measured travel ability by walking speed for children as a separate age group, ignoring the special situation of parents helping children to access UGSs. Given the scalability of the proposed method, future studies could use the FSD-2SFCA method to explore interesting environmental

justice issues among different population subgroups, and model parameters could be adjusted to measure multimodal UGS accessibility by considering travel modes for different population subgroups.

Fourth, this study has limitations in terms of UGS accessibility prediction. Because of data acquisition and length constraints, I only considered changes in population size and structure in this study and did not address other potential influencing factors such as technological advances. Therefore, the predictions of UGS accessibility in this study are linear. Considering the importance of predicting future UGS development under multiple scenarios, future studies should consider the multifaceted effects of more variables on UGS development. I believe that the methodology presented in this study will a critical tool for predicting UGS development.

Fifth, although the UGS in Higashiosaka City is dominated by urban parks, there are many natural UGS as well as affiliated UGS. limited by effort and time, I was not able to measure all types of UGS in the city. In this chapter, I narrowly defined UGS as urban parks and measured inequality only in urban parks, which would result in a certain degree of bias.

Finally, the approach considers residents’ travel costs through a distance function. However, safety or built environment factors related to residents’ paths to the UGS may also affect the probability of residents traveling there. Meanwhile, the public facilities or infrastructure near the UGS may also affect the probability of residents visiting the UGS. In this study, I was unable to fully consider these factors due to time and effort

constraints, but the new methodology could support taking them into account by adding UGS quality evaluation factors. Future studies could measure these factors in more detail.

5. Conclusion

In this chapter, I have reframed the key question in the development of UGSs in the context of demographic change as follows: "How can UGS planning and accessibility be comprehensively reviewed to accommodate current and upcoming demographic changes?" In response to this critical question, I introduced the FSD-2SFCA method, a novel approach to spatial accessibility that adjusts for population heterogeneity. This method not only considers the environmental quality of UGS, but also considers gaps in the preferences and travel abilities of population subgroups and compensates for the limitations of previous methods in measuring spatial accessibility for specific population subgroups. Through a case study in Higashiosaka City, I compared this approach to traditional methods, examining differences in UGS accessibility across age structures and urban areas.

The innovative method effectively avoids the overestimation of UGS accessibility by previous methods and is more sensitive to the measurement of inequities in UGS accessibility. The results of the case study suggest that cities should continuously examine the fairness of UGS planning from a dynamic perspective and pay attention to the impact of demographic changes (size and structure) on UGSs rather than blindly concentrating resources in a certain area of the city.

In summary, the findings advocate for a continual, adaptive approach to UGS planning that addresses demographic trends head-on, ensuring that urban development remains inclusive and responsive to the changing needs of its population.

Chapter VI. How to mitigate UGS inequality in the context of demographic change

1. Summary of results of each chapter: UGS inequality trends and different dimensional drivers

The empirical study answers each of the five objectives posed in Chapter I. Building on previous research, this study shows that UGS inequality is an issue that evolves through the stages of urban development and is the result of the interaction of three factors: urban form, UGS and population.

1.1 Equitable development of UGS should be emphasized

The chapter II quantifies the inequality in UGS in Japanese municipalities from 2000 to 2020 through the Gini coefficient. Findings indicate an increasing trend in UGS inequality, with significant variances across different city sizes and geographical areas. It is worth emphasizing that medium-sized cities have the most unequal UGS of all city groups; and that small cities and towns/villages are experiencing rapidly rising levels of inequality in UGS. Yet these cities have typically faced severe population decline and fiscal shrinkage over the last two decades. This could have the very serious consequence that the environmental justice issues raised by UGS inequality could interact with urban contraction to create a vicious cycle, such as the white flight that occurred in the United States in the last century.

In the past, the Japanese government has focused solely on the per capita UGS area when planning UGS. However, the purpose of this study is to point out that we should also pay attention to the inequality in UGS while considering the per capita UGS area. The significance of UGS cannot be overstated, as the erosion of ESs they offer can precipitate grave health consequences. In the post-pandemic era, with Japan grappling with urbanization and a declining population, the escalating inequality in ESs could exacerbate health disparities. I strongly recommend that the government incorporate UGS inequality-related indicators into UGS planning and pay attention to the equal distribution of UGS while considering per-capita UGS area to promote healthy urban sustainable development.

1.2 Urban dimension: the relationship between urban form and UGS inequality

Based on the results of Chapter II, I further investigate the issue of urban form in cities with declining populations and link it to UGS inequality. The chapter III analyzes the relationship between urban form and UGS inequality in shrinking cities by mapping and measuring urban form indicators and UGS inequality indicators in 147 shrinking cities in seven regions of Japan for the first time. The results show that 1) partial Japanese urban shrinkage affects equitable development of UGSs; 2) cities with compact populations facilitate equitable urban development; 3) the shape and continuity of urban patches affect the distribution of UGSs in shrinking cities in all regions; 4) urban size, centrality, compactness of urban patches, and urban patch fragmentation affect the distribution of UGSs in shrinking cities in local regions.

It is worth emphasizing that the complexity and continuity of urban patches are the most important drivers of UGS inequality. The more complex the urban patch the lower the UGS inequality. This implies that it is particularly important to focus on the integration of built-up areas with UGSs in long-term urban planning, rather than building uncontrolled gray infrastructure in built-up areas. In addition, the lower the continuity of urban patches, the lower the UGS inequality. However, past studies have found that the continuity of urban patches ensures the efficient functioning of cities. For example, Wang and Debbage (2021) claim that continuous urban housing is associated with reduced traffic congestion [135]. This finding emphasizes the paradoxical aspect of urban built-up area construction and UGS construction, i.e., continuous patches usually provide more efficient services for urban functioning, but this can make the residents' UGS exposure severely unbalanced. Therefore, it is particularly important to address or balance this phenomenon through some greening tools, such as street greening. This is because street greening or vertical greening, while disrupting the urban patch in plane, still ensures the continuity of the built-up area of the urban patch in elevation, such as the High Line Park in the United States [37]. It ensures equal development of the UGS along with urban transportation. The results of study can provide city managers with reliable urban development strategies to promote equitable distribution of UGSs in shrinking cities.

1.3 Neighborhood dimension: the relationship between UGS spatial pattern and UGS inequality

Based on the results in Chapter III, I have reason to believe that the development of urban form affects the form of UGS, thereby changing residents' UGS exposure. Therefore, the spatial morphological pattern of UGS may also affect UGS inequality. Due to urban land and financial constraints, it is not possible to maintain UGS inequality by simply increasing the number of UGSs. Therefore, it is necessary to explore what defines a reasonable UGS structure from an equality perspective to support sustainable urban development. Especially in cities rich in natural UGS, the spatial pattern of UGS forms in the city is more complex. Therefore, I have explored the association between the spatial pattern of UGS and UGS inequality in Yokosuka City as an example to provide a strategy for UGS equality planning for this type of city. MSPA was used to understand the morphological structure of UGSs in different regions and to transform them into potential structural classes. Finally, a UGS inequality prediction model was constructed by ridge regression to provide a UGS morphological structure that is conducive to equitable UGS development. The main results show that islet, edge, loop and branch components of the UGS are effective in mitigating UGS inequality, and their corresponding potential UGS morphology is fragmentation, complexity, internal connectivity, and partial connectivity, respectively. However, the core of UGS is not conducive to the equitable development of UGS, i.e., large UGS.

From a landscape ecology perspective, large UGS are often considered to provide diverse ESs [360,361]. However, this study found that large UGS have a detrimental effect

in promoting the equitable development of UGS. This finding reveals a conflict between environmental justice perspectives and ecological perspectives. While large UGS provide rich ESs to the surrounding population, they also lead to unequal distribution of these services among different neighborhoods, with residents far away from the large UGS not being able to enjoy these services. However, large UGS provide many ESs to urban ecosystems. As urbanization progresses, the number of large UGS in cities is decreasing, further exacerbating urban ecological problems. In order to promote equal development of UGS, it is obviously undesirable to solve the problem by reducing the number of existing large UGS. Therefore, it is particularly important to explore other effective methods to mitigate UGS inequality.

First, the complexity of large UGSs can contribute to the equitable development of UGSs. This finding indirectly corroborates some of the results in Chapter III, as morphologically complex UGS tend to also be able to increase the complexity of urban patches and promote the integration of urban patches with green landscapes, thus allowing the ESs of large UGS to serve more residents. Moreover, increasing the shape complexity of UGS patches can also enhance the edge effect of the plate to improve the ecological benefits of the landscape [362–364]. In addition, past conservation planning has typically ignored small, isolated UGSs because of their perceived relatively low ecological value, focusing instead on the protection of large UGSs. however, a growing body of research suggests that these fragmented UGSs play an important role in key ecosystem services, such as biodiversity, cooling effects, and more [161,321,365]. they call for small UGS patches that should be restored and construction of more small UGS patches [365]. Our study also found that building flexible small UGSs in neighborhoods far

from large UGSs can be effective in mitigating inequalities in UGSs because they are closer to the neighborhood and more evenly distributed. Thus, increasing the number of small UGSs not only serves as an ecological steppingstone, but also provides residents with more equal access to public open space. Finally, our study also reveals the importance of UGS connectivity. It is well known that UGS connectivity plays an important role in the landscape ecology of cities, providing potential movement pathways for organisms. This means that UGS connectivity is not only ecologically significant, but can also contribute to environmental justice. Therefore, the construction of ecological networks is consistent with the idea of environmental justice, and increasing connectivity between UGSs not only provides residents and organisms with shared margins, but also provides them with green corridors to the UGSs.

In general, this chapter further improves the analytical framework for describing the morphological structure of UGSs based on MSPA from a morphological perspective and provides a spatial morphological strategy to support the equitable development of UGSs.

1.4 Population dimension: changes in UGS inequality due to demographic changes and demographic preferences

Rapid demographic change has reshaped the demand for and use of UGS, profoundly affecting UGS inequality. In response to the need for UGS equality planning under demographic change, I have rethought the gaps in existing UGS accessibility research. In chapter V, I propose a composite method—the Floatable Supply and Demand

Improved 2SFCA (FSD-2SFCA) method. The FSD-2SFCA method considers gaps in environmental facility preferences and travel abilities among population subgroups to better meet the needs of UGS planning based on demographic changes. The method measured UGS accessibility in Higashiosaka City under existing and projected population dynamics (2020–2060). Higashiosaka city represents a shrinking city with urban parks as the main UGS, and this category of city is more susceptible to environmental facilities within the UGS. Therefore, the case study of Higashiosaka city can provide a more practical reference for this category of shrinking cities.

The results show that preferences for UGS environmental amenities vary across age groups and that the quality of UGS environmental amenities as well as demographic preferences affect UGS accessibility and inequality for residents. This provides higher demands on the city's UGS policies due to demographic changes. Spatial differences and inequalities in UGS accessibility exist in Higashiosaka City and that UGS inequalities among age groups showed different trends as the population changed. Considering the time lag of UGS construction, the government should give population forecasts, be more forward-looking in UGS planning, and constantly adjust and optimize the planning scheme based on the actual changes in the demographic structure. In addition, UGS accessibility is generally the lowest and most inequitable for older adults. In a society with a declining and aging population, governments should pay more attention to UGS accessibility and inequality for older people in pursuit of healthier and sustainable urban development. It has been argued that older adults in Japan are more likely to have access to small neighborhood parks [366]; but the study found that the quality of environmental facilities in small parks was generally low and

that they lacked adequate facilities for the aging. It is important to link small parks to form a UGS network within specific areas of the city. This network will not only provide residents with more diverse recreational opportunities, but also enhance the city's ecosystem services. By linking small parks, they can complement each other's respective roles and promote equal distribution of UGS. In an aging society, it is particularly important to build more UGS environmental facilities that meet the preferences of the older adults, such as planting more green vegetation, building enough leisure space (seats), and some convenience facilities (toilets) that meet the needs of the older adults. These facilities can encourage older adults to visit UGS more frequently.

Moreover, the study found that the current urban planning strategy of Higashiosaka city, while adapting to some extent to changes in population decline, does not necessarily promote equitable development of the UGS. The bottom-up migration of residents and the bottom-up policy of a compact city run counter to each other, thus contributing to the worsening of inequality in the UGS. Therefore, cities should avoid "one-size-fits-all" urban development strategies, especially in the context of demographic change. The government can incorporate UGS development into urban planning policies, and UGS-centered community building can, in turn, induce the migration of residents.

This study also highlights that in addressing demographic change, policymakers must consider present equitable distribution of UGSs, and future UGS accessibility based on population projections to ensure equality-oriented, sustainable UGS planning.

2. Policy recommendations

Unlike most studies, this study focuses on the challenges and opportunities that shrinking cities face. Not only do shrinking cities face a range of problems such as the loss of urban vitality and increase in abandoned land [367], but long-term urban shrinkage may also lead to a worsening of UGS inequality. In response to the various problems caused by urban shrinkage, the Japanese government has proposed a development strategy for compact cities. This urban policy aims to concentrate resources on developing urban centers and induce suburban residents to DIDs to maintain the density of urban city population and enhance the efficiency of social resource utilization [368]. This approach seems sensible from the perspective of environmental justice, as population compact cities are beneficial to the equitable development of UGSs. However, studies also demonstrate that planning policies to accommodate urban shrinkage may lead to new environmental justice issues in the actual process of implementation [96,369]. The execution will be greatly constrained by fiscal austerity and the preferences of residents [98,245]. It may cause the emergence of an unequal distribution of resources in peri-urban areas. Cities should avoid "one-size-fits-all" urban development strategies, particularly in the context of demographic change. The results of this study raise red flags regarding the existing "Location Normalization Program" policy, which appears to fit the "nice to have" narrative. Inducing and ignoring bottom-up urban sprawl by limiting the amount of infrastructure (including UGS) in some areas leads to extreme UGS inequality in parts of the city.

Some effective policy recommendations can help to UGS equity planning in Japanese

shrinking cities. First, in the urban dimension, considering the non-smooth relationship of the shrinking urban form in Japan, the shrinking cities should formulate different development strategies according to their urban characteristics to support the sustainable development of UGS. Two recommendations seem to apply to all Japanese shrinking cities: rational use of vacant plots in cities for green transformation; an emphasis on urban greenways and roadway greening. Vacant plots are a great “asset” for shrinking cities [102], and transforming vacant lands into urban natural amenities (e.g., community gardens, parks) can enhance the complexity of shrinking urban patches, thus improving the equitable distribution of UGS. UGS inequality can be effectively mitigated by increasing the complexity of urban patches. Greenways, roadway greening, or vertical greening can enhance the equity and accessibility of UGSs, while ensuring the continuity of urban patches. In shrinking cities, some abandoned gray infrastructure can be a potential GI resource, and the High Line Park is a worthy case study [37]. Meanwhile, in the Hokkaido and Tohoku regions, the monocentric urban development pattern seems to be more conducive to UGS development. In contrast, the Kanto, Chubu, Kansai, Chugoku & Shikoku, and Kyushu & Okinawa regions are more suitable for loose and fragmented urban development that is more conducive to equitable UGS development. Cities can develop locally appropriate urban development strategies based on the degree of impact of different morphological indicators on the equality of UGS and seek sustainable development of UGS.

Second, for shrinking cities that are rich in natural UGS, UGS inequality can be mitigated from the perspective of UGS spatial pattern design. The results of this study show that by correctly designing the spatial pattern and layout of UGS, it is possible to

save money and maximize the benefits of UGS. I suggest that a UGS strategy should prioritize: 1) Connecting UGSs through street greening and greenways to promote the construction of ecological networks within the city can also provide a more equitable green environment for residents; 2) the active use of vacant land created by urban contraction to increase the number of small UGSs in neighborhoods far from the UGS core as a springboard for biology and daily recreation for residents; and 3) for large UGSs, increasing the complexity of their shapes can not only effectively enhance the edge effect of UGSs, but also promote the integration between UGSs and communities. It is worth noting that reducing the proportion of large UGS, although it can alleviate UGS inequality to some extent, may lead to serious ecological problems as a result, which is undesirable. Considering the insufficiency of the absolute amount of existing UGS in Japan, the construction of new UGS in regions with insufficient UGS by taking the measures described above will not only gradually increase the absolute amount of UGS, but will also be able to reduce the proportion of existing large UGS, thereby alleviating the disparity in the absolute value of UGS and inequality of UGS among residents.

For shrinking cities that are highly urbanized, urban parks serve as the main UGS; the UGS inequality in these cities is more susceptible to environmental facilities. To address this issue, I suggest that the governments of such shrinking cities should focus on functional reorganization and repositioning of parks. Specifically, the actual needs should be considered in the light of demographic changes, and the functional settings of the parks should be adjusted so that some of the facilities in the over-served areas can be reallocated to the under-served areas. In this way, the rational allocation of UGS can be

realized and the overall welfare of urban residents can be enhanced. In this process, considering the time lag of UGS planning, the government needs to continuously adjust the reorganization area of UGS according to the trend of demographic changes. The government can incorporate UGS development into urban planning policies, and UGS-centered community building can induce residents to relocate. In addition, as the population ages, the demand for UGS for older adults will continue to grow. The mismatch between supply and demand for UGS accessibility for older adults among neighborhoods will grow, and designing and improving environmental facilities of UGS for older adults can encourage them to use UGS more frequently. for example, adding vegetation, seating, and toilets to parks. La Rosa et al. (2018) found that older adults in Japan were more likely to use small UGS [366]. This means that the role of small UGS in cities cannot be ignored. By linking multiple small parks in a given area to form a continuous network of UGS, not only can it provide more leisure and recreational opportunities for residents, but also enhance the ES function of the city. This linkage mechanism can make up for the shortcomings of individual small parks in terms of environmental facilities, achieve complementary functions and optimal use of resources, and help to reduce the inequality in the distribution of UGS.

Finally, Because of urban shrinkage and economic decline, Japan's financial expenditures for UGSs have gradually decreased in recent years. Some UGSs in disadvantaged communities are facing decay and management and maintenance problems [370], which leads to further deterioration of UGS equality. Therefore, a more rational and scientific UGS planning model is needed to guide UGSs. Convenient public urban transportation, low-cost parks and greening maintenance programs, and resident

participation in environmental management may be the way to address this problem [98,110,371]. Meanwhile, some scholars have proposed "just green enough" greening strategies to encourage cities to use informal UGS through resident participation and rough management to mitigate urban UGS inequities [372]. The "just green enough" strategy is a good fit for shrinking cities to improve the community UGS environment by using more vacant land for small amounts of money and should be combined with a land bank to build temporary/permanent public spaces or informal UGS [373]. In addition, the Japanese government has proposed a "Parks-PFI" park activation policy, which aims to jointly maintain existing parks and improve their quality through cooperation with companies [374]. This initiative not only relieves the government's financial pressure, but also promotes UGS development and private participation.

Policy recommendations at different scales, from global to local, can help different types of shrinking cities achieve equitable and reasonable UGS sustainable development in the context of demographic change.

Chapter VII. Conclusions and perspectives

1. Conclusions

Against the backdrop of Japan's population decline, the issue of UGS inequality has become increasingly prominent, posing an urgent environmental justice challenge. With aging demographics and falling birth rates, many cities are confronting unprecedented population reductions and urban shrinkage. This context not only exacerbates inequalities in urban infrastructure and services but also makes UGS accessibility and equal distribution key factors affecting residents' quality of life. In such a societal environment, exploring the equality of UGS distribution is not just a matter of environmental justice but also a necessary path to sustainable urban development.

This study offers a multidimensional analysis of the complexities and driving factors behind UGS inequality. By quantitatively investigating UGS inequality in Japanese municipalities from 2000 to 2020, I find that UGS inequality is rising at the municipality level in Japan against the context of population decline. Among them, the rise in UGS inequality is most pronounced in small and medium-sized municipalities. Further, the study delves into the relationship between urban form, UGS spatial structure, UGS environmental facilities quality, and demographics and UGS inequality, and proposes strategies and recommendations to promote more equitable UGS development. Specifically, at the urban dimension I first measure UGS inequality and urban form indicators for 147 shrinking cities in Japan and use GWR to explore the

relationship between urban form and UGS inequality. Then, at the neighborhood dimension, I measure UGS inequality and MSPA classes in Yokosuka, a city with declining population, and measure the direct relationship between UGS inequality and MSPA structure using ridge regression. Finally, in the population dimension, I focus on developing a new spatial measure that considers the quality of environmental facilities in the UGS as well as differences in residents' preferences and ability to travel. Using the case of Higashiosaka City (another city with declining population), I reveal the impact of the UGS's quality of environmental facilities and demographic changes on UGS inequality.

Shrinking cities, unlike growing ones, deal with issues like loss of urban vitality and increased abandoned land, worsening UGS inequality. The Japanese government's compact city strategy, which concentrates resources and maintains urban population density, can help address these issues. However, its implementation must avoid new environmental justice problems, particularly in peri-urban areas. This study finds that strategies should be tailored to each city's characteristics. Overall, increasing the complexity of urban patches and focusing on greenways and roadway greening can improve UGS inequality. Cities in certain regions may benefit from varying degrees of centralization and fragmentation in urban development. For cities rich in natural UGS, strategies should prioritize connecting UGS through greenways, utilizing vacant land to create fragmented small UGS in underserved areas, and increasing the complexity of UGS shapes to enhance edge effects and community integration. While reducing large UGS can alleviate inequality, it poses ecological risks, requiring a balanced approach. Highly urbanized shrinking cities should reorganize and reallocate UGS to meet

changing demographic needs. Adjusting UGS facilities based on actual needs and trends can ensure rational allocation and improve urban welfare. Emphasizing the functionality and connectivity of small UGS is crucial, particularly for the elderly. Due to economic constraints, shrinking cities in Japan need a rational UGS planning model. Promoting public transportation, low-cost maintenance, and resident participation can address these challenges. The "just green enough" strategy and the "Parks-PFI" policy offer viable solutions through resident participation and public-private partnerships. This study emphasizes that, given the unique challenges of population and urban shrinkage, effective UGS system planning in Japan must go beyond simple quantity and area considerations to incorporate UGS exposure equity indicators into urban and UGS planning, focusing on the equitable distribution of UGS. By adapting urban form and UGS spatial patterns and considering the design of UGS environmental facilities in the context of demographic change, it is possible to promote the equitable development of UGS and improve the health and well-being of residents. This not only helps mitigate current UGS inequalities but also provides sustainable development strategies for the future as cities face demographic shifts and spatial compression.

Overall, this study makes significant contributions in several areas. First, by exploring the issue of UGS inequality in the context of Japan's population decline, it deepens the theory of environmental justice and provides a new theoretical basis for understanding and addressing environmental justice issues in shrinking cities. Second, this study provides long-term evidence of the relationship between urban development and UGS distribution in Japan, aiding in the formulation of targeted management strategies to better address the challenges of urban shrinkage. Third, the study employs multi-scale

analysis methods to comprehensively explore the relationship between UGS inequality and its drivers at different scales, filling gaps in previous research. Fourth, in the context of an aging population, it reveals the impact of demographic changes on UGS equity, offering theoretical support for designing UGS that are friendly to older adults. Finally, the study proposes a new methodology for measuring UGS equity, considering the quality of environmental facilities as well as residents' travel abilities and preferences, providing an innovative framework for future research and urban planning to ensure the fairness and rationality of UGS distribution. These contributions offer new perspectives and methods for addressing UGS inequality in shrinking cities, promoting more equitable, healthy, and sustainable UGS development.

2. Limitations and future directions

This study has several limitations when examining the inequality of UGS, as follows.

1) Consideration of specific ESs

This study defined UGS based on land covered by vegetation without considering the specific types of ESs they provide, such as cooling effects, recreational opportunities, etc. Future research should focus on identifying and quantifying the specific ESs generated by UGS exposure and accessibility. This approach will offer a more nuanced understanding of the inequality of benefits provided by different UGS.

2) Consistency in UGS definitions

In Chapters II to IV, UGS was defined as land covered by vegetation. However, in Chapter V, due to time and effort constraints, a narrower definition of UGS (urban parks) was used. This inconsistency in definitions may have introduced some degree of

bias in the results. Future studies should aim for consistency in defining UGS to avoid such biases and ensure comparability across chapters.

3) Complexity of factors in UGS inequality in Japan

This study concluded that UGS inequality in Japan is mainly driven by factors such as urban development, socioeconomic disparities, and residential segregation. However, it did not fully elucidate how these factors interact and collectively influence UGS inequality. While the investigation in Japan might have been easier due to fewer intertwined factors compared to countries in the Global North, where structural racism, planning, and cultural factors play a significant role, the complexity of interactions among these factors in Japan remains underexplored. Future research should clarify these complex relationships to better address UGS inequality.

4) Increasing UGS inequality trends

In Chapter II, the study showed that UGS inequality at the municipal level increased from 2000 to 2020, potentially due to the interaction of urbanization and demographic dynamics. However, the precise factors driving this increase were not fully identified. In Chapter III, the impact of urban form on UGS inequality was highlighted, but the intricate relationships between urban form, socioeconomic conditions, and demographic changes were not deeply explored. Chapter IV demonstrated the influence of spatial patterns on UGS inequality, yet these patterns are shaped by urban planning and socioeconomic factors. Chapter V indicated that changes in population structure and the quality of UGS facilities affect UGS inequality, which are also closely related to urban development and socioeconomic contexts.

5) Lack of cross-city comparisons

The research in Chapters IV and V focused on specific case studies of Japanese cities without cross-city comparisons, and while the results are relevant in the context of the cities studied, future research should include more city-level case studies. Validate the findings and understand the differences between cities.

6) Unidentified drivers of UGS inequality

This study explored various drivers of UGS inequality but acknowledged that cities are complex systems with potentially unidentified factors contributing to UGS inequality. Future research should build on existing theoretical foundations to identify and explore other possible drivers. Additionally, while correlations between UGS inequality and its drivers were examined, the study did not deeply investigate the causal relationships. Future studies should aim to uncover these causal links to provide stronger evidence for mitigating UGS inequality.

7) Dynamic nature of urban development

The results of this study reflect specific outcomes at a particular time and context, offering policy recommendations for UGS planning. However, the relationship between trends and drivers of UGS inequality is dynamic. Urban development and UGS inequality are influenced by continuously changing processes. Continuous monitoring and assessment are necessary to adapt to these changes and update policy recommendations accordingly.

8) Data availability constraints

In this study, due to data availability constraints, 500m precision population grid data were used in Chapter II; finer population grid data (100m) were used in Chapters III to IV; and neighborhood aggregated population data were used in Chapter V. Thus, the Gini coefficients are all based on the same scale of basic units when measuring areas at

different scales. It is worth noting, however, that the basic units of population used in different chapters may be different and therefore cannot be compared cross-sectionally.

9) Focus on outcome justice

This study mainly addressed the outcome justice of UGS inequality in terms of environmental justice and did not delve into process justice. Future research should investigate policy factors leading to UGS inequality in Japanese cities and explore inequalities in the decision-making processes. This approach will help address both the outcomes and the underlying processes contributing to UGS inequality.

To address these limitations and provide clearer future research directions, several key areas should be considered:

1) Introduction of indicators for UGS inequality

Consider UGS inequality indicators alongside UGS area per capita. Developing comprehensive indicators to evaluate UGS inequality can help in quantitatively assessing and addressing it. Incorporating these indicators into urban and UGS planning will allow for more effective strategies to mitigate inequality.

2) Disclosure of information on UGS inequality

Actively disclosing information about UGS inequality can raise public awareness and promote equitable development of UGS. This transparency can also encourage policymakers and urban planners to consider UGS inequality in their decision-making processes.

3) International collaboration

UGS inequality is a common issue globally. International collaboration can facilitate the sharing of information and strategies to address UGS inequality. Comparative analysis

of different countries’ experiences can provide deeper insights into the factors driving UGS inequality and effective measures to combat it.

4) Exploring mitigation measures

Future studies should discuss in greater depth specific measures to mitigate UGS inequality. For example, how to rationalize the use of vacant land to alleviate UGS inequality; how to determine the reasonable location of new parks in a more reasonable manner, and so on. Through in-depth research on these specific implementation measures, UGS equity planning can be made more reasonable and feasible.

By addressing these future research directions, a more comprehensive understanding of UGS inequality can be achieved, leading to more effective strategies for promoting equitable access to UGS and their associated benefits.

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Acknowledgments

I would like to express my heartfelt gratitude to all the professors, family, and friends who have provided guidance and support during my PhD studies. First and foremost, I would like to extend my deepest thanks to Professor Takeshi Kinoshita. Your unwavering support and guidance in my academic research have been invaluable to me. I also wish to thank Professor Konomi Ikebe from the Urban Environment Design Laboratory. Your insights and suggestions have greatly benefited my research.

I am also deeply grateful to my thesis reviewers: Professor Katsunori Furuya, Professor Shigeto Yanai, and Associate Professor Akira Kato. Your valuable feedback and guidance during the thesis review process have helped to refine and improve my work.

Additionally, I would like to thank my parents and family for their unwavering support and encouragement throughout my academic journey. Your care and companionship during difficult times have been a source of immense motivation for me.

I am equally grateful to my friends for their help and support in both my academic and personal life. Your friendship has brought warmth and strength to my life, even while being far from home. I would especially like to thank my girlfriend for her companionship and support throughout my studies and life. Your understanding and encouragement have enabled me to persevere and complete this long and challenging academic journey.

Finally, I would like to thank the Japan Science and Technology Agency for the support

of the project “Support for Pioneering Research Initiated by the Next Generation” project, which made it possible for me to successfully complete my research during my PhD.

My heartfelt thanks to everyone!