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Livability assessment of 101,630 communities in China's major cities: A remote sensing perspective

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Abstract Some of China's major cities have entered the middle and late stages of urbanization, and the development focus of these cities has gradually shifted from outward expansion to inward renewal. The community, as the basic unit of a city, is undoubtedly the main object of urban renewal. In order to efficiently and effectively address the problems in current community construction, it is necessary to conduct a large-scale in-depth assessment of the community livability, which can directly imply the satisfaction of residents with their quality of life. This study achieved the first comprehensive livability assessment at the individual community scale for 42 major cities of China from the perspective of remotely sensed and crowd-sourced geographic information. Specifically, we produced abundant fine-grained datasets for 42 cities, including high-resolution land cover maps interpreted from Ziyuan-3 satellites (ZY-3, 2.1 m), building height, point-of-interest, and boundaries of 101,630 communities. As designed in our proposed framework, the community livability was evaluated by 5 level-1 indicators, 27 level-2 indicators and an integrated community livability index (CLI). A number of interesting findings were obtained from this assessment: (1) According to the expert questionnaires, living comfort was considered as the most important livability factor for residents with the highest weight, while the building environment was rated the least. The negative factors (e.g., the factories around the community) impacted more on livability than the positive ones. (2) Most communities in major Chinese cities were characterized by dense buildings and sparse green spaces. (3) In these cities, community security construction was severely insufficient, particularly in less developed regions. (4) Imbalanced community livability development was prevalent across cities, and simultaneously, the CLI distribution within cities also exhibited significant spatial aggregation and heterogeneity. This research is expected to reveal the status quo of community livability in China, and thus allow for targeted policy formulation.

Keywords Community, Livability, Living comfort, Building environment, Security, Remote sensing

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1. Introduction

After decades of rapid expansion, by the end of 2020, the urbanization rate of China's permanent population has exceeded 60% (National Bureau of Statistics, 2020), marking the mid-late stages of the urbanization process. The original urban functions can no longer meet the demands of modern urban residents, which, therefore, promotes the Urban Renewal Projects (URP). Compared to the earlier incremental development model, the focus of URP has shifted from extensional construction to the quality improvement of urban internal space, especially for highly urbanized areas (Zhao et al., 2021). This kind of URP is more manifested as a gradual and small-scale transformation. Some scholars have proposed that city is similar to a living organism with self-growth laws, and URP can be considered as the metabolism at a cellular level. From this perspective, the community, as the cell of the city, is the optimal unit to achieve URP and

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refined management (Clark, 2018).

Livability is undoubtedly a key concern for urban planners when it comes to planning efforts for communities. This buzzword is derived from the concept of "sustainability" and, to a large extent, they share similar definitions, objectives, and implementation approaches (Litman, 2010). The difference is that sustainability is a long-term planning goal geared toward global economic, ecological, and equity issues, and it sets broad principles (for example, enhancing regional cooperation and controlling carbon emissions, etc.) for human society. Livability, by contrast, focuses on creating comfortable spaces to meet the community's residents' aspiration of a better life for the present (Ruth and Franklin, 2014). Moreover, it concretizes the idea of sustainability by designing land types and patterns from the macro-scale of cities, metropolitan areas and regions to the micro-scale of neighborhoods, streets and buildings (Godschalk, 2004). Correspondingly, the community livability is not only related to the life quality of the individual, but also determines the competitiveness and attractiveness of the city, and is even a prerequisite and basis for the sustainable development of entire country.

Although understandings and preferences for livability may vary significantly across populations with different ages, gender, nationality, and race, the focus is invariably on their own quality of life and experience (Wagner and Caves, 2012). Out of this consideration, the pioneering researchers suggested defining livability from two dimensions: the social environment and the natural environment that meet the basic needs of residents (Ruth and Franklin, 2014). The key characteristics of livable areas, as outlined in the Healthy Cities Campaign initiated by the World Health Organization (WHO) in the 1960s, are beautiful residential environment, high-level social civilization, prosperous economic development, abundant material resources, convenient living conditions, and reliable public safety (Kaal, 2011).

To date, most studies have investigated livability at the city-wide or regional scale (Teo, 2014; del Martínez-Bravo et al., 2019; Zhang et al., 2020; Pan et al., 2021), with typical results such as the annual "Global Livable Cities Index Report" released by the Economist Intelligence Unit (EIU) in the U.K. In contrast, livability issues at finer spatial scales (i.e., the livability of individual communities) have attracted less attention. The few relevant studies are mostly localized or case-specific (Stanislav and Chin, 2019; Zhu et al., 2020), which hinders a systematic perception of the community environment. Moreover, as the frequency, severity, and duration of global public health emergencies (e.g., the Ebola virus and COVID-19 epidemics) increase and communities become the primary places to live and work, there is a growing awareness of the urgency of comprehensive community livability assessments.

To achieve this goal, we have to resolve the following challenging difficulties. Firstly, in conventional practice, it takes considerable labor, materials and time to obtain basic community data such as community area, ecological area, number and spacing of houses, and the amount of infrastructure in and around the surveyed communities. Secondly, some of the data used to calculate livability indicators, especially those in three-dimensional (3D) space, are not yet openly accessible. Thirdly, in the era of big data, massive amounts of crowd-sourced data are often gathered together to serve a common task. However, heterogeneous data attributes (e.g., resolution, acquisition time, accuracy, etc.) make it difficult to employ these data with a uniform rule. Fourthly, there still lacks an applicable and transferable methodological framework to translate theoretical and qualitative concepts of livability into quantitative assessment results that can guide practical planning efforts.

In these contexts, one of the attempts of this study is to use satellite observations and geo-information crawling to replace manual surveys. The remote sensing (RS) technology is a well-known favorable tool to quickly and frequently obtain information about the Earth's surface over large areas with low cost, and more importantly, it is less restricted by ground and climatic conditions. In particular, the emergence of stereo mapping satellites provides opportunities for us to depict 3D morphology of land surface (Liu et al., 2017; Huang et al., 2017; Huang et al., 2018). Some studies have demonstrated the great potential of RS data and its derivative products in community livability assessment. For example, Zhang et al. (2019) evaluated a number of communities in Haidian District, Beijing, China, with the Gaofen-2 satellite data and the Moderate Resolution Imaging Spectroradiometer (MODIS) products. Similarly, Zhang et al. (2020) reported the influence of land-use patterns on the residential environment quality within the fifth loop of Beijing, China. On the basis of these works, this study moves forward in integrating massive and multi-dimensional RS data and crowd-sourced geographic information into the community livability assessment in 101,630 communities of 42 Chinese major cities. The results are expected to facilitate a thorough comprehension of the current situation of China's livable community construction.

Another contribution of this paper is we developed a multi-level livability assessment framework adapted to the local community context. According to the "first principle of livability" proposed by Ruth and Franklin (2014), livable areas are characterized by satisfying the majority, if not all, of people. Therefore, the assessment indicators were carefully considered to ensure that they are vital and constant for different individuals in different regions. Based on the land cover and building height data derived from remote sensing imagery and auxiliary geographic information, a total of 5 level-1 indicators (i.e., building environment (BE), ecological livability (EL), traffic convenience (TC), living comfort

(LC), and security (SE)) and 27 level-2 indicators were selected. Meanwhile, a ranking Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was adopted to generate an integrated livability index (CLI) for each community. These results together constitute the indicator layer of the framework after being processed in a pipelined manner, which provides a data foundation for the final monomial evaluation, integrated evaluation and comprehensive analysis (Figure 1).

To our knowledge, this study is the first quantitative livability assessment at the individual community scale over a large number of communities and cities of China, and also the first attempt to conduct a comprehensive livability evaluation both on the 2D and 3D levels. Specifically, our main work includes: (1) delineating the boundaries of a total of 101,630 communities in 42 Chinese cities, and producing the land cover maps and building height maps of all communities based on ZY-3 high-resolution remote sensing images (2.1 m); (2) proposing an assessment scheme of community livability from the perspective of remotely sensed and geographic information, in order to offer guidance for intelligent planning and scientific decision-making.

2 Material and methods

2.1 Study area

Forty-two representative metropolitan cities in China, including 21 provincial capitals, 4 municipalities directly under the central government, 5 autonomous regions, 1 special economic zone, and 11 other large cities, were selected for this study (Appendix Figure S1, Table S2, https://link.springer.com). Considering the high urbanization rate in these metropolises, we focused our investigation on the main urban areas (see Appendix 2.1), where the urban population mostly reside. Further, in line with the Chinese city classification list (China Business Network Co., Ltd. (2019). https://www.yicai.com/news/100200192.html), these cities were classified into 4 Super First-Tier (T1) cities, 14 First-Tier (T2) cities, 18 Second-Tier (T3) cities, and 6 Third-Tier (T4) cities based on five dimensions: concentration of commercial resources, urban hubs, urban residents' vitality, lifestyle diversity, and future potential, so as to compare the community livability between cities at different development levels.

2.2 Community livability assessment method

According to our proposed framework (Figure 1), the procedure of community livability assessment can be summarized in the following steps:

(1) Data collection. A total of 8 types of points-of-interest (POI) data and 69 scenes of ZiYuan-3 (ZY-3) high-resolution stereo images within the main urban areas of 42 cities were collected (Section 3 in Appendix), as well as some necessary auxiliary data such as A-Map, Map World, and Open Street

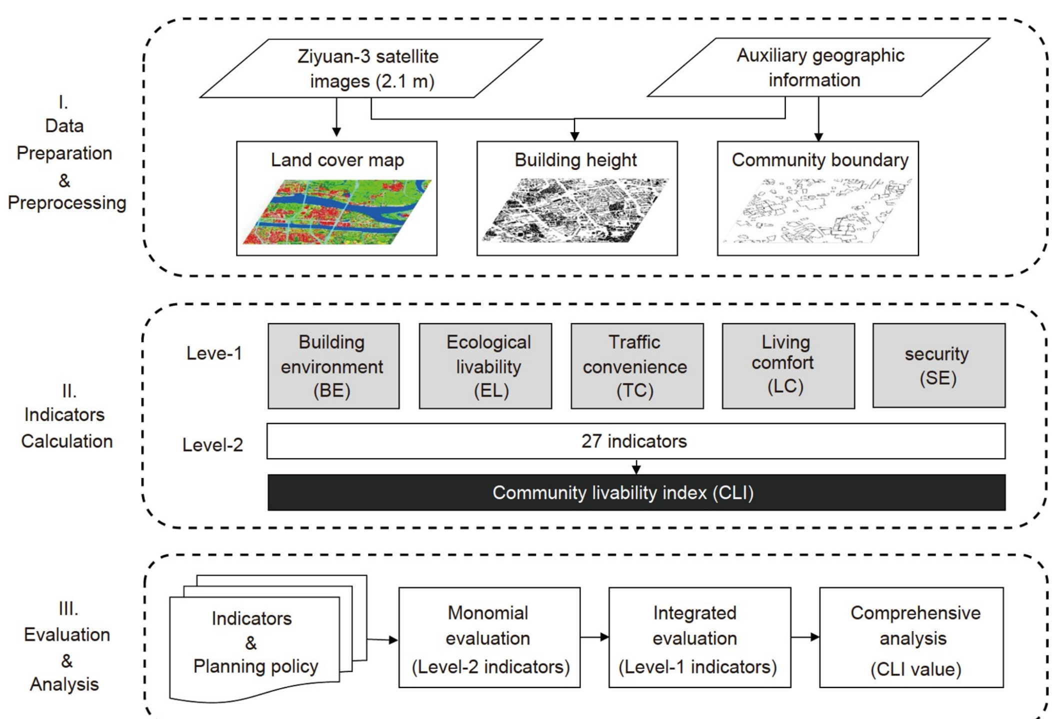

Figure 1 The framework of community livability assessment for Chinese cities from the perspective of remotely sensed and crowd-sourced geographic information.

Map (OSM).

(2) Land cover mapping. High-resolution urban land cover maps derived from remote sensing data are fundamental information for investigating community environments. In this study, seven land cover categories were extracted, including: grassland, trees, bare soil, buildings, water bodies, roads, and other impervious surface areas (OISA).

(3) Estimation of building height. To understand the 3D building environment within the community, the multi-angle ZY-3 stereo image pairs were utilized to estimate the building height.

(4) Delineation of community boundary. We retrieved the boundaries of POIs labeled as residential areas through the Application Programming Interface (API) of online web maps, followed by vectorization and manual post-processing. In total, 101,630 community boundaries were obtained in 42 cities. Figure 2 shows the spatial distribution of communities in Guangzhou city as an example.

(5) Selection of indicators and weight setting. The community livability assessment indicators of this study were set up chiefly with reference to the "Urban Investigation Plan (2020)" issued by the Ministry of Housing and Urban-Rural Development of the people's Republic of China (http://www.gov.cn/zhengce/zhengceku/2020-06/22/content_5520991.htm), which is composed of 5 level-1 indicators (building environment (BE), ecological livability (EL), traffic convenience (TC), living comfort (LC), and security (SE)) and 27 level-2 indicators (Table 1). In addition, the Delphi method and Analytic Hierarchy Process (AHP) method were jointly applied to determine the weight of each indicator.

(6) Community livability assessment. The livability of these communities was assessed from three levels: firstly, a monomial evaluation was conducted for 27 level-2 indicators to provide a full picture of the 101,630 communities; secondly, an integrated evaluation for 5 level-1 indicators was carried out at community scale and city scale, respectively; thirdly, based on the CLI of each community obtained by TOPSIS method, a comprehensive analysis was completed to reveal the status quo of community livability construction of China.

The technical details of the aforementioned methods and processes are provided in Appendix.

3 Results

3.1 Weight of indicators

The selected indicators and their final weight were exhibited in Table 1 and Figure 3, respectively. Among the 5 level-1 indicators, the highest weight was assigned to living comfort (LC, 0.31), followed by traffic convenience (TC, 0.23), ecological livability (EL, 0.19), security (SE, 0.17), and building environment (BE, 0.10). This result directly reflected that the living service facilities near the communities were most valued by stakeholders when evaluating the livability of a community, whereas the built environment was taken the least consideration.

In level-2 indicator layer, for LC, some shopping (SM_1 km and FB_1 km) and medical (MSS_1 km) sites were given the highest weight of 0.12, followed by educational

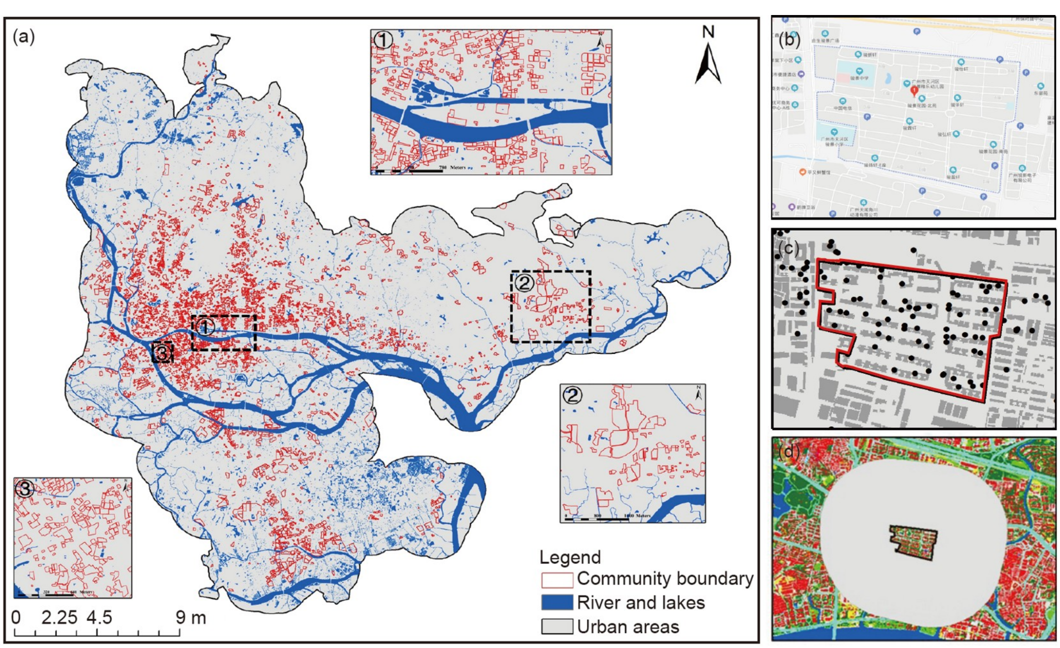

Figure 2 Communities of Guangzhou (GZ). (a) Spatial distribution of communities within the main urban areas; (b) community boundary displayed in Baidu Map; (c) vectorized community boundary generated by ArcGIS software, with black dots representing POIs; (d) 1-km buffer zone generated outward from the community boundary.

Table 1 The multi-level indicators selected for community livability assessment in this study

ID	Level-1 indicators	Level-2 indicators		Correlation with community livability
1	Building environment (BE)	Intensity of building within community (BI, %)		−
		Sky-View-Factor of building within community (B_SVF)		+
2	Ecological livability (EL)	Intensity of green space within community (GI, %)		+
		Spatial patterns of green space within community	Largest patch index (LPI)	+
			Mean shape index (SHA)	+
			Cohesion (COH1)	+
		Areas of green space in 1-km buffer zone (GS_1 km, %)		+
		Spatial patterns of green space in 1-km buffer zone	Cohesion (COH2)	+
		Areas of ecological space in 1-km buffer zone (ES_1 km, %)		+
		Areas of water body in 1-km buffer zone (WAT_1 km, %)		+
		Number of factories in 1-km buffer zone (FAC_1 km)		−
3	Traffic convenience (TC)	Total length of road in 1-km buffer zone (ROA_1 km, m)		+
		Number of available buses in 1-km buffer zone (BUS_1 km)		+
		Number of available subways in 1-km buffer zone (SUB_1 km)		+
4	Living comfort (LC)	Education	Number of kindergartens in 1-km buffer zone (KG_1 km)	+
			Number of primary schools in 1-km buffer zone (PS_1 km)	+
			Number of middle schools in 1-km buffer zone (MS_1 km)	+
			Number of universities in 1-km buffer zone (UNI_1 km)	+
		Medical treatment	Number of hospitals in 1-km buffer zone (HOS_1 km)	+
			Number of pharmacies in 1-km buffer zone (PHA_1 km)	+
			Number of medical services in 1-km buffer zone (MSS_1 km)	+
		Shopping	Number of supermarkets in 1-km buffer zone (SM_1 km)	+
			Number of food baskets in 1-km buffer zone (FB_1 km)	+
		Sport	Number of sport facilities in 1-km buffer zone (SF_1 km)	+
			Total length of greenway in 1-km buffer zone (GW_1 km, m)	+
5	Security (SE)	Number of emergency shelters in 1-km buffer zone (REF_1 km)		+
		Number of public security stations in 1-km buffer zone (PSS_1 km)		+

indicators like PS_1 km and KG_1 km, which were weighted at 0.11 and 0.1, respectively. For TC, the weight of SUB_1 km (0.53) was significantly higher than that of BUS_1 km (0.3) and ROA_1 km (0.17). This revealed the preference of residents in major cities for daily transportation. An interesting result is that, with regard to EL, people tend to place more attention on the negative aspects (FAC_1 km in this study) than the positive ones, which had not been noticed in previous studies. As for SE, the demand for PSS_1 km (0.54) was slightly higher than that of REF _1 km (0.46), which can be mainly attributed to the higher frequency of man-made accidents than natural disasters. In contrast, the BE, especially at the 3D level, was rarely discussed in the existing community livability assessments. Our results suggest that in the perception of community residents, the importance of BI (0.52) in horizontal space is similar to that of B_SVF (0.48) in cubic space, which may shed lights on rule making.

3.2 Monomial evaluation of level-2 indicators

Table S7 and Figure S4 presented the statistics and box plots of level-2 indicators for 101,630 individual communities. Indicators 1 and 2 portrayed the BE characteristics of communities. It could be noted that the BI and B_SVF showed remarkable differences between communities, ranging from 1% to 90% and 0.01−1.00, respectively. According to the Planning and Design Standards for Urban Residential Areas in China (GB50180-2018), the density of low- and medium-rise buildings is not allowed to exceed 43%, and for high-rise buildings, the upper density limit is usually 22%. However, the average BI of 101,630 communities in our results is 33%, which implied that in most communities of these 42 cities, the distribution of buildings was relatively crowded. Among them, the average BI of communities in T1 cities (34%) was marginally higher than other cities, with Guangzhou (GZ) city (41%) being particularly prominent (see Table S2 for

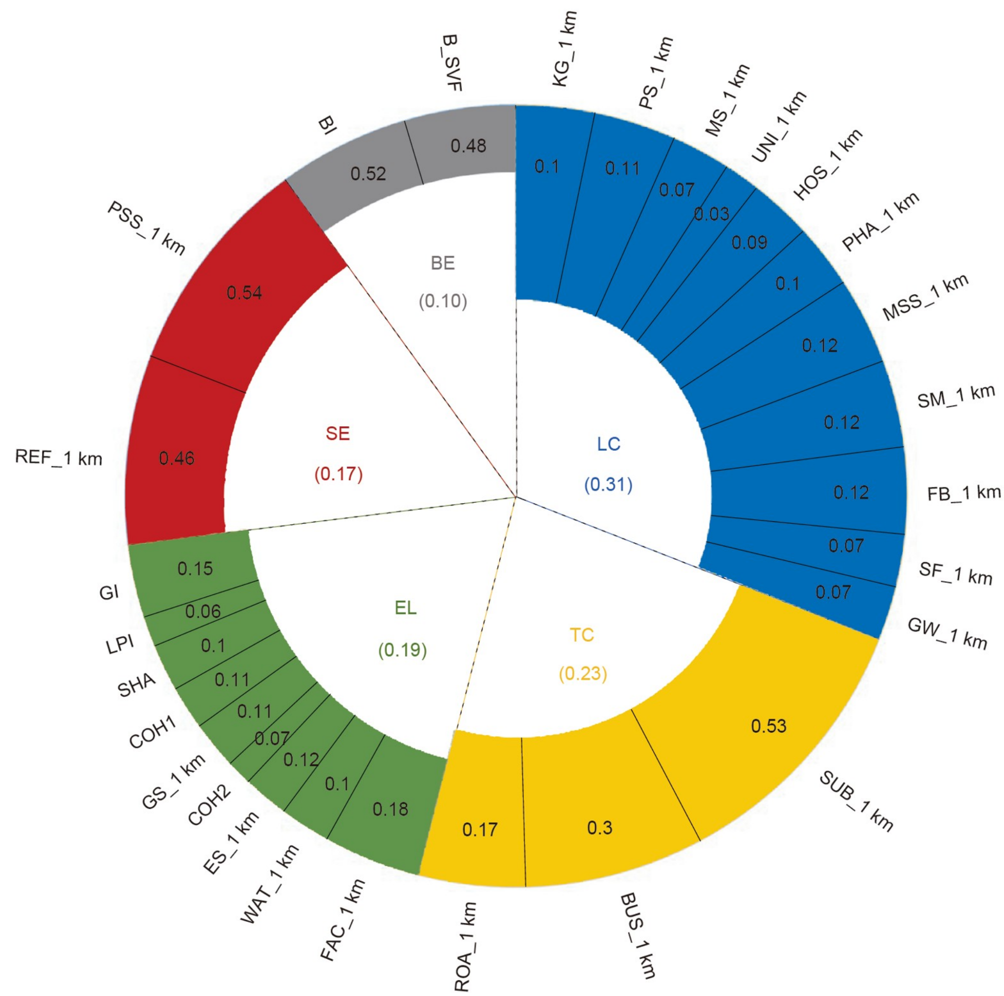

Figure 3 The weight of level-1 indicators and level-2 indicators determined by Delphi method and AHP. The abbreviations of indicators see Table 1.

abbreviations of city names). With respect to B_SVF, except for T1 cities (0.62), the mean of other cities was all lower than the overall mean (0.48), and the lowest is T2 cities (0.43). This result indicated that despite the high BI in T1 cities, their structural design in the vertical space was comparatively reasonable, which ensures a wide view of the sky. By contrast, in T2 cities, the community buildings were compactly built both in 2D and 3D space.

Among the indicators 3 to 11, the most weighted one is indicator 3 (intensity of green space, GI), whose values varied from 0% to 99%, with a mean of 17%. As the document GB50180-2018 stipulated (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2018), the minimum greening rate for each community should be 30%. In this regard, the cities at higher development levels were better (T1: 19%, T2: 18%, T3: 14%, T4: 11%). Nevertheless, apart from Jinan (JN) city, where the average GI of communities met the standard, all other cities do not provide residents with a required vegetation coverage at the community level (Figure S4 (3)). Looking at the landscape metrics (indicators 4, 5, 6, and 8), whose CVs were evidently lower than other indicators (i.e., 0.57, 0.38, 0.33, and 0.02, respectively), it can be perceived that the dominance, shape complexity and connectivity of green space did not vary much among communities. Contrary to these four indicators, indicator 11 (FAC_1 km) has the highest CV of 2.97, implying significant inter-community differences. Amongst the top three cities with the mean value of this indicator, Foshan (FS) city ranked the first with average 29.91 factories per community buffer, followed by Guangzhou (GZ) city (16.43), while LZ city, which ranked last, has only 0.01 factories per community neighborhood on average.

Indicators 12 to 14 mainly demonstrated the transportation conditions around the community. The mean of ROA_1 km, BUS_1 km, and SUB_1 km for 101,630 communities were 51864.07 m, 25.10 and 1.07, respectively. Unlike the city-level assessment, TC of an individual community largely depends on the distribution pattern of infrastructures surrounding it. Although road networks are generally more developed in higher-level cities, considering their larger urban areas, the road density around the community in some T2 cities (52,583.94 m on average) is even lower than that in T4 cities (56,957.20 m on average). However, for the allocation of buses and subways around communities, T1 and T2 cities still outperformed the cities at lower development levels.

Indicators 15 to 25 provided a comprehensive picture of the factors that determine the LC of community. Out of the same reason mentioned above, i.e., although the resources of T1 cities are more abundant than those less-developed cities, their distribution is relatively sparser, and hence, the mean community-level indicator values of developed cities are not necessarily higher than other cities. For example, the average KG_1 km (11.50) and UNI_1 km (0.95) is highest in T3 cities and lowest in T1 cities (10.07 and 0.50, respectively). For medical resources (PHA_1 km, MSS_1 km, HOS_1 km) and shopping sites (SM_1 km, FB_1 km), the situation is similar: T2 cities are at the top. Notwithstanding, T1 cities still take the lead in the averaged values of PS_1 km (4.06), MS_1 km (3.93), SF_1 km (15.23) and GW_1 km (3941.78 m), suggesting that regardless of the community-scale or city-scale, developed cities have far more primary- and senior-education resources and sports grounds near their living space.

Indicators 26 and 27 measured the level of public safety around the community. The averaged REF_1 km and PSS _1 km were 1.42 and 11.19, respectively. The former varies greatly among communities, with a CV of 1.35, while the latter exhibits moderate variation with a CV of 0.89. By and large, some T1 cities (e.g., GZ) and T2 cities (e.g., NJ, ZZ, WH) have paid more strivings for community safety in their urban planning, while T3 and T4 cities have yet to be strengthened in this regard, especially Haikou (HK), Yantai (YT), Lhasa (LS), Hohhot (HH), Hefei (HF), and Tangshan (TS) (Figure S4(26), Figure S4(27)).

3.3 Integrated evaluation of level-1 indicators

The level-1 indicators for 101,630 communities were averaged and rated as follows: BE (2.75), EL (2.67), LC (2.28), TC (2.15), and SE (1.89) (Figure 4a). When up-scaled to the single-city level (Figure 4b), for the mean of five level-1 indicators, BE, EL, TC, LC and SE are respectively predominant in 17 cities (e.g., Beijing (BJ), Changsha (CS), Changzhou (CZ), etc.), 14 cities (e.g., Foshan (FS), Fuzhou (FZ), Hefei (HF), etc.), 2 cities (Chengdu (CD), Shenzhen (SZ)), 6 cities (e.g., Changchun (CC), Harbin (HB), Hohhot (HH), etc.) and 3 cities (Guangzhou (GZ), Wuhan (WH), Zhengzhou (ZZ)). From these results, it can be inferred that for the majority of communities in China, the built and ecological environment is of relative livability, whereas the safety issues, to a large degree, were in a worrisome situation.

In Figure 4b, we can intuitively notice the strength and weakness of community construction in each city. For example, in Haikou (HK), Tianjin (TJ), Taiyuan (TY), and Urumqi (UQ) cities, the BE values were in the forefront of 42 cities, but their other four level-1 indicators were not well performed; similarly, Jinan (JN) city has the highest EL values among cities, but is weak in TC, LC, and SE. Aside from this "severely unbalanced" development pattern of community livability, there are others that are "slightly unbalanced" (e.g., Changchun (CC), Chengdu (CD), Hefei (HF) cities), "moderately balanced" (e.g., Changzhou (CZ), Dalian (DL), Foshan (FS) cities), and "highly balanced" (e.g., Beijing (BJ), Chongqing (CQ), Changsha (CS) cities).

Further, we aggregated the results of a single city by their levels. As Figure S5 depicted, there are minor differences in the mean BE and EL for the four levels of cities. Specifically, the mean value of BE in T1 cities (3.07) exceeds that of T4 (2.78), T2 (2.72), T3 cities (2.69), and the averaged EL in T1 cities (2.84) is also mildly higher than that of T2 (2.76), T3 (2.63) and T4 cities (2.35). Meanwhile, it was noteworthy that the higher the city level, the greater the average TC (2.79, 2.52, 1.97, 1.44 for T1–T4 cities, respectively) and SE ((2.65, 2.17, 1.77, 1.08 for T1–T4 cities, respectively). However, such a positive correlation was not found between

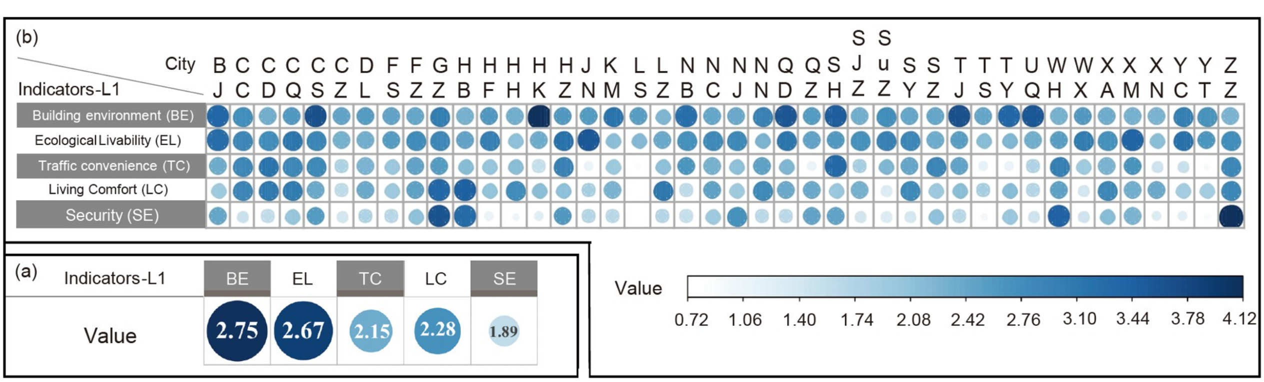

Figure 4 (a) Overall mean values of level-1 indicators (Incators_L1) for 101,630 communities in 42 cities; (b) mean values of the level-1 indicators for communities in each city. The size of the circle and their shade of the color indicate the size of the level-1 indicator value. City abbreviations: BJ-Beijing, CC-Changchun, CD-Chengdu, CQ-Chongqing, CS-Changsha, CZ-Changzhou, DL-Dalian, FS-Foshan, FZ-Fuzhou, GZ-Guangzhou, HB-Harbin, HF-Hefei, HH-Hohhot, HK-Haikou, HZ-Hangzhou, JN-Jinan, KM-Kunming, LS-Lhasa, LZ-Lanzhou, NB-Ningbo, NC-Nanchang, NJ-Nanjing, NN-Nanning, QD-Qingdao, QZ-Quanzhou, SH-Shanghai, SJZ-Shijiazhuang, SuZ-Suzhou, SY-Shenyang, SZ-Shenzhen, TJ-Tianjin, TS-Tangshan, TY-Taiyuan, UQ-Urumqi, WH-Wuhan, WX-Wuxi, XA-Xi'an, XM-Xiamen, XN-Xining, YC-Yinchuan, YT-Yantai, ZZ-Zhengzhou.

the LC and city level: the mean values of LC in T1 cities (2.31) were similar to those in T2 (2.34) and T3 cities (2.33), but slightly higher than T4 cities (1.96). Overall, residents in T1 cities have better built environment, transportation, and safety guarantees, but less living comfort; in T2 cities, all five level-1 indicators exhibited a satisfied performance; in T3 cities, the transportation and public safety facilities around communities need to be strengthened; and for T4 cities, the strategies to promote community livability should focus on three aspects: TC, LC and SE.

3.4 Comprehensive analysis of CLI

The CLI of each community obtained by TOPSIS algorithm reflected their relative proximity to the ideal solution. In Figure 5a, among the 101,630 communities, the top five communities in terms of CLI values were located in Suzhou (SuZ, 42.02), Wuhan (WH, 37.75), Guangzhou (GZ, 36.78), Wuhan (WH, 36.63), and Suzhou (SuZ, 35.80) cities, respectively, and the last five communities were located in BJ (2.83, 2.84, 2.85, 3.11, respectively) and LS (3.14). On average, communities in Zhengzhou (ZZ) city had the highest CLI values (15.71±4.54), followed by Guangzhou (GZ) city (14.69±6.02) and Wuhan (WH) city (12.59±4.73), while those in Yantai (YT) city (7.62±2.01), Tangshan (TS) city (7.36±1.89), and Lhasa (LS) city (5.91±1.74) were ranked last.

Also, in Figure 5a, only 13 out of 42 cities (Zhengzhou (ZZ) city to Beijing (BJ) city) were assessed to have a mean CLI above the Mean_all (11.75). Beyond that, the statistical distribution of CLI within most cities, especially Guangzhou (GZ), Shanghai (SH), Shenzhen (SZ), Nanjing (NJ), and Foshan (FS), is severely skewed (i.e., the difference between the median and the mean is remarkable). The results further confirmed the serious imbalanced and insufficient development of community livability in China today, no matter among

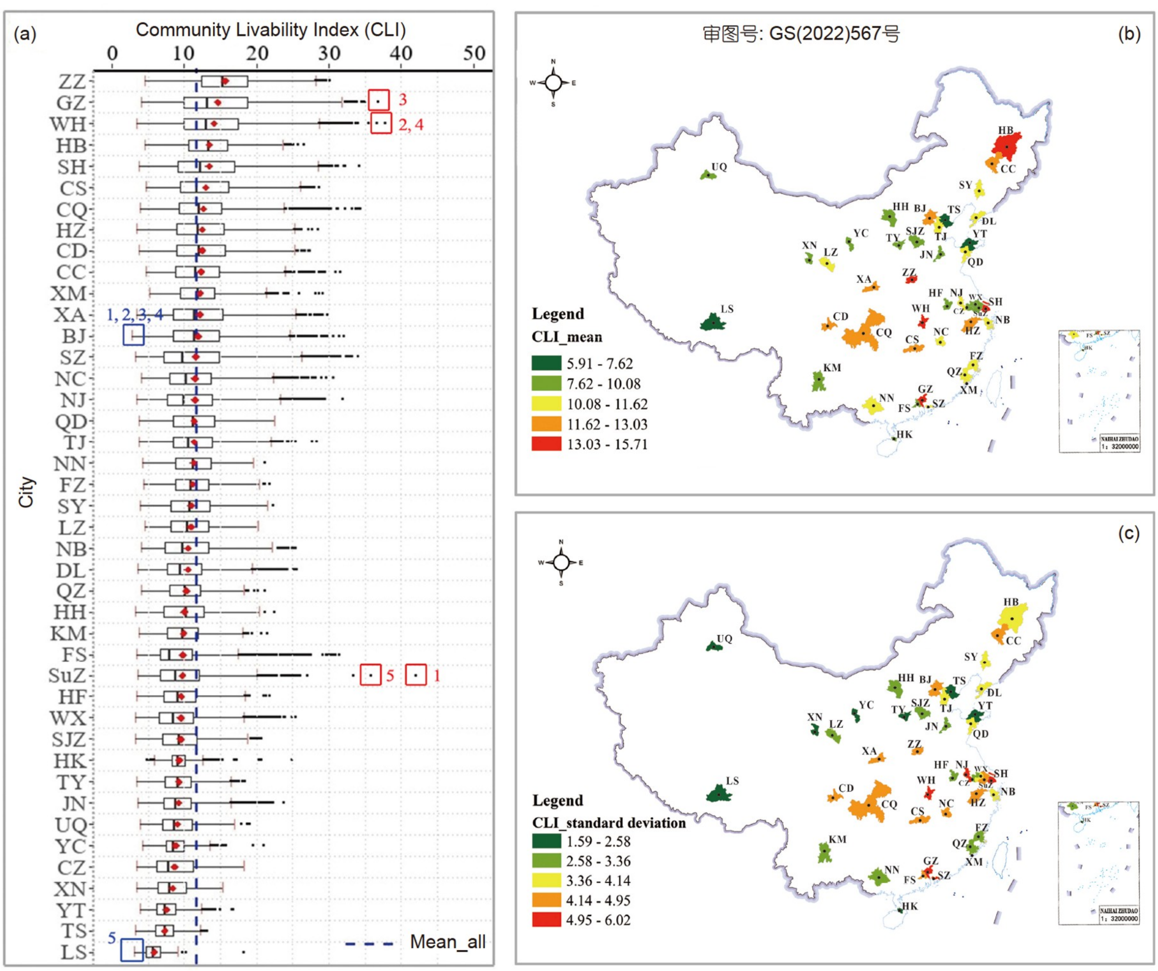

Figure 5 (a) The box plot of CLI values in 42 cities, where the upper and lower truncated lines of each box represent the inner limit of CLI values for that city, discrete points beyond the inner limit indicate mild outliers, the horizontal line inside the box indicates the median, the red dots indicate the mean, and the blue dashed line indicates the mean CLI for 101,630 communities (Mean_all). The five points contained in the red box indicate communities with the top five CLI values, the five points contained in the blue box indicate the communities with the last five CLI values, and the numbers labeled next to the boxes represent their CLI rankings; (b) the spatial distribution of the mean CLI value in each city; (c) the spatial distribution of the standard deviation of CLI in each city. See the description in Figure 4 for city abbreviations

cities or communities. On the whole, the number of livable communities is much smaller than those less livable ones.

To explore the specific manifestation of this imbalance among cities, Figure 5b and 5c illustrated the spatial distribution of CLI mean and standard deviation (SD) for each city, respectively. It can be observed that cities with similar mean CLI tended to aggregate in space. For instance, cities with outstanding CLI (e.g., Zhengzhou (ZZ), Wuhan (WH), Changsha (CS)) were mainly concentrated in the central region of China, while those with a medium-level CLI were mostly located in the east and south. By contrast, communities in western and northern cities were assessed as less livable in general. The spatial distribution pattern of SD across cities was roughly the same as the CLI mean. In particular, some cities in the northeastern region have relatively high CLI mean and moderate SD, meaning that most of their internal communities are livable.

It should be pointed out that although community livability and city livability are correlated to a certain degree, they focus on different aspects. For example, city livability involves climatic conditions and industrial structure while community livability does not; community livability depends on the environment within and around the communities, while city livability measures the sustainability or development of a whole city. Accordingly, some cities reckoned as "unlivable" can be highly ranked in the community CLI, and a typical case is Harbin (HB). Despite the cold climate and isolated geographic location, its small urban areas (see Figure S6), abundant medical and educational resources, and the well-equipped public safety system (Figure S4) make the bulk of communities in Harbin surrounded by various types of infrastructures. Not only that, the pleasant built and ecological environment (Figure 4b) also contribute to the high livability of Harbin's communities (Figure 5a). In this way, a comprehensive assessment of community livability can provide new perspectives and insights for people to choose where to live.

Furthermore, we visualized the hotspots and coldspots of the CLI distribution within each city at the individual community scale (Figure S6). For most of the cities, the hotspots with confidence levels above 90% are distributed in clusters in the center of the main urban areas (e.g., Beijing (BJ), Changchun (CC), Chengdu (CD), etc.), while for a few cities, the hotspots are scattered (e.g., Changsha (CS), Haikou (HK), Yinchuan (YC), etc.) or distributed along the water (e.g., Shanghai (SH), Wuhan (WH), etc.). Unlike hotspots, the coldspots with confidence levels above 90% are all distributed in peripheral urban areas. The spatial pattern of CLI hotspots is basically consistent with the distribution of core urban function zones. As far as the assessment results are concerned, the resources in a considerable number of cities, especially high-level cities, are exceedingly concentrated, which is also a typical characteristic of over-urbanization.

The imbalance of livable communities is also manifested among cities at different development levels. Unlike the results of level-1 and level-2 indicators (Table S7, Figure S5), both the mean and SD of the CLI show a clear positive correlation with city levels (Figure 6). On one hand, this implies that the higher-level cities have achieved better results in creating livable communities than some lower-level cities. On the other hand, from the view of SD, the conspicuous heterogeneity of community livability in high-level cities should draw particular attention from urban managers.

3.5 The cases of representative communities

The top three and bottom three communities in CLI rankings were selected as representative cases for analysis (Figure 7, Figure 8). According to the results of integrated evaluation, the top three communities (hereafter referred to as "CLI_H1", "CLI_H2" and "CLI_H3") are located in the northern part of the main urban area of Suzhou (SuZ) (i.e., the transition zone between the urban core and the periphery), and in the urban center of Wuhan (WH) and Guangzhou (GZ), respectively, while the bottom three communities (hereinafter referred to as "CLI_L1", "CLI_L2" and "CLI_L3") are all located in the periphery of Beijing (BJ). Intuitively observed from the land

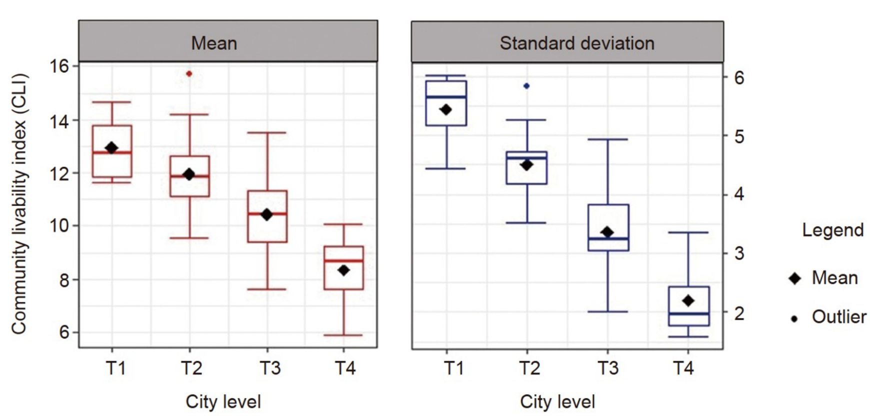

Figure 6 Mean and standard deviation of CLI in cities at different development levels.

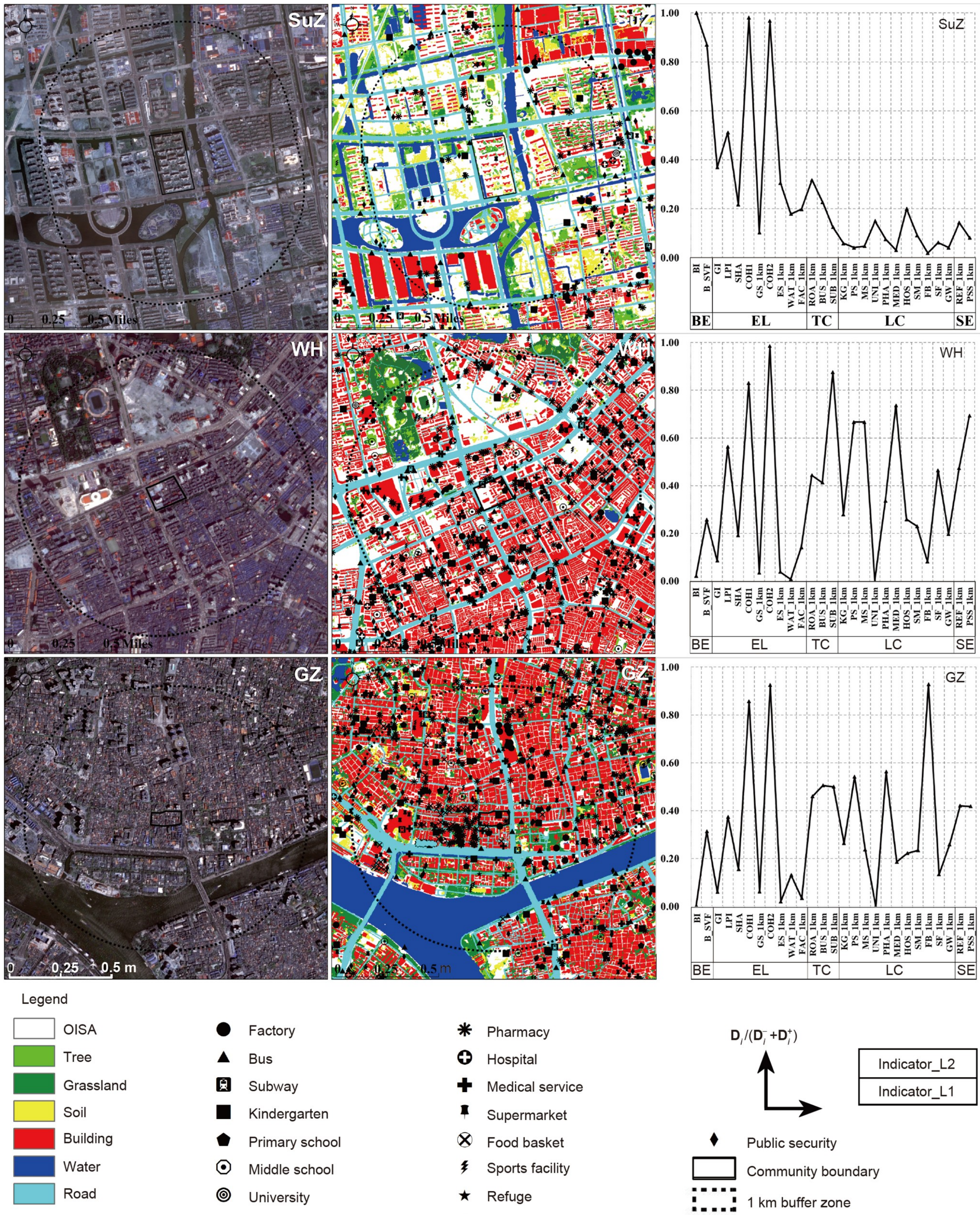

Figure 7 The top three communities in CLI ranking are located in Suzhou (SuZ), Wuhan (WH) and Guangzhou (GZ), respectively. The first to third columns are, in order: ZY-3 high-resolution remote sensing images, land cover and POI distribution maps within 1-km buffer zone of community, and the relative proximity of the community's level-1 indicators (Indicator_L1) and level-2 indicators (Indicator_L2) to the ideal solution (i.e., $(\mathbf{D}_i^-)/(\mathbf{D}_i^- + \mathbf{D}_i^+)$). Refer to Table 1 for the abbreviations of the indicators.

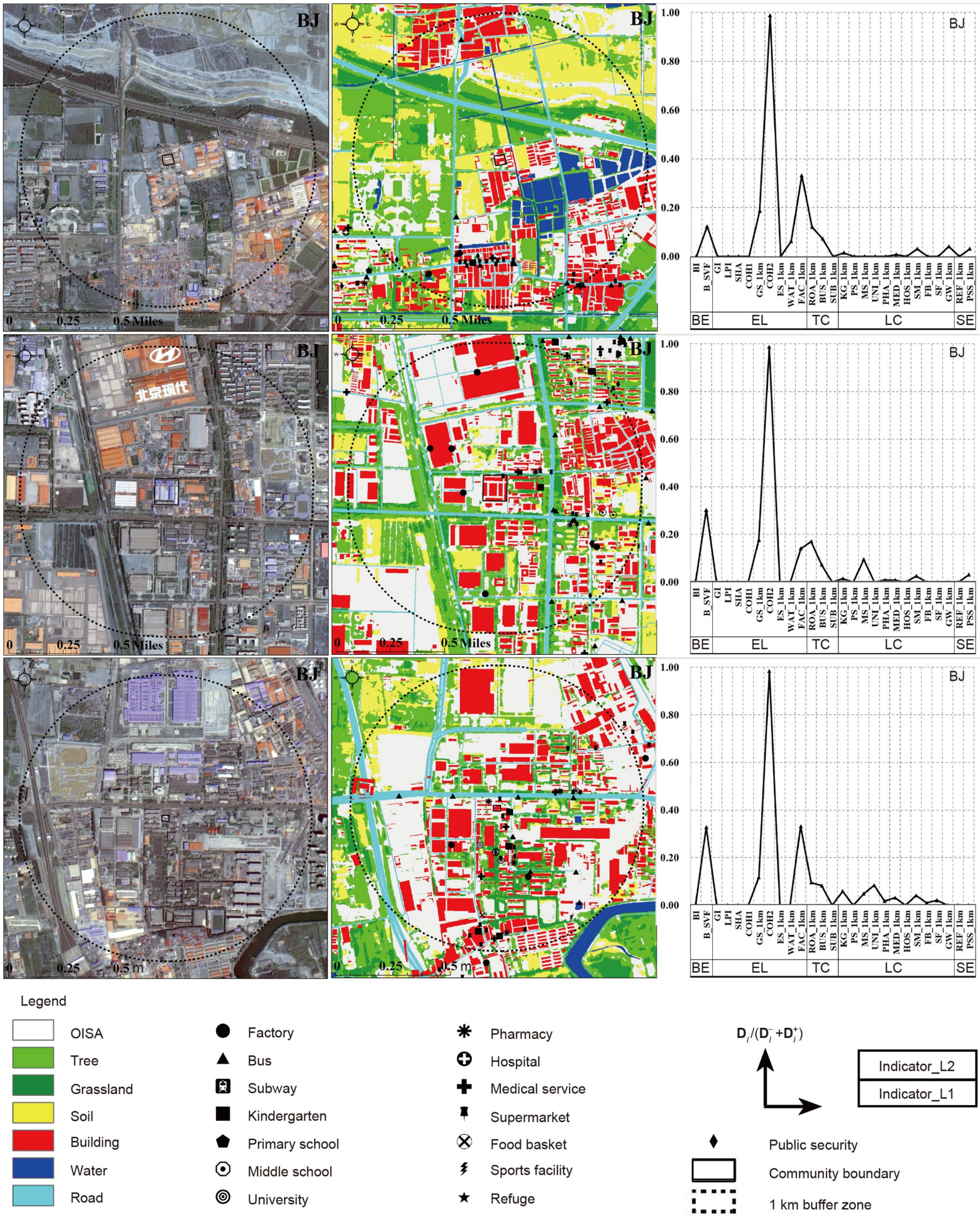

Figure 8 The last three communities in the CLI ranking are all located in Beijing (BJ). The first to third columns are, in order: ZY-3 high-resolution remote sensing images, land cover and POI distribution maps within 1-km buffer zone of community, and the relative proximity of the community's level-1 indicators (Indicator_L1) and level-2 indicators (Indicator_L2) to the ideal solution (i.e. $(\mathbf{D}_i^-)/(\mathbf{D}_i^- + \mathbf{D}_i^+)$). Refer to Table 1 for the abbreviations of the indicators.

cover and POI distribution maps, CLI_H1 has a low density of buildings, a large area of water and green space, a well-developed road network, and various types of infrastructure (although the number is small); CLI_H2 and CLI_H3 have a relatively dense distribution of buildings, convenient transportation, and a large variety and number of resources. In contrast, CLI_L1, CLI_L2 and CLI_L3 present a similar community environment: buildings are compactly distributed with low vegetation coverage, and roads are sparse, but the ecological environment around the community is pleasant, especially the lush and highly connected green spaces. The relative proximity of the indicators to ideal solution (the right column in Figures 7 and 8) showed, although most of the indicators of the top three communities were excellent, there are some obvious shortcomings, such as the LC and SE for CLI_H1, and the BE and EL for CLI_H2 and CLI_H3. That is to say, no community was found to be perfect through all indicators in this assessment, which again highlighted the inadequacies of community livability. In light of the "barrel principle," the presence of "short boards" can lead to a significant reduction in overall functionality. Accordingly, an effective way to amplify the livability of these communities is to purposefully fill the gaps identified in this study. As for the three communities with the lowest CLI, it can be found that they have a large number of indicators with relative proximity close to 0, which means these indicator values are the lowest among all communities.

4. Discussion

4.1 The proposals for improving the community livability in China

First of all, it is necessary to go back to the question, what and to what extent can a community be described as a livable community? During the initial stage of establishing the assessment framework, discussions should be held to build consensus on the concept of livable communities among various groups (Wagner and Caves, 2012). In the universally acknowledged definition, community livability is a relative concept that measures the satisfaction of residents with their living space (Pacione, 2003), and it "means something different to different people" (Ruth and Franklin, 2014). Although diversified indicators of livability were proposed annually by different organizations around the world, which are meaningful for comparing the quality of life in different cities or regions, a comprehensive community-scale livability assessment in a large number of cities has not yet been attempted. The community livability needs to be understood and perceived in the local and social context. From this perspective, the first step of improving community livability is to fully and precisely acquaint its status quo in the study area and the real needs of local residents for a livable community.

Our results demonstrated that the most prominent characteristic of Chinese community development is the imbalance, which is a natural consequence of "centralized" urbanization. This problem is widespread across regions, cities, and communities, and its root cause is the uneven distribution of resources (Guan et al., 2018). At the individual community scale, the inequity is manifested in the over-concentration of basic public services such as infrastructures, security equipment, and ecosystem service. In these 42 cities, the vast majority of public services, as well as the urban functional zones, presented a spatial pattern of monocentric distribution, and the quantity and quality of all types of resources declined along the urban-rural gradient. As a result, 8 of the 27 level-2 indicators (ES_1 km, WAT_1 km, FAC_1 km, SUB_1 km, UNI_1 km, HOS_1 km, FB_1 km, REF_1 km) in the monomial evaluation had a CV above 1, indicating evident inter-community disparities, which also directly leads to the disparity of ecological livability (EL) and living comfort (LC) in the integrated evaluation. More than this, at the city level, cities with higher development levels and cities located in central and northeastern China were also found to have high SD of CLI.

In response to this issue, a possible solution is "decentralization". The "decentered" urban development mode in Germany provides us with good experiences in solving "urban diseases" and thus constructing livable communities (Ziblatt, 2008). The core idea of this development mode is to prevent over-concentration of population and resources through the balance of planning and legislation, the secondary distribution of resources, the equalization of public service availability, and the decentralization of administrative institutions (Oteman et al., 2014). As the basic unit of the city, the community plays a key role in urban governance and services. Dedicated to achieving a fine-grained community management in evenly distributing the ecology and facilities, regional inequities will be mitigated accordingly. To achieve this goal, a two-way strategy can be adopted, that is, a combination of top-down planning led by the government and bottom-up feedback with the participation of residents.

Another issue identified in our assessment was the insufficiency of community constructions. The integrated evaluation on the level-1 indicators revealed that security (SE) was the main shortcomings that limit the development of livability in most communities, especially those in T3 and T4 cities. The main reason for this problem may be related to the social environment. Some areas with high crime and poverty rates (e.g., Lima, Borkowski (2019)) tend to cite public safety as the most important characteristic of livable cities. For contemporary China, the relatively stable social and public order has led to a lack of concerns attached to community safety by residents (reflected in the low weight of the SE indicator), and accordingly, managers have limited investments in the construction of safety facilities in and around their communities. In fact, the sense of safety has always been one of the crucial attractions of communities (Zhan et al., 2018). There is a need for managers to increase the number of safety stations and shelters around the community and establish a safety linkage mechanism so that the probability of injury accidents can be minimized. In addition, the evaluation results of the level-2 indicators revealed that the green space coverage within communities generally did not reach the 30% standard, owing to the high-density built environment. Therefore, interventions should be planned to intensify the community green networks, especially in those low-quality areas. Over the long haul, maintaining environmental comfort requires not only "addition" but also strict control of some negative factors around the community, such as FAC_1 km, which is considered to be a decisive level-2 indicator of EL due to its highest weighting. Only through problem-oriented planning and governance can we guarantee a good interaction between community construction and environmental protection, thus enhancing livability.

In view of the social context and rapid urbanization in China, the results of this study provided feedback to the situations of community livability, aiming to encourage the formulation of effective policies. In summary, it is clear that the following points are particularly essential for pursuing the quality of life in communities: (1) Credible and indicative statistical data: As the foundation of evaluations, pivotal data should be collected and updated regularly. In this study, the web map Application Programming Interface (API) provides open access to reliable information on infrastructure (amounts and locations) around communities, and land cover maps derived from high-resolution remote sensing imagery can effectively describe the whole picture of urban planning. (2) Global perspective and local regulations: At the policy formulation stage, a holistic awareness and large-scale consideration of the deficiencies in current China's community environment (e.g., the over-concentration of resources and security issues) is imperative. The establishment of overarching goals ensures that balanced development can be achieved throughout the region and the resources can be allocated to areas of greatest need. Under this framework, the strategic objectives should be further transformed into specific projects based on the assessment results. (3) Collaboration: In the era of big data, it is no longer possible for a single organization to construct a database with both depth and breadth to support the implementation of major projects, and a new form of collaboration involving government, researchers, enterprises, and residents must be developed to successfully promote livable communities.

4.2 The superiorities of high-resolution remote sensing data in community livability assessment

Remote sensing, as a means of detecting large-scale information on land surface, has been widely applied in urban planning and management, such as dynamic monitoring of land use, evidence collection of illegal buildings, and urban environmental assessment (Wen et al., 2015; Yang J et al., 2020; Yang Q et al., 2020; Huang et al., 2020a). However, the commonly used low- and medium-resolution satellite data like MODIS (500 and 1000 m) and Landsat (30 m) are not suitable for depicting fine-grained features (e.g., shadows, textures, structures, etc.), making the potential of remote sensing data for urban applications not yet fully recognized. The advent of high spatial resolution sensors in recent years enables fine-scaled ground observations. Driven by the data, several new application scenarios have emerged, typically including urban micro-renewal and old city renovation (Jing et al., 2021). Community livability assessment is the preliminary work of urban micro-renewal. This study provided a real-world example of community livability assessment using high-resolution RS data (ZY-3, 2.1 m) as a reference for future work.

Concretely speaking, when designing neighborhoods to enhance livability, urban land covers interpreted from high-resolution RS imagery were served as a base map, with the advantage of realistically describing the landscape composition and configuration of the settlement environment (Huang et al., 2020b). For one thing, some scattered and fragmented patches can be effectively detected. For the other thing, which is often overlooked in previous studies, the structure of green space (e.g., shape and edges) can be clearly depicted. This is conducive to understanding its impact on the community's thermal environment and air quality (Rui et al., 2018). A study of Li et al. (2013) have utilized RS products with three different spatial resolutions (QuickBird, 2.44 m; SPOT, 10 m; Landsat TM, 30 m) to identify the percentage and spatial pattern of green spaces in the same region, and the results proved that the precision of higher-resolution data is more satisfactory, in regard to both completeness and accuracy.

Besides, due to the multi-angle imaging mode, high-resolution remote sensing data is also extraordinarily competitive in obtaining vertical or height information of ground objects (e.g., buildings). Compared with radar data and light detection and ranging (LiDAR) point cloud data, it is more accessible, faster to update, and less costly, which is very proper for large-scale assessment and update of 3D building morphology. Hitherto, several studies have attempted to use the height information derived from high-resolution RS data to estimate urban population (Xu et al., 2020) and ground biomass (Li et al., 2016) with trustworthy results.

4.3 The relationship between community livability and city levels under different classification schemes

Our results revealed that, under the city classification scheme adopted in this paper (i.e., T1, T2, T3, T4 cities, hereafter referred to as “Scheme 1”), most of the level-2 and level-1 indicators, as well as the mean and SD of CLI, were positively correlated to the city level. In order to investigate the influence of other city classification schemes to the results, in this study, we also provided the results by classifying the cities by population (hereafter referred to as “Scheme 2”).

Scheme 2 referred to the Scheme 1 “City Scale Standard” issued by the State Council in 2014, which classified cities into five categories based on their permanent urban population: super megacities (P1 cities), megacities (P2 cities), large cities (P3 cities), medium cities (P4 cities), and small cities (P5 cities). Table S8 showed the classification results of the 42 Chinese cities in this study. Moreover, according to Scheme 2, we recalculated the level-1 indicators, level-2 indicators, and CLI for different levels of cities. Compared with the previous findings (Table S7, Figure S5, and Figure 6), some variations can be found in the recalculated results (Table S9, Figures S7 and S8): in the level-2 indicators, the mean values of community BI, KG_1 km, PHA_1 km, MSS_1 km, and HOS_1 km in P1 cities were the lowest among all categories of cities; while for level-1 indicators, communities in P1 cities took the lead in building environment (BE), ecological livability (EL), and traffic convenience (TC) but weak in living comfort (LC) and security (SE); moreover, the mean and SD of CLI no longer showed a positive correlation with city levels in Scheme 2.

These findings suggested that in some P1 cities (i.e., with huge populations), the rationing of community resources, especially those related to LC and SE, was still difficult to meet the needs of local residents, whereas communities in P2 cities seemed more livable. The results reminded us that the community livability of a city was not primarily affected by its population size. We believed that the analysis based on different classification schemes could provide city managers with diverse perspectives on how to enhance community livability, which was helpful for targeted planning and construction.

4.4 Limitations

For a multi-city, individual community-scale livability assessment, some objectives remain elusive due to a series of inherently intractable problems. Firstly, this study attempted to evaluate community livability from the perspective of geospatial information. We emphasized the physical instead of the social, economic, and cultural environments of the community as well as its surroundings. This is mainly owing to the fact that the physical environment, as a carrier of other environments (Zhang et al., 2020), can directly or indirectly affect the physical and psychological conditions of local residents. For example, when there are extensive green spaces or shopping malls, libraries and other facilities in an area, we can assume that the local residents have more opportunities to enjoy the related goods and services (e.g., walkability, bike-ability, access to shopping and reading, etc.) to meet their demand and maintain the health. Secondly, the subjective evaluations of local residents on the livability of their communities were also not directly included. Although this study has considered the subjective perceptions through expert scoring and weighting, with diverse samples to ensure the reliability and representativeness of the results, nevertheless, as mentioned in the introduction section, there is no fixed standard for livability, as different individuals have different expectations on it. Consequently, the assessment indicators selected in this paper can only attempt to give a minimum standard for livable communities that covers the needs of most people, without taking the diverse individual lifestyles into account. Finally, community livability is also an elastic term in the temporal dimension, since human needs are dynamic, and accompanied by the changes of assessment criteria. Some of the conclusions of this paper may no longer be valid in the future. However, our proposed framework is flexible and low-costed to update, and the indicators and weighting criteria can be modified according to actual needs.

5. Conclusion

For urban planners, a practical, quantitative, and in-depth assessment of community livability is of extreme necessity to formulate targeted policies, which is exactly what the existing research lacks. Hence, this study conducted a comprehensive community livability assessment in 101,630 real communities of 42 Chinese cities to bridge this research gap. On the one hand, we provided a possible solution to the challenges remained in practical assessment work: high costs, poor data availability, heterogeneity of data from multiple sources, and the absence of an applicable assessment framework. On the other hand, our results firstly elucidated the authentic and exhaustive situation of livability of 101,630 Chinese communities: (1) the weighting of indicators showed that LC was the most decisive factor of community livability, and the least important is BE. Some of the negative factors (e.g., FAC_1 km) required particular attention, as their weighting exceeded most of the positive factors. (2) The monomial evaluation of the level-2 indicators showed that the high-density buildings within communities made it impossible for most communities in these 42 cities to provide residents with a green space coverage that meets the standard (30%). In this regard, communities in higher-leveled cities outperformed those in lower-leveled cities. (3) The integrated evaluation of the level-1 indicators revealed a salient deficiency of community construction in the major Chinese cities, i.e., the security of communities, especially in some T3 and T4 cities (e.g., Hefei (HF), Hohhot (HH), etc.). (4) Generally speaking, the imbalance of livability construction were widespread between cities and communities, e.g., eastern, southern and central cities had significantly higher CLI means and SDs than western and northern cities. Significant spatial clustering effect of high CLI communities was also observed within each city.

Our results and conclusions would help consolidate the achievements and make up for the shortcomings of livable community construction in these 42 representative large cities in China. It should be noted that the situation of some small and medium-sized cities may be different to some degree. Therefore, more extensive research, guided by the unified methodological framework developed in this study, will continue.

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