

Article

Ineffective Expansion of 15-Minute Community Life Circles: Cross-Scale Evidence from Food and Physical Activity Environments in Aging Communities

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Abstract

Proximity-based planning frameworks such as the 15 min city and community life circle (CLC) are widely promoted to improve age-friendly access to essential resources, based on the assumption that enlarging spatial scale improves access. This assumption remains largely untested in high-density aging cities, where neighborhood-level deprivation may persist even as aggregate access improves. Using 3737 residential communities in central Tianjin, China, this study jointly evaluates food and physical activity environments across 5, 10, and 15 min walking thresholds. We apply a three-dimensional demand–matching–spatial association framework that combines health-weighted accessibility, location quotient matching, and bivariate spatial autocorrelation. Food access shows a continuous core–periphery gradient, whereas physical activity access is fragmented and facility-dependent. Supply–demand matching shows divergent scale responses across resource domains. Aggregate accessibility increased as the CLC scale expanded. However, 45.88% of communities classified as LL at the 10 min scale remained LL at 15 min, substantially exceeding the overall LL proportion of 18.70% at the 15 min scale. Only 5.42% of communities classified as HL or LH transitioned to HH. This divergence between aggregate accessibility improvement and persistent local disadvantage is defined as ineffective expansion. Eight diagnostic types reveal a clear divide between deprived peripheries and advantage-maintenance conditions in the urban core. These findings suggest that age-friendly CLC planning should move beyond uniform service-area expansion toward type-specific, place-based interventions.

Keywords: 15 min city; community life circle; ineffective expansion; age-friendly planning; food and physical activity environments



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1. Introduction

Proximity-based planning emphasizes access to essential daily services and activities within short travel times. The 15 min city conceptualizes this principle as a neighborhood-scale urban model in which residents can reach essential functions within approximately 15 min by walking or cycling [1]. In China, the community life circle (CLC) operationalizes a similar principle through differentiated walking-time scales for public-service and amenity planning [2,3]. The two concepts share an emphasis on everyday proximity but differ in institutional orientation: the 15 min city is a broad normative model, whereas the CLC is embedded in China's territorial spatial-planning and public-service allocation systems.

Both frameworks are grounded in spatial accessibility, but proximity alone does not establish whether provision is adequate relative to demand or equitably distributed. Enlarging a service area may incorporate additional facilities while leaving high-demand communities relatively underserved, and aggregate improvements may coexist with persistent local disadvantage. CLC enlargement should therefore be evaluated empirically rather than assumed *a priori* to produce equivalent benefits across communities.

This study adopts three analytical dimensions: aging-related demand captures the intensity of community-level need; supply–demand matching evaluates whether resource accessibility is proportionate to that demand; and spatial association identifies whether food and physical activity accessibility form locally clustered or mismatched configurations. Their integration enables an assessment of whether expanded service areas improve aggregate conditions while enabling disadvantaged communities to transition toward more favorable spatial configurations.

Existing research presents three limitations. First, single-threshold assessments provide limited evidence on how accessibility and disadvantage change as service areas expand. Second, resource accessibility and population demand are often evaluated separately. Similar accessibility levels may therefore imply different planning priorities under different demand conditions. Third, food and physical activity environments are commonly examined as separate resource domains despite both being important components of health-supportive neighborhood environments [4–7]. Joint spatial analysis can identify whether their local accessibility patterns are associated, jointly disadvantaged, or mismatched. However, spatial association alone does not demonstrate coordinated use, functional interaction, or behavioral coupling.

These limitations are especially consequential in the context of population aging. Older adults are among the most sensitive groups to spatial mismatches between resource availability and everyday mobility constraints, as their daily activities are typically structured around relatively short and routine-based mobility ranges [8,9]. They generally rely more strongly on nearby services and walkable neighborhood environments because their needs for daily food access, recreation, and physical activity are recurrent. Yet most studies addressing age-friendly cities continue to assess single-resource accessibility or adopt a single spatial scale [10], offering limited insight into whether—and how—resource configurations improve as proximity thresholds expand. Consequently, it remains unclear whether scale expansion under frameworks such as the CLC genuinely alleviates neighborhood-level deprivation for older adults or merely inflates accessibility metrics. In this study, ineffective expansion refers to a condition in which aggregate accessibility improves as the CLC scale enlarges, while initially LL communities remain LL at a higher proportion than the overall LL proportion at the enlarged scale. Effectiveness is therefore judged by whether scale expansion reduces local disadvantage, not by aggregate gains alone. The operational criteria are specified in Section 2.6.3.

To address these gaps, this study examines food and physical activity environments across 5, 10, and 15 min CLC scales in central Tianjin. It addresses three questions: (1) How do the accessibility and supply–demand matching patterns of food and physical activity environments change across CLC scales? (2) Are aggregate improvements accompanied by transitions out of local disadvantage, or do unfavorable spatial configurations persist as service areas expand? (3) How can aging demand, supply–demand matching, and local spatial association be integrated to identify differentiated community conditions and planning priorities?

A three-dimensional demand–matching–spatial association framework is developed to answer these questions. The framework integrates the Comprehensive Aging Index (CAI), location quotient–based supply–demand matching, and bivariate spatial association. Using

3737 residential communities, the analysis compares scale-dependent accessibility patterns, examines whether LL communities remain LL and whether HL or LH communities shift to HH across scales, and classifies communities into eight diagnostic types at the 15 min scale.

This study contributes to proximity-based planning research in three ways. (1) It evaluates scale expansion by examining aggregate accessibility change and whether disadvantaged communities improve. (2) It distinguishes aging demand, resource adequacy, and local spatial association. (3) It combines these dimensions to classify communities into eight types for differentiated and place-based planning. The findings show that larger CLC service areas do not necessarily reduce local disadvantage and help identify communities that need further investigation and intervention.

2. Materials and Methods

2.1. Study Area

The central urban area of Tianjin was selected as the study area (Figure 1). Tianjin is located in northern China and is one of the country's four municipalities directly under the central government. The study area includes six districts: Heping, Hedong, Hexi, Hebei, Nankai, and Hongqiao. It covers approximately 576.16 km², accounting for 13.29% of Tianjin's total area, and accommodates approximately 4.057 million permanent residents, representing 29.26% of the city's total population [11].

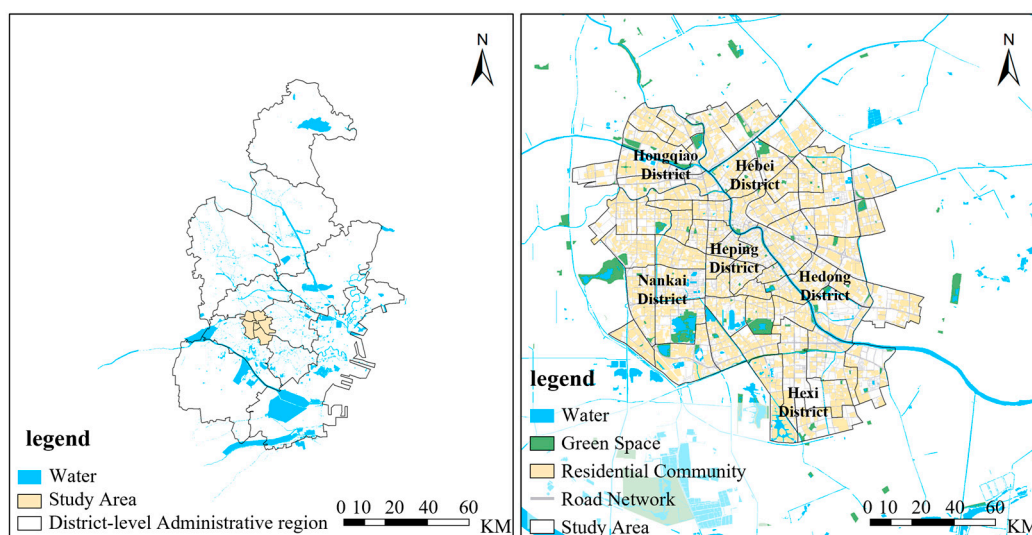


Figure 1. Location and spatial composition of the study area in Tianjin, China.

According to the Seventh National Population Census, residents aged 60 years and older accounted for 18.70% of China's population [12] and 21.66% of Tianjin's population in 2020. Based on the aggregated street-level census data used in this study, the corresponding share in the six central districts was 28.51%. By the end of 2024, residents aged 60 and above accounted for 25.88% of the city's total population [13], indicating continued population aging. The concentration of older residents, together with the dense and mixed-use urban form of the central districts, provides an appropriate context for examining accessibility and supply–demand matching across multiple CLC scales.

2.2. Data

Data were obtained from open data platforms, government sources, and online map services, covering four categories: older-adult population data, food environment data, physical activity environment data, and road network data. All datasets were processed

and integrated using ArcGIS 10.8 and Python 3.12.7 to ensure spatial consistency and analytical comparability.

- (i) Residential community (AOI) data. AOI data for 3737 residential communities were obtained from Lianjia, a major real estate platform in China (accessed in March 2025). The dataset includes relevant indicators such as community area, number of households, and average housing prices.
- (ii) Population data. Population data were sourced from street-level tabulations of the Seventh National Population Census, including age-specific population data. To estimate the older-adult population at the community level, a household-based proportional allocation method was applied. The street-level population aged 60 years and older was allocated to residential communities according to each community's share of households within its street. The household-based estimate was used in the main analysis. Robustness was assessed using an alternative residential-area-based allocation. WorldPop 2020 estimates of the population aged 60 years and older were also used to compare the population rankings [14]. The estimated values were rounded to integers for subsequent community-level analysis.
- (iii) Food environment data. Food environment data were obtained from the Amap POI database. POI categories related to daily food acquisition were selected, including catering, shopping, and life services. Data cleaning was conducted through keyword filtering and manual verification to exclude non-food facilities. In addition, spatial data on community-based meal service sites for older adults released by the Tianjin Civil Affairs Bureau [15] were integrated to construct a food facility database with health attributes.
- (iv) Physical activity environment data. Physical activity environment data were compiled from official lists of urban parks [16] and publicly accessible sports facilities [17–20] and POI data from Amap. After geocoding, verification, and deduplication, these datasets were merged into a unified physical activity environment database. Based on planning guidelines [21] and previous studies [22], service radii of 900 m, 2100 m, 3750 m, and 7500 m were adopted to represent community-, neighborhood-, district-, and city-level facilities.
- (v) Road network data. Road network data were obtained from OpenStreetMap (OSM), including road classifications and administrative boundaries. A topological road network was constructed in ArcGIS 10.8 for the subsequent accessibility analysis.

2.3. Conceptual Framework and Analytical Workflow

Figure 2 summarizes the conceptual framework and analytical workflow of this study. The framework is designed to provide an integrated diagnosis of food and physical activity environments in high-density aging communities from a three-dimensional perspective of demand, matching, and local spatial association. Potential demand is represented by a comprehensive aging index (CAI), constructed at the residential community level to capture the intensity of aging-related needs. Supply–demand matching for food and physical activity environments is assessed using location quotient–based indicators across multiple CLC scales. Local cross-spatial association between HFEA and CSEA is examined using bivariate spatial association analysis to identify HH, LL, HL, LH, and non-significant configurations. These configurations characterize spatial correspondence and mismatch rather than functional interaction or coordinated resource use.

By integrating these dimensions, a three-dimensional diagnostic decision matrix is constructed to classify communities into distinct diagnostic types. This framework links population demand, resource matching, and local spatial association, thereby achieving a transition from single-factor accessibility assessment toward an integrated, planning-

oriented diagnosis. Cross-scale transition analysis is then used to examine whether aggregate improvements coincide with reductions in local disadvantage based on the persistence and transition indicators defined in Section 2.6.3.

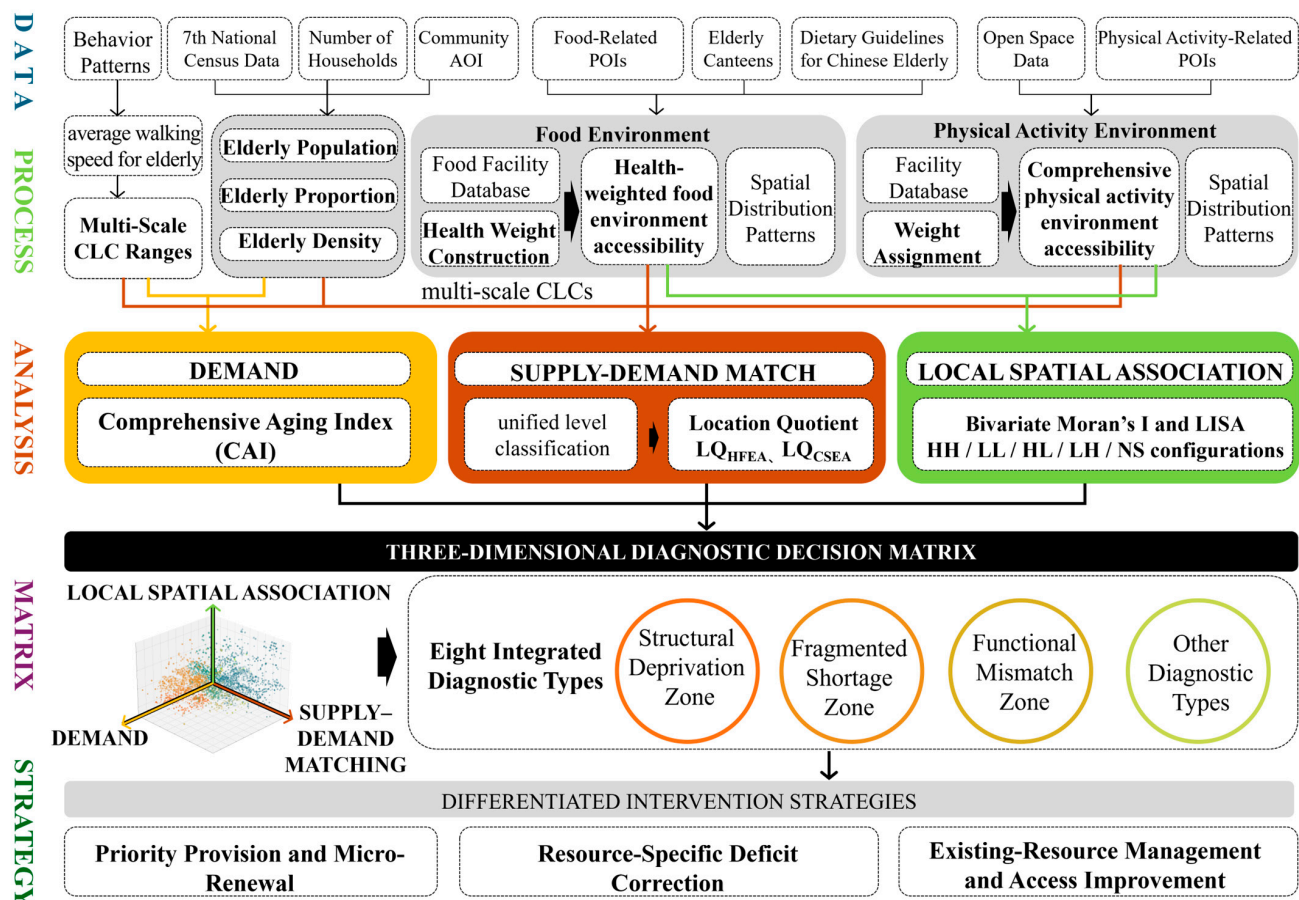


Figure 2. Conceptual framework and analytical workflow. Note: Yellow, orange, and green arrows indicate the demand, supply–demand matching, and local spatial association pathways, respectively; black arrows indicate their integration into the diagnostic matrix and subsequent intervention strategies.

2.4. Spatial Units and Demand Proxy Construction

2.4.1. Delineation of Multi-Scale CLCs

Older adults' daily mobility is characterized by short distances, high frequency, and strong regularity, with walking as the dominant travel mode [23]. Routine activities mainly include shopping, dining, social interaction, exercise, and leisure [24,25].

According to international age-friendly transportation planning parameters and Guidelines for 15 min Community Life Circle Planning, the average walking speed for older adults is approximately 0.83 m/s [26]. Based on this, 5, 10, and 15 min walking thresholds correspond to 250 m, 500 m, and 750 m, respectively. Based on these parameters, network-based service area analysis was conducted to delineate multi-scale CLCs along the road network. These CLCs provide a unified spatial framework for accessibility assessment and subsequent supply–demand matching and spatial association analyses.

2.4.2. Construction of the Comprehensive Aging Index

The size, proportion, and density of the older population are widely used indicators for population aging and represent three core dimensions of regional aging levels [26]. To capture the spatial pattern of aging in Tianjin's central urban area, this study constructed a Comprehensive Aging Index (CAI) using these three indicators at the residential commu-

nity level. All indicators were first normalized using the min–max method. The entropy weight method was then applied to determine the objective weights of each indicator. The CAI was calculated as a weighted composite index:

$$CAI = W_1 \times X_1 + W_2 \times X_2 + W_3 \times X_3 \quad (1)$$

where X_1 , X_2 , and X_3 represent the standardized values of older population size, proportion, and density, respectively, and W_1 , W_2 , and W_3 denote the corresponding entropy weights. The weights were 0.42 for population size, 0.19 for proportion, and 0.39 for density.

The household-based allocation was used in the main analysis. To test robustness, the CAI was recalculated using an alternative allocation based on each community's share of residential AOI area within its street. The full 15 min analysis was then repeated with all other settings unchanged. Spearman's rank correlation and classification agreement were used to compare the results. The two population estimates were also compared with WorldPop 2020 data [14].

2.5. Measuring Supply-Side Accessibility of Food and Physical Activity Environments

2.5.1. Measurement of Health-Weighted Food Environment Accessibility

The generalized 2SFCA method is widely used to assess spatial accessibility and supply–demand balance of public facilities [27] and has led to various extensions such as distance decay functions [28] and adjusted service catchments [29]. However, conventional 2SFCA formulations do not differentiate supply points according to their health-related contribution. Inspired by these, we introduced health-related weights to develop the Health-Weighted Improved 2SFCA (HW2SFCA) method. It can reflect the dietary health needs of the older-adult population and variations in their food environments. The method consists of two steps:

Step 1: Calculation of health weights and supply-side assessment.

Food environment is defined as the built food supply accessible to residents, excluding household-level food availability [30]. A Healthy Food Diversity Weight (HFDW) was constructed by drawing on the modified Retail Food Environment Index (mRFEI) [31] and the characteristics of urban food retail in Chinese cities. Based on the Dietary Guidelines for Chinese Older Adults (2022), the recommended intake amounts and proportional structure of different food categories were identified, representing population-level recommendations rather than individual preferences. We acknowledge that actual dietary behavior varies by health status, socioeconomic position, and cultural practice. However, guideline-based weighting provides a standardized, replicable baseline for cross-community comparison. By calculating the geometric area of each category within the food pyramid, we derived the proportion of each category. The product of this proportion and the recommended dietary guideline ratio served as the health score for that food category. The final healthy food diversity weight was then calculated by summing the health scores of the food varieties sold by each retailer, as detailed in Table 1.

For each food facility j , facility supply was adjusted by the *HFDW*, and the supply–demand ratio (R_j) was computed as follows:

$$R_j = \frac{(S_j \times HFDW)}{\sum_{(k \in d_{kj} \leq d_0)} D_k \times f(d_{kj})} \quad (2)$$

where S_j denotes the capacity weight assigned to facility j . In the main analysis (S_0), $S_j = 1$ for all food facilities because establishment-level capacity data were unavailable. Robustness was assessed at the 15 min scale using linear area weights (S_{1a}) and square-root area weights (S_{1b}), while all other model parameters were held constant. Effective food

supply was calculated as $S_j \times HFDW$. Representative floor areas were assigned with reference to the national standard *Classification of Retail Formats* [32] and the *Standard for Design of Catering Buildings* [33]; where no direct standard was available, proxy values were assigned by analogy with comparable facility types (Table S5). D_k represents the older-adult population at demand location k , d_{kj} is the network-based distance between k and j , $f(d_{kj})$ is the distance decay function [34], and d_0 denotes the service radius threshold.

Table 1. Classification of food retailers and corresponding Healthy Food Diversity Weights (HFDWs).

Health Category Level	Food Retailers	Healthy Food Diversity Weight (HFDW)
High-level	Supermarkets	1.000
	Community-based elderly canteens	1.000
	Traditional food markets	0.823
	Fruit and vegetable stores	0.457
	Restaurants	0.381
Mid-level	Fast food and snack outlets	0.370
	Vegetable stores	0.269
	Fruit stores	0.188
	Dairy stores	0.161
	Butcher and seafood shops	0.065
Low-level	Convenience stores and corner shops	0.015
	Nut shops	0.014
	Bubble tea & fried food shops	0.004

Step 2: Health-weighted food environment accessibility.

At the residential community level, the Health-weighted Food Environment Accessibility Index (HFEA) was calculated by aggregating the supply–demand ratios (R_j) of food facilities located within each CLC catchment and weighting them by distance decay:

$$A_i = \sum_{j \in d_{ij} \leq d_0} R_j \times f(d_{ij}) \quad (3)$$

$$f(d_{ij}) = \begin{cases} \frac{e^{-\frac{1}{2}(\frac{d_{ij}}{d_0})^2} - e^{-\frac{1}{2}}}{1 - e^{-\frac{1}{2}}} & , d_{ij} \leq d_0 \\ 0 & , d_{ij} > d_0 \end{cases} \quad (4)$$

where A_i represents the health-weighted food accessibility for community i . Higher A_i values indicate greater availability of healthy food resources. Service thresholds (d_0) were set to 250 m, 500 m, and 750 m, respectively.

2.5.2. Comprehensive Physical Activity Environment Accessibility

Previous studies often define physical activity environments mainly through parks and green spaces while overlooking publicly accessible sports facilities.

For older adults, all open spaces that support low-intensity physical activity and social interaction can be considered part of their daily physical activity. Therefore, this study extends the analytical scope beyond parks and green spaces to include public sports facilities, forming an integrated physical activity environment system.

An improved 2SFCA method was applied, with supply parameters specified by facility type. For parks and green spaces, supply capacity (S_j^{park}) was defined by park area and adjusted using the nearest accessible entrance based on actual walking distance. For public sports facilities, supply capacity ($S_j^{athletics}$) was defined by service radius and treated as a unit supply.

Given the functional differences between parks and sports facilities, accessibility was calculated separately for the two facility types. The resulting accessibility scores were normalized using the min–max method. Objective weights were then determined using the entropy weight method to construct the Comprehensive Sport Environment Accessibility (CSEA) index:

$$CSEA_i = W_1 A_{park,i} + W_2 A_{athletics,i} \quad (5)$$

$$A_{park,i} = \sum_{j \in park, d_{ij} \leq d_0} \left(\frac{S_j^{park}}{\sum_{k \in \{k: d_{ik} \leq d_0\}} D_k f(d_{kj})} \right) f(d_{ij}) \quad (6)$$

$$A_{athletics,i} = \sum_{j \in athletics, d_{ij} \leq d_0} \left(\frac{S_j^{athletics}}{\sum_{k \in \{k: d_{ik} \leq d_0\}} D_k f(d_{kj})} \right) f(d_{ij}) \quad (7)$$

where $A_{park,i}$ denotes park accessibility and $A_{athletics,i}$ denotes public sports facility accessibility for the community i . The entropy weights for parks and public sports facilities were 0.58 and 0.42, respectively.

To examine the spatial distribution patterns of key variables, this study used spatial autocorrelation analysis and the univariate local indicators of spatial association (LISA) to examine the clustering patterns and spatial heterogeneity of key variables [35].

2.6. Diagnostic Approaches for Supply–Demand Matching and Local Spatial Association

2.6.1. Supply–Demand Matching Assessment

To quantify the degree of supply–demand matching between community food and physical activity environments and aging-related demand, the Location Quotient (LQ) was introduced. The LQ reflects the relative concentration of a given resource in a specific area and is widely used to assess comparative supply advantages [36]. The LQ was calculated as follows:

$$LQ_i = \frac{E_i / P_i}{E / P} \quad (8)$$

where E_i denotes the accessibility index of community i and P_i represents the CAI of that community. E and P denote the total accessibility and aging index across all communities under the same CLC scale. An $LQ_i > 1$ indicates that the supply–demand ratio of community i exceeds the overall average of the study area. Based on the LQ value, communities were further classified into four matching levels—extreme shortage ($LQ < 0.5$), relative shortage ($0.5 \leq LQ < 0.9$), balance ($0.9 \leq LQ < 1.1$), and surplus ($LQ \geq 1.1$)—to support the subsequent diagnostic assessment (Table S1).

2.6.2. Bivariate Spatial Association Between Food and Physical Activity Environments

After computing accessibility indices under each CLC scale, bivariate spatial association analysis was employed to examine whether HFEA in a focal community was spatially associated with CSEA in neighboring communities. The global bivariate Moran's I statistic was calculated using Equation (9) [37]:

$$I_{XY} = \frac{N}{\sum_{i=1}^N \sum_{j=1}^N w_{ij}} \cdot \frac{\sum_{i=1}^N \sum_{j=1}^N w_{ij} (X_i - \bar{X})(Y_j - \bar{Y})}{\sqrt{\sum_{i=1}^N (X_i - \bar{X})^2 \sum_{j=1}^N (Y_j - \bar{Y})^2}} \quad (9)$$

where I_{XY} measures overall spatial association between the two variables, N is the number of communities, X_i represents HFEA in community i , Y_j represents the CSEA value of neigh-

boring community j , $\bar{X}$ and $\bar{Y}$ are their mean values, and w_{ij} is the spatial weight between communities i and j . Statistical significance was assessed using a random permutation test ($n = 999$), with a significance threshold of $p < 0.05$.

To further identify localized patterns of local cross-spatial association across different CLCs, bivariate local indicators of spatial association (bivariate LISA) were applied. A k -nearest neighbors spatial weight matrix ($k = 4$) was constructed, and statistical significance was assessed using 999 permutations. Based on the four-quadrant classification, local spatial patterns were categorized as follows:

- High–High (HH): high–high spatial association;
- Low–Low (LL): low–low spatial association;
- High–Low (HL)/Low–High (LH): spatial mismatch;
- Not Significant (NS): no significant local spatial association.

To examine scale effects, a Sankey diagram was used to visualize transitions among bivariate LISA configurations across 5, 10, and 15 min CLC scales.

2.6.3. Operational Identification of Ineffective Expansion

Cross-scale transitions were examined from 5 to 10 min and from 10 to 15 min. For a transition from a smaller scale s to an enlarged scale t , the proportion of initially LL communities remaining LL was calculated as follows:

$$\frac{N(LL_s \rightarrow LL_t)}{N(LL_s)} \quad (10)$$

This proportion was compared with the overall proportion of LL communities at the enlarged scale:

$$\frac{N(LL_t)}{N} \quad (11)$$

where $N(LL_s \rightarrow LL_t)$ is the number of communities classified as LL at both scales, $N(LL_s)$ is the number of LL communities at the smaller scale, $N(LL_t)$ is the number of LL communities at the enlarged scale, and N is the total number of communities.

If LL classifications at the two scales were unrelated, the proportion of initially LL communities remaining LL would be close to the overall LL proportion at the enlarged scale. Ineffective expansion was identified when aggregate accessibility increased, while the proportion of initially LL communities remaining LL exceeded the overall proportion of LL communities at the enlarged scale. The proportion of HL and LH communities that transitioned to HH was also calculated to assess improvement among mismatched communities. This criterion assesses whether aggregate gains are accompanied by reduced local disadvantage rather than treating aggregate improvement alone as evidence of effective expansion.

2.7. Comprehensive Diagnostic Decision Matrix

This study constructed a comprehensive diagnostic decision matrix at the community level to integrate the results of demand assessment, supply–demand matching, and local spatial association analysis.

The matrix serves as an operational tool to consolidate the preceding analytical findings and identify differentiated diagnostic types. The diagnostic matrix integrates three dimensions:

Demand was measured by the CAI, reflecting the relative intensity of aging-related demand across communities.

Supply–demand matching was measured by LQ results, indicating the relative adequacy of food and physical activity environment supply in relation to local aging demand.

Local spatial association was measured by bivariate LISA results, characterizing HH, LL, HL, LH, or non-significant local spatial patterns between HFEA and CSEA.

By logically overlaying these dimensions, the diagnostic decision matrix enabled a systematic classification of community-level health resource configurations. This diagnosis provided a structured basis for prioritizing targeted spatial interventions and resource optimization strategies.

3. Results

3.1. Spatial Distribution of Aging Demand

Figure 3a showed that aging demand in Tianjin's central urban area displayed a pronounced core–periphery pattern. Higher levels of the Comprehensive Aging Index (CAI) were concentrated in peripheral districts, while the central core exhibited relatively lower aging intensity. Global Moran's I showed a strong and statistically significant positive spatial autocorrelation of aging demand ($I = 0.5469$, $z = 51.31$, $p = 0.001$), demonstrating clear spatial clustering rather than random distribution.

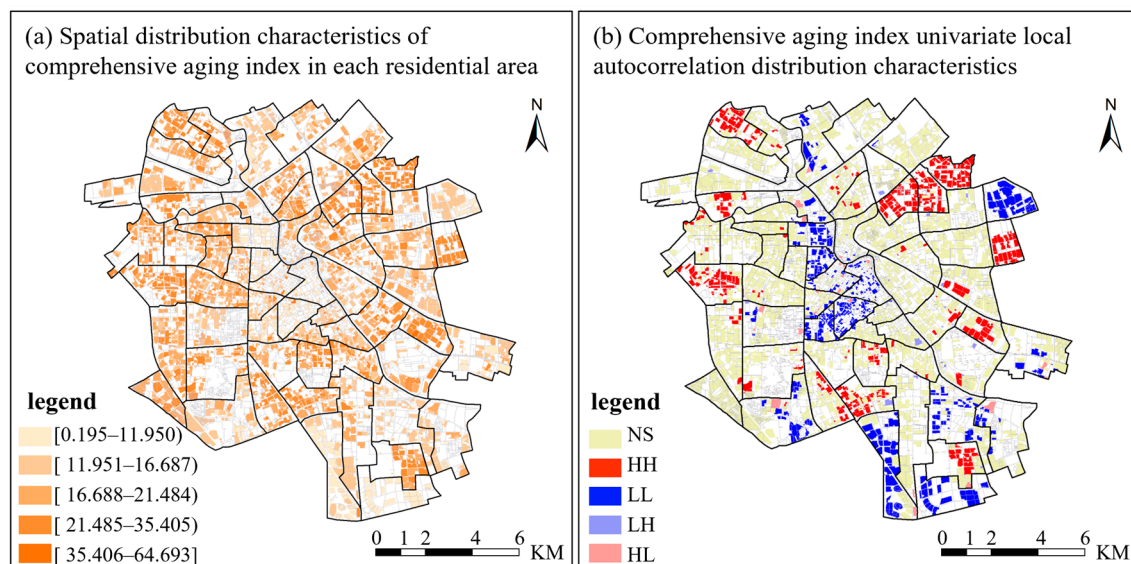


Figure 3. The spatial distribution of aging demand across residential communities: (a) the Comprehensive Aging Index (CAI); (b) univariate LISA clusters of the CAI.

Local indicators of spatial association (LISA) further revealed distinct neighborhood-level concentrations. High–high (HH) clusters were primarily located in northeastern Hebei District, southern Hexi District, and western Nankai District. In contrast, low–low (LL) clusters were concentrated in the central core and southern areas. These patterns indicated substantial spatial heterogeneity in aging-related demand across the study area.

Overall, the results revealed higher aging-related demand in several peripheral districts and relatively lower demand in the central core. This distribution provided the demand-side basis for the subsequent assessment of accessibility and supply–demand matching across CLC scales.

The household- and area-based estimates produced similar rankings for both the older-adult population (Spearman's $\rho = 0.765$) and the CAI ($\rho = 0.716$; both $p < 0.001$). At the 15 min scale, the two methods agreed on the urgent-deprivation classification for 77.57% of communities. In addition, 78.77% of communities identified as urgent deprivation by the household-based method retained this status under the area-based method. The WorldPop comparison also showed that the population rankings were broadly consistent (Table S6).

3.2. Scale-Dependent Accessibility Patterns of Food and Physical Activity Environments

3.2.1. Health-Weighted Food Environment Accessibility

Health-weighted food environment accessibility (HFEA) exhibited pronounced spatial clustering across all three CLC scales (Figure 4a–c). Global Moran's I values indicated significant positive spatial autocorrelation at all three scales (5 min: $I = 0.3332$; 10 min: $I = 0.1141$; 15 min: $I = 0.3306$; all $p < 0.01$; Table S2), indicating that HFEA values were spatially clustered rather than randomly distributed.

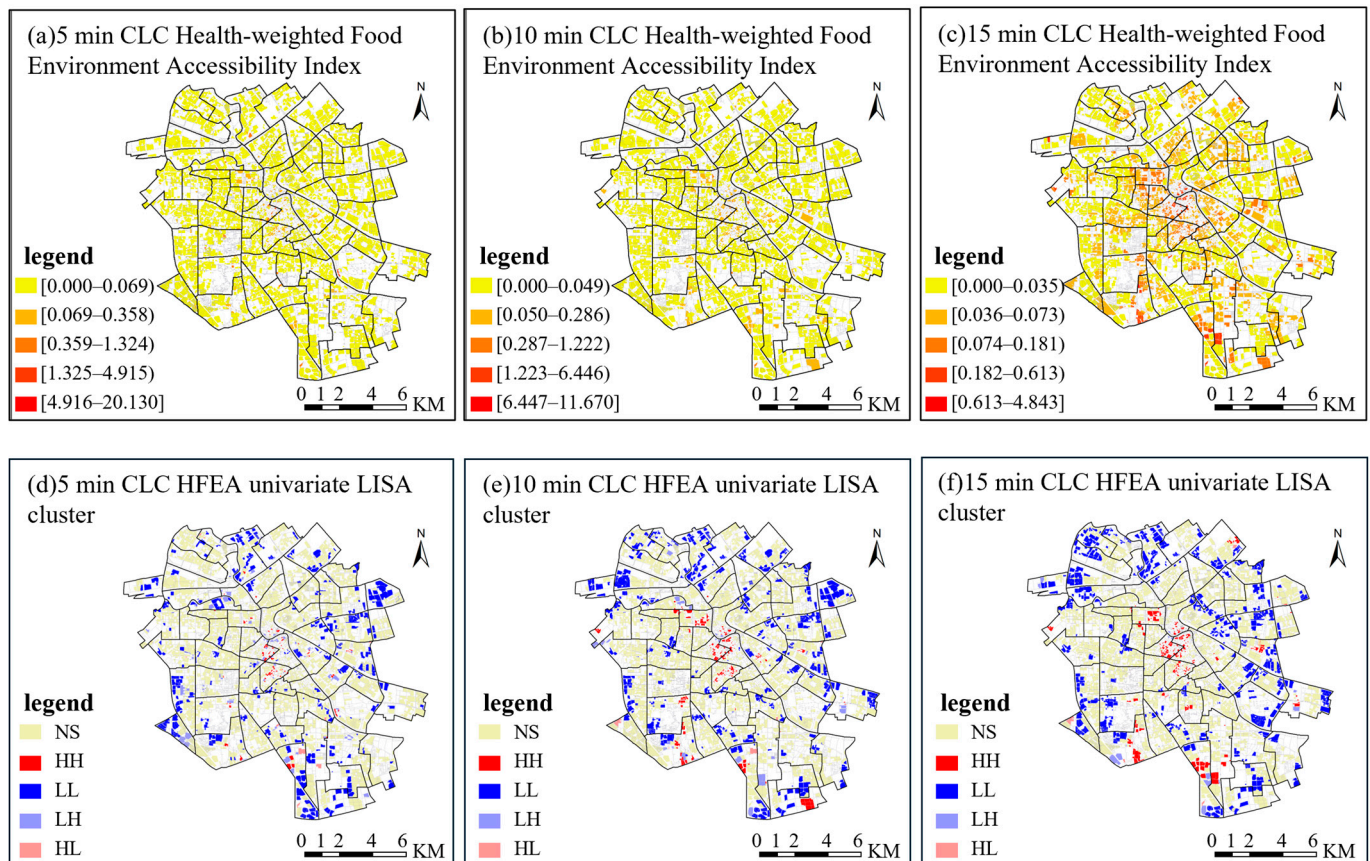


Figure 4. The spatial distribution of health-weighted food environment accessibility within 5, 10, and 15 min walking catchments. (a–c) HFEA at the 5, 10, and 15 min CLC scales; (d–f) univariate LISA clusters of HFEA at the corresponding scales.

At the 5 min CLC, overall accessibility remained limited. Only 2.7% of communities were classified as high–high (HH) clusters, concentrated in the commercial core of Heping District (e.g., Quanyechang and Wudadao). In contrast, extensive low–low (LL) clusters were distributed across northern Hebei, eastern Hedong, and peripheral Hongqiao, indicating widespread deficits in neighborhood-scale healthy food access.

As the walking threshold expanded to 10 and 15 min, the share of communities classified as HH increased modestly to 5.45% and 6.5%, respectively. HH clusters also extended toward parts of Nankai and Hexi. However, this improvement was accompanied by a simultaneous expansion of LL clusters in peripheral areas.

Rather than converging toward spatial balance, food accessibility retained a consistent core–periphery structure across scales. Global spatial clustering varied non-monotonically, weakening markedly at the 10 min scale before strengthening again at 15 min.

3.2.2. Physical Activity Environment Accessibility

In contrast to the food environment, physical activity environment accessibility, measured using the Comprehensive Sport Environment Accessibility (CSEA) index, displayed a fragmented and facility-dependent spatial pattern (Figure 5). At the 5 min scale, only 23.2% of communities fell within the higher-accessibility categories, while 46.6% remained in the lower-accessibility categories at the 15 min scale, indicating limited gains from scale enlargement.

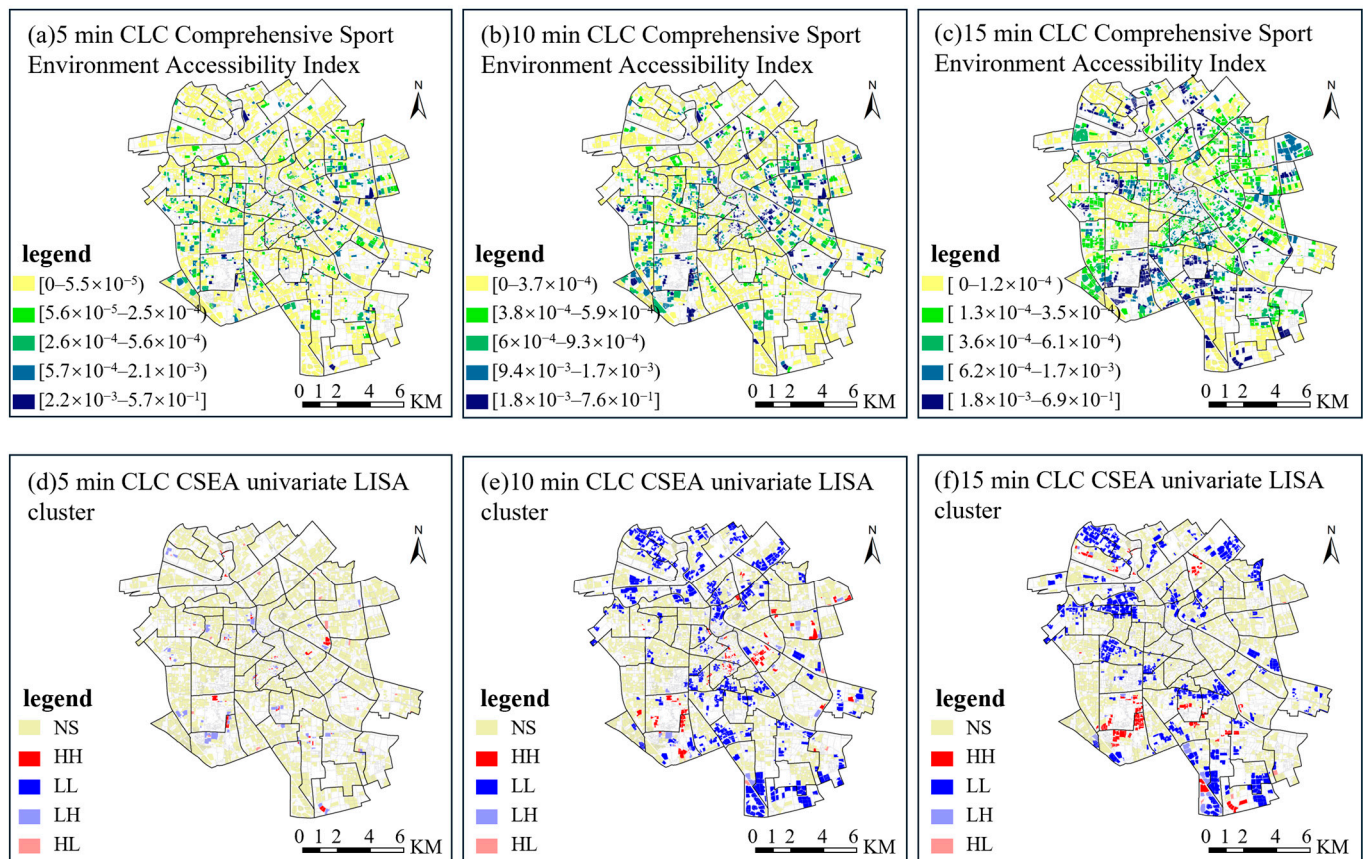


Figure 5. The spatial distribution of the Comprehensive Sport Environment Accessibility (CSEA) index across CLC scales: (a–c) CSEA at the 5, 10, and 15 min scales; (d–f) univariate LISA clusters of CSEA at the corresponding scales.

Global Moran's I values indicated weak but statistically significant spatial autocorrelation across all scales (Table S3), consistent with relatively weak clustering and a fragmented distribution. District-level patterns showed a clear south–north contrast: Hongqiao and Hebei were dominated by low-accessibility areas, whereas parts of Nankai and Hexi exhibited localized high-accessibility clusters around major parks and sports complexes.

Local LISA results further revealed substantial variation in spatial clustering. At the 5 min CLC, most communities were classified as non-significant, with only sparse HH clusters adjacent to major facilities. As the CLC expanded, HH clusters remained spatially limited and were concentrated around major facilities, while LL clusters became more contiguous across the northern parts of the study area. Overall, the expansion of the walking threshold produced limited improvement in physical activity accessibility, particularly in Hongqiao and Hebei.

3.2.3. Synthesis: Divergent Scale Responses Across Resource Types

Taken together, the two accessibility patterns revealed distinct scale-dependent constraints. Food accessibility exhibited strong spatial clustering and persistent core–periphery inequality, whereas physical activity accessibility displayed a fragmented pattern and remained spatially concentrated around major facilities. Although scale expansion increased nominal access to both resource types, the magnitude and spatial distribution of these gains differed. These divergent scale responses provided the basis for the subsequent examination of supply–demand matching and local cross-spatial association.

3.3. Scale-Dependent Supply–Demand Matching of Food and Physical Activity Environments

To assess changes in the balance between population demand and resource supply across the 5, 10, and 15 min community life circle (CLC) scales, supply–demand matching was evaluated using a unified location quotient (LQ) framework. Matching conditions for both food and physical activity environments were classified into four levels—extreme shortage, relative shortage, balance, and surplus—based on LQ thresholds. This approach enabled consistent comparison across 5, 10, and 15 min walking service areas.

3.3.1. Overall Matching Trajectories Across CLC Scales

At the aggregate level, CLC-scale expansion produced divergent changes in supply–demand matching across the two resource domains. From the 10 min to the 15 min scale, the proportion of communities classified as balanced or surplus increased from 27.49% to 37.89% for the food environment but decreased from 18.94% to 12.78% for the physical activity environment. Thus, supply–demand matching did not improve uniformly across resource domains.

These aggregate differences were accompanied by uneven community-level trajectories. Some communities experienced marked gains in matching status as the CLC expanded, whereas others showed limited or negative change. Communities located in peripheral areas tended to remain in shortage categories, even at larger scales. These divergent trajectories showed that scale expansion did not produce uniform benefits across either resource domains or communities.

3.3.2. Food Environment Matching Patterns Across Scales

Supply–demand matching in the food environment displayed a pronounced spatial hierarchy, with surplus and balanced conditions concentrated in central urban areas and persistent shortages in peripheral zones (Figure S1). Within the 5 min CLC, extreme shortages dominated, particularly in northern Hebei, northwestern Hongqiao, and eastern Hedong districts; in Hongqiao alone, 83.8% of communities fell into the extreme-shortage category. In contrast, 32.0% of communities were classified as balanced or surplus, with these communities concentrated in the Wudadao and Quanyechang subdistricts of Heping District.

As the CLC expanded to 10 min, matching conditions improved in central areas, with balanced and surplus zones extending into western Nankai and southern Hexi. Nevertheless, large clusters of food-deficient communities persisted in peripheral districts. At the 15 min scale, 65.6% of communities in Heping District were classified as surplus, whereas 51.9% of communities in Hongqiao remained in the extreme-shortage category. Thus, scale expansion improved food-environment matching in central areas, while substantial shortages remained spatially concentrated in peripheral areas.

3.3.3. Physical Activity Environment Matching Patterns Across Scales

Compared with the food environment, supply–demand matching for physical activity resources displayed a more fragmented spatial pattern (Figure S2). At the 5 min CLC, overall matching was low, and communities with $LQ_{CSEA} \geq 0.9$ were concentrated around major physical activity resources, including the Olympic Sports Center, Water Park, waterfront green corridors, and historic sports parks.

With CLC expansion, physical activity matching followed divergent trajectories across districts. In Heping, Hedong, and Nankai, matching peaked at the 10 min scale. At the 15 min scale, however, matching scores in these districts declined relative to the 10 min scale, indicating that matching did not improve monotonically with service-area expansion.

In contrast, Hexi, Hongqiao, and Hebei exhibited modest improvements between the 5 and 10 min scales but showed more substantial gains at the 15 min threshold. Overall, physical activity matching followed district-specific and non-monotonic trajectories across CLC scales.

3.4. Evidence of Ineffective Expansion: Cross-Scale Persistence and Transition

CLC expansion increased aggregate accessibility but produced divergent matching outcomes across resource domains. Cross-scale bivariate LISA transitions were then examined to assess changes in local disadvantage.

At the 5 min CLC, mismatch configurations were widely distributed (Figure 6a): 233 communities were classified as high local HFEA–low spatially lagged CSEA (HL), and 116 as low local HFEA–high spatially lagged CSEA (LH). High–high (HH) clusters were rare and concentrated around several locations, including Wudadao, the Olympic Sports Center, and the Water Park.

As the CLC expanded to 10 min, the local spatial configuration changed markedly (Figure 6b). Low–low (LL) clusters expanded substantially, particularly in Hebei and Hongqiao. Sankey flow analysis (Figure 6d) showed that approximately 23% of communities classified as non-significant (NS) at the 5 min scale transitioned into LL clusters, showing that expansion to the 10 min scale was not uniformly accompanied by more favorable local configurations. Distinct HH clusters were observed in Heping District and the Dawangzhuang area of Hedong District.

At the 15 min CLC, the global bivariate spatial association between the two environments was statistically significant (Moran's $I = 0.0413$, $p < 0.01$; Table S4), while the local pattern remained uneven (Figure 6c). HH clusters observed in Heping at the 10 min threshold largely shifted to non-significant status at 15 min, showing that local association classifications were sensitive to scale. At the 15 min scale, HH clusters were concentrated in Nankai (47 communities) and Hexi (31 communities), primarily around the Water Park and Olympic Sports Center.

LL clusters remained concentrated in Hongqiao and Hebei at the 10 and 15 min scales. Among communities classified as LL at the 10 min scale, 45.88% remained LL at 15 min. This proportion was substantially higher than the overall proportion of LL communities at the 15 min scale (18.70%), a difference of 27.18 percentage points. Only 5.42% of communities classified as HL or LH at the 10 min scale transitioned to HH at 15 min. Together with the aggregate accessibility gains from 10 to 15 min, these results indicate that the expansion met the operational definition of ineffective expansion.

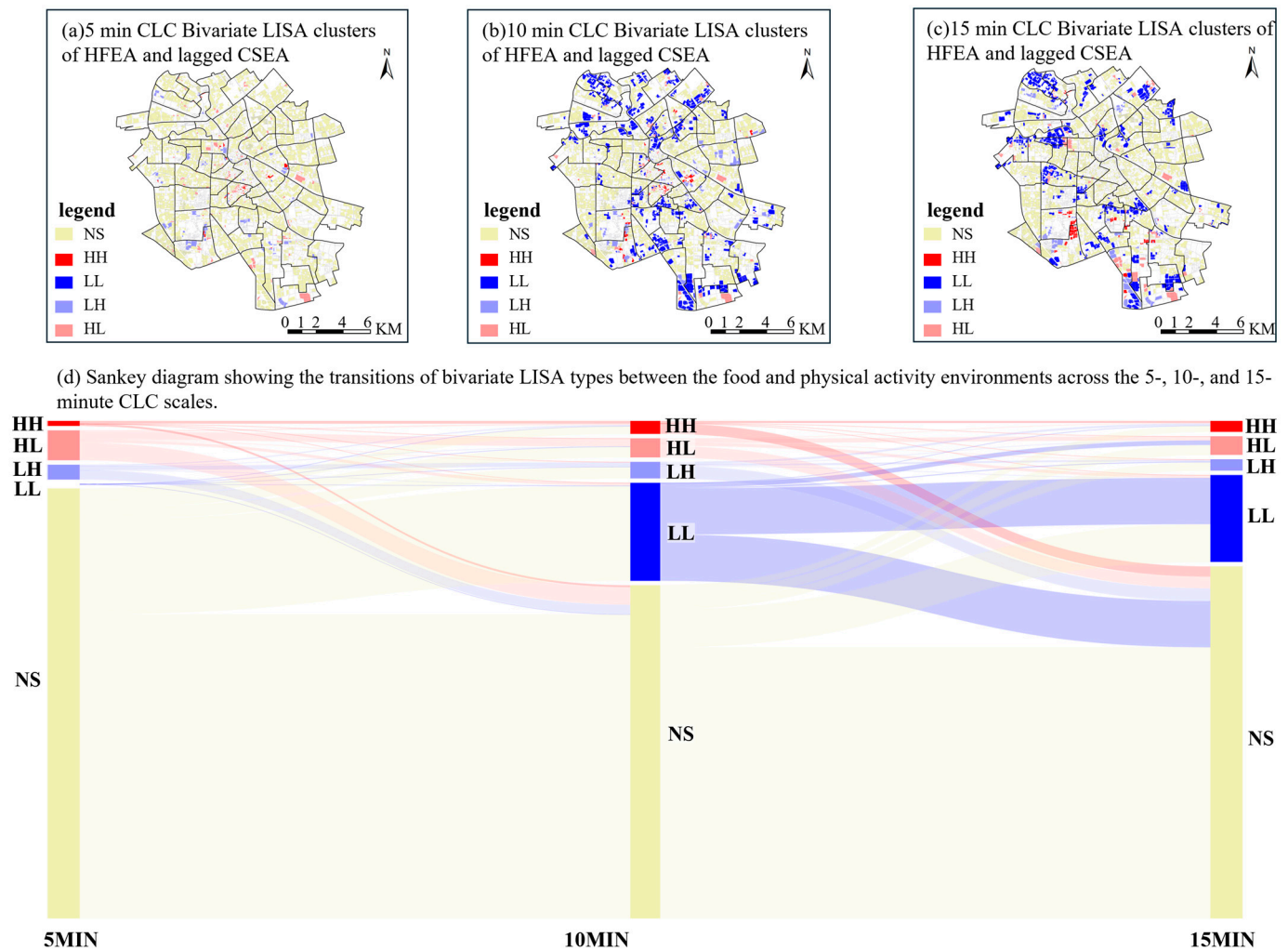


Figure 6. Bivariate LISA clusters and cross-scale transitions between local HFEA and the spatial lag of CSEA. (a–c) Bivariate LISA cluster maps at the 5, 10, and 15 min CLC scales; (d) the Sankey diagram showing transitions among bivariate LISA types across the three scales.

3.5. Community Typologies Based on the Demand–Matching–Spatial Association Framework

Based on a three-dimensional demand–matching–spatial association decision matrix, an integrated diagnostic framework was constructed to characterize community-level configurations of aging demand and health-related resources at the 15 min CLC scale (Figure 7). By jointly considering aging intensity, the supply–demand matching status of food and physical activity environments and the local bivariate spatial association between HFEA and CSEA, the 3737 residential communities were classified into eight diagnostic types (Table 2). This classification scheme enabled a systematic comparison of community conditions across the study area.

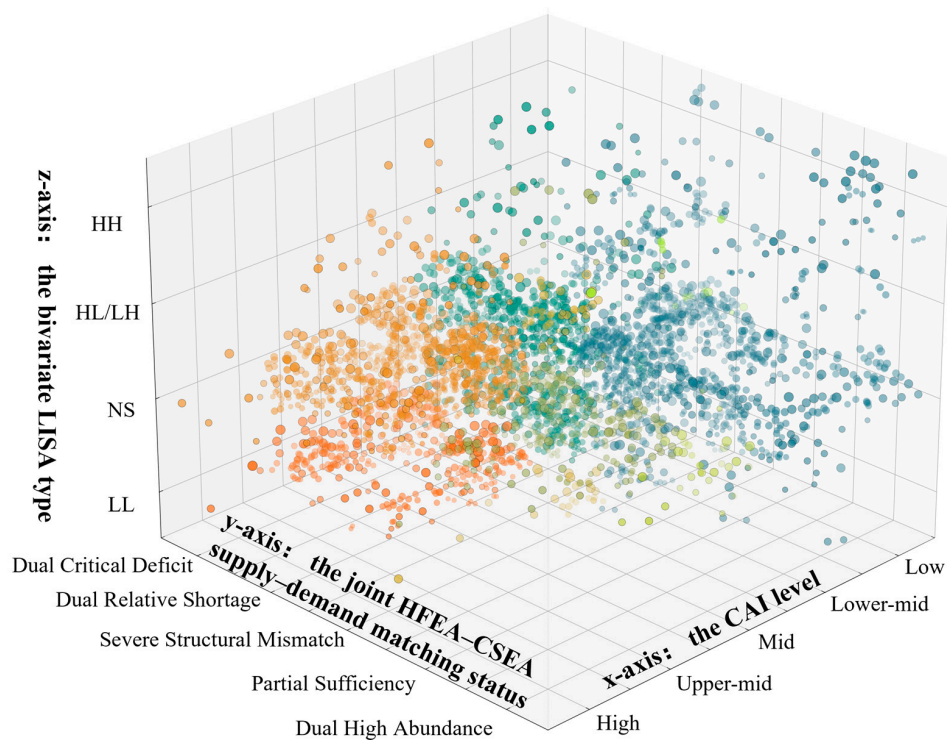


Figure 7. Three-dimensional diagnostic framework integrating aging demand, supply–demand matching, and local spatial association. Point colors represent the eight integrated diagnostic types, using the same color scheme as Figure 8.



Figure 8. The spatial distribution of the eight diagnostic community types at the 15 min CLC scale.

Table 2. The classification rules and distribution of the eight integrated diagnostic types.

Broad Category	Diagnostic Type	CAI Level	Supply–Demand Matching	Bivariate LISA Type	Percentage (%)
Urgent deprivation	Structural Deprivation Zone	mid/upper-mid/high	both resources in extreme/relative shortage	LL	10.84%
	Fragmented Shortage Zone	mid/upper-mid/high	both resources in extreme/relative shortage	Non-LL	23.23%
Mismatch and partial integration	Functional Mismatch Zone	mid/upper-mid/high	one resource adequate, the other insufficient	HL/LH/LL	2.03%
	Fragile Spatial Coordination Zone	mid/upper-mid/high	one resource adequate, the other insufficient	HH/NS	7.95%
	Spatially Dispersed Adequacy Zone	mid/upper-mid/high	both resources adequate	Non-HH	0.83%
Advantage maintenance	Balanced Adaptation Zone	mid/upper-mid/high	both resources adequate	HH	0.43%
	Underutilized Potential Zone	low/lower-mid	both resources in extreme/relative shortage	HH/HL/LH/LL/NS	21.35%
	Surplus Potential Zone	low/lower-mid	at least one resource is adequate	HH/HL/LH/LL/NS	33.34%

The resulting diagnostic types exhibited pronounced spatial differentiation. Structural Deprivation and Fragmented Shortage communities were concentrated in peripheral districts. Hongqiao and Hebei accounted for 52% and 28% of these communities, respectively (Figure 8). Typical examples included Xiyuzhuang Subdistrict in Hongqiao and Jianchangdao Subdistrict in Hebei, where high aging demand coincided with shortages of both food and physical activity resources. Structural Deprivation communities additionally exhibited an LL configuration at the 15 min scale, whereas Fragmented Shortage communities were classified as Non-LL.

Moving inward from the urban periphery, the dominant diagnostic types shifted from dual-resource shortage to one-sided resource mismatch. Hexi and Nankai Districts together contained approximately 36.7% of communities classified as Functional Mismatch and Fragile Spatial Coordination. In these areas, one resource domain was relatively adequate while the other remained insufficient, but the communities differed in their local bivariate LISA classifications. For example, communities surrounding major parks and sports complexes in Nankai and Hexi often displayed a “high physical activity–low food” configuration, whereas communities adjacent to dense commercial centers exhibited the opposite pattern. Nankai District also showed substantial internal heterogeneity, containing both a large number of Fragmented Shortage communities and nearly 90% of all Balanced Adaptation communities.

In the urban core, the diagnostic pattern was dominated by Surplus Potential and Underutilized Potential types. These communities extended from Heping District toward central areas of Nankai and Hexi, forming a relatively continuous band of advantage-maintenance conditions. Heping District alone accounted for 83.9% of all Surplus Potential communities, which combined lower aging demand with at least one relatively adequate resource domain. However, the spatial classification did not demonstrate actual underutilization or cross-community resource spillover, both of which would require facility-use or mobility evidence.

Overall, the spatial distribution of the diagnostic types revealed a broad contrast between higher-demand shortage conditions in peripheral areas and lower-demand advantage-maintenance conditions in the urban core. The continued presence of deprivation-oriented types in peripheral districts at the 15 min scale was consistent with the cross-scale evidence that expanded spatial coverage did not consistently remove localized disadvantage.

The robustness of the eight-type classification was further evaluated under alternative food-facility capacity assumptions. Relative to the equal-capacity reference, HFEA rank correlations were 0.860 under the linear area-weighted scenario (S1a) and 0.980 under the square-root scenario (S1b) (both $p < 0.001$). Agreement in the eight diagnostic types reached 88.37% and 95.79%, respectively, while 90.10% and 92.62% of communities classified as urgent deprivation under the reference scenario retained that status under S1a and S1b, respectively (Table S7).

4. Discussion

4.1. Scale-Dependent Disparities and Ineffective Expansion

CLC enlargement did not produce uniform effects across resource domains. Food accessibility retained a relatively continuous core–periphery gradient, consistent with the dense and commercially distributed structure of food provision, whereas physical activity accessibility remained fragmented and concentrated around major parks and sports facilities. These contrasting trajectories indicate that the effects of scale enlargement depend on the spatial organization of each resource system rather than on service-area size alone. A uniform proximity threshold therefore cannot be expected to generate equivalent gains across domains.

Aggregate accessibility gains coexisted with persistent local disadvantage. Communities classified as LL at the 10 min scale were disproportionately likely to remain LL at 15 min, while few HL or LH communities shifted to HH. This indicates that larger service areas can improve overall accessibility without producing corresponding improvements in disadvantaged communities. This finding is consistent with evidence that nominal proximity does not necessarily translate into effective or equitable access [38–41].

By tracing whether the same communities move out of disadvantage as the CLC scale expands, the cross-scale analysis extends conventional fixed-threshold assessments. Ineffective expansion therefore describes aggregate accessibility gains accompanied by persistent local disadvantage. Possible explanations include spatial path dependence in older districts, investment priorities favoring newly developed areas, and market-oriented facility siting. These explanations require further testing.

4.2. Diagnostic Value of the Demand–Matching–Spatial Association Framework

The framework distinguishes aging demand, resource adequacy, and neighborhood spatial context, which are often conflated in conventional facility counts or proximity rankings. The CAI identifies concentrated aging-related demand, the LQ evaluates whether resource accessibility is proportionate to that demand, and bivariate LISA characterizes local cross-spatial association between food and physical activity accessibility. Their integration shifts assessment from ranking resource levels to diagnosing the form and location of disadvantage, consistent with research emphasizing the multidimensional and context-dependent nature of aging in place [42,43].

The resulting typology supports previous findings that nominal compliance with a 15 min threshold can coexist with supply–demand mismatch [40,41]. However, the present study further shows that mismatch has different planning meanings. High-demand communities with shortages in both resource domains represent concentrated deprivation,

whereas one-sided deficits require domain-specific correction. Communities with adequate local provision but unfavorable neighboring configurations require closer examination of service reach and cross-community access. Low-demand shortages should be distinguished from high-demand deprivation, while relatively abundant provision in low-demand areas raises questions of utilization and flexible allocation. The framework therefore extends mismatch assessment from identifying whether a deficit exists to distinguishing its form, urgency, and corresponding planning task.

The robustness analyses showed that the broad priority pattern remained stable under alternative population-allocation and food-capacity assumptions. The main urgent-deprivation areas also remained similar. The typology should therefore be interpreted as a screening and prioritization tool. Project-level decisions still require local audits, facility operational data, and stakeholder knowledge because the spatial classifications do not directly represent facility use, behavioral interaction, or community functioning.

4.3. Type-Specific and Place-Based Planning Implications

Intervention priorities should be differentiated according to the severity and source of disadvantage. Consistent with research emphasizing demand-responsive and adaptable facilities for older adults [44,45], the diagnostic types can be consolidated into three planning tasks: securing essential provision in urgent-deprivation communities, correcting resource-specific deficits in mismatch and partial-integration communities, and improving the accessibility and management of existing resources in advantage-maintenance communities.

Urgent-deprivation communities, particularly those that remain LL across successive CLC scales, should receive the highest priority. District governments and subdistrict administrations should coordinate food-service, sports, civil-affairs, and urban-renewal programs to address simultaneous shortages. Community canteens, fresh-food service points, pocket exercise spaces, and small multipurpose activity rooms can be introduced into underused community buildings, accessible ground-floor spaces, and residual parcels where large-scale redevelopment is constrained. Community assessments, age-friendly retrofit inventories, and micro-renewal project lists can translate the spatial diagnosis into project selection and funding priorities.

Mismatch and partial-integration communities require correction of the deficient resource domain. Where physical activity accessibility is weak, measures may include pocket exercise nodes, additional park entrances, shared sports spaces, and safer walking connections. Where food accessibility is weak, community meal services, fresh-food retail, mobile service points, and delivery support are more appropriate. Where local provision is adequate but the neighboring configuration remains unfavorable, route continuity, crossings, entrances, opening hours, and service boundaries should be audited before additional facilities are introduced [46]. This sequence directs investment toward the actual constraint and reduces the risk of duplicating existing capacity.

In advantage-maintenance communities, planning should prioritize facility quality, flexible use, adaptable spaces, extended opening hours, shared programming, and periodic demand monitoring rather than further fixed provision. These measures are consistent with participatory research emphasizing flexible and multiple-use community spaces [45]. Potential support for adjacent shortage areas may be strengthened through pedestrian connections and coordinated services, but such cross-community effects should be verified using mobility, operational, or user data before being interpreted as established spillover.

4.4. Limitations and Future Research

Several limitations should be acknowledged:

- (1) Community-level aging demand was estimated by allocating street-level census counts according to household shares. The area-based method and WorldPop comparison provided additional checks, but none of these approaches provides directly observed older-population counts at the community level.
- (2) The main food-accessibility analysis assumed equal facility capacity while applying type-specific healthy-food weights; floor-area-based capacity scenarios were used only for sensitivity analysis. Actual provision may vary with facility size, affordability, opening hours, and service intensity. Physical activity accessibility also did not account for facility quality, operational capacity, or age-specific suitability. Future studies should incorporate facility-level data and field audits.
- (3) Bivariate LISA identifies local cross-spatial association between food and physical activity accessibility, but it cannot establish functional interaction, coordinated use, or behavioral coupling. Likewise, the continued LL classification of initially disadvantaged communities and the limited transition of HL or LH communities to HH indicate persistent disadvantage across scales without identifying its underlying causes. Future research should combine mobility data, surveys, interviews, and facility-use records to test whether the identified spatial configurations correspond to actual resource use and activity patterns.
- (4) The cross-sectional and single-city design limits causal inference and direct generalization to cities with different urban forms, demographic structures, and planning institutions. Longitudinal and multi-city studies are needed to examine the temporal stability and broader applicability of the framework.

5. Conclusions

This study develops and applies an empirical framework for assessing health-supportive environments for older adults in high-density cities from a demand–matching–spatial association perspective. By jointly evaluating aging-related demand, supply–demand matching, and local cross-spatial association between food and physical activity accessibility, the study identifies distinct scale-dependent patterns in these two resource environments across 5, 10, and 15 min community life circles in central Tianjin. The results show that expanding life-circle service areas can improve aggregate accessibility and some dimensions of matching without consistently reducing local disadvantage, as initially LL communities remained LL at a substantially higher proportion than the overall LL proportion at the enlarged scale. This pattern is identified as ineffective expansion.

By identifying eight diagnostic community types, the framework provides a structured basis for differentiated and place-based planning. Rather than applying uniform facility expansion, age-friendly renewal should distinguish among urgent-deprivation, mismatch and partial-integration, and advantage-maintenance conditions. Persistent high-demand shortages require priority provision, resource-specific deficits require targeted correction, and communities with adequate or potentially underused resources require improved access, flexible management, and demand verification.

Overall, the framework offers a structured means of identifying supply–demand mismatches and cross-scale persistence that may be obscured by aggregate accessibility measures. Future research should integrate finer-scale demographic and facility data with mobility records and longitudinal evidence to examine how the identified spatial configurations relate to actual resource use and health-supportive activities.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/buildings16153061/s1>. Figure S1: The spatial distribution and cross-scale changes in LQ_{HFEA} across the study area; Figure S2: The spatial distribution and cross-scale changes in LQ_{CSEA} across the study area; Table S1: LQ Index Classification Criteria; Table S2:

Global univariate Moran's I for HFEA; Table S3: Global univariate Moran's I for CSEA; Table S4: Global bivariate Moran's I between HFEA and CSEA across CLC scales; Table S5: Food-facility types, HFDW values, representative floor areas, and capacity weights; Table S6: Key robustness indicators under alternative older-population allocation methods; Table S7: Robustness of HFEA and integrated diagnosis under alternative capacity assumptions.

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Data Availability Statement: The data supporting the findings of this study are derived from publicly available sources described in Section 2. Population census data are available at <https://www.macrodats.cn/article/1147468682> (accessed on 27 July 2026); point-of-interest data are from Amap: <https://lbs.amap.com/> (accessed on 27 July 2026). Road network data are from OpenStreetMap: <https://www.openstreetmap.org/copyright> (accessed on 27 July 2026). Residential community (AOI) data obtained from Lianjia are subject to the platform's terms of use and are available from the author on reasonable request.

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