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Community-Scale Classification and Governance Policy Implications for Demographic, Economic, and Land-Use Linkages in Mega-Cities

Yonghong Mao [1,2], Jie Fan [1,2,*], Daojing Zhou [2], Yao He [1,3,4], Meng Yuan [5] and Huixin Zhang [5]

[1] University of Chinese Academy of Sciences, Beijing 100049, China; maoyh@igsnrr.ac.cn (Y.M.)
[2] Institutes of Science and Development, Chinese Academy of Sciences, Beijing 100190, China
[3] Key Laboratory of Regional Sustainable Development Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[4] College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China
[5] School of Geography, Nanjing Normal University, Nanjing 210023, China
* Correspondence: fanj@igsnrr.ac.cn

Abstract: Analyzing the spatio-temporal relationship between socio-economics and land-use structure at the micro-scale is crucial for effective spatial governance in large cities. This paper focuses on Beijing, utilizing long time-series remote sensing images and multi-source data spanning 30 years. We employ spatio-temporal clustering based on kilometer grid cells and a community-scale multi-factor aggregation method to categorize the linkages and spatio-temporal matching of population, GDP, land development, and ecological protection at the community level in a problem-oriented approach. Results indicate significant changes in Beijing's population, GDP, and land use, with a 11.53% increase in land development intensity. We identify significant temporal and spatial disparities between population–GDP dynamics, population–land development trends, and GDP–land development patterns, underscoring the multifaceted challenges inherent in urban governance. Areas characterized by lagging population concentration, sluggish economic growth, rampant land development, and ecological fragility collectively encapsulate notable portions of Beijing's expansive urban terrain. Mismatches pose governance risks, with medium to high-risk communities comprising 18.08% of community units and high-risk types representing 4.27% in Beijing. These discrepancies pose formidable governance risks, with communities ranging from moderate to high-risk categories, necessitating tailored interventions to address their unique challenges. This systematic exploration of comprehensive governance issues within mega-cities promises to furnish decision-makers with invaluable insights, facilitating nuanced and strategic urban governance approaches tailored to the intricacies of urban dynamics and challenges.

Keywords: land use; time series; sustainability; spatial pattern; coupling analysis

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1. Introduction

With the continuous growth of the global population and the expanding scope of urbanization, a substantial proportion of the world's major cities and their contiguous urban regions are undergoing rapid transformations. These changes encompass diverse dynamics, such as population concentration, economic expansion, and the swift proliferation of urbanized areas. The theoretical framework of the New Economic Geography posits a cumulative cyclical connection between population concentration and economic growth. It asserts that the spatial clustering of populations fosters overall regional economic advancement [1]. However, perspectives from sociologists and environmentalists caution against excessive population concentration, highlighting the potential emergence of social predicaments and impediments to regional economic progress [2–4].

The symbiotic relationship between population concentration and economic growth also brings forth challenges related to urban sprawl, food production, and ecological preservation. These challenges precipitate substantial shifts in the functional and structural aspects of land use. This intricate interplay generates a complex network of spatial interconnections within the realm of large cities [5–7]. Given that the fundamental unit of spatial governance in large cities is essential, the synchronization of population distribution, economic composition, and land-use functionality, both temporally and spatially, becomes paramount in influencing the sustainable development and spatial governance of these urban centers. Past scholarly investigations have categorized several typologies of metropolitan spatial configurations. These range from traditional monocentric models [8] to dual-center arrangements [9] and dispersed or convergent polycentric layouts [10]. The specific spatial structure adopted by different metropolitan regions is contingent upon the level of economic development and the prevailing policy frameworks within each area. Scholars such as Heider and Siedentop underscore the presence of diverse spatial structures—monocentric and polycentric—across different regions in the United States and Germany [11]. Even within the same metropolitan area, the spatial configuration may exhibit distinct patterns during various historical periods, influenced by internal and external factors such as population dynamics, employment, transportation, and trade [12].

A comprehensive review of prior research reveals that the analysis of large cities' spatial structures largely hinges on three foundational analytical approaches: location theories and regional spatial structure analyses encompassing population, economy, industry, and innovation within the domain of economic geography [5,13,14]; network analyses reliant on transportation networks, infrastructure, green spaces, and landscapes—commonly employed in landscape ecology [15]; and analyses of land-use functionality and structure within the context of land science [16]. However, these studies grapple with constraints arising from limited data availability and methodological platforms, making it challenging to strike a harmonious balance between temporal and spatial resolutions. While the interrelationships between population and economy, as well as between population/economy and land-use structures, have been explored in prior research, investigations delving into the intricate linkages among population, economy, and land-use spatial structures are notably scarce [17].

Moreover, many studies have explored the scale of urban spatial governance. With the deepening of research, the discussion on the scale of governance and spatial governance is gradually forming three clear levels. First, the redesign of governance scale is seen as an important tool for spatial reconstruction. The redesign of the scale of governance, represented by researchers in urban geography, urban planning, and spatial political economy, is seen as a reorganization of social, economic, and political systems or a migration to new spaces of transnational, quasi-national, and trans-regional states [18]. Secondly, the redesign of governance scale is regarded as an important tool for relational adjustment in the process of spatial reorganization, mainly focusing on the scale of governance at the city, national, and global levels, and it is believed that the redesign of governance scale is to reconcile the contradictions and conflicts in the process of capital accumulation [19]. Third, the redesign of governance scale is seen as an important tool for organizing cross-border cooperation in the process of spatial reconstruction. The change in the scale of governance can be seen as a result of highly elastic competition between traditional administrative organizations and traditional organizational forms and the merger of these organizations [10,20]. Spatial governance necessitates finer resolutions, such as community and grid-based scales, which require accurate data and integration methods. Long-term analyses and multi-scale data conversion can provide some support. However, spatial governance also faces challenges in integrating sustainability considerations, balancing economic, social, and ecological concerns. Addressing both dimensions concurrently poses significant hurdles in terms of data and element integration, as well as policy application.

This paper aims to uncover the discordant relationship among population dynamics, economic trends, land development, and ecological protection by employing a method that integrates long-term, multi-source data and grid cells. This integration seeks to facilitate sustainability governance at finer scales, such as community and grid-based scales. In this study, we focus on the case of Beijing, employing a community-based analytical framework. By leveraging extensive multi-source remote sensing data and community-level segmentation, we delineate population, economic, and land-use structures at the community scale in Beijing across spatial and temporal dimensions. Based on these analyses, we undertake a coupling analysis of these three facets, uncovering the principal characteristics and driving forces underlying their temporal and spatial variations. The innovation of this study lies in its use of long time-series, multi-scale, and multi-source data to identify areas at risk of unsustainable development. The insights garnered from this exploration provide valuable recommendations for enhancing the spatial governance of large cities, with a particular emphasis on the community scale.

2. Study Area and Data Sources

2.1. Study Area

Beijing, situated in the northern segment of the North China Plain, falls between the geographical coordinates of 39°26′~41°3′ N and 115°25′~117°30 E, covering a total expanse of 16,410 km^2 (Figure 1). The topography varies, ascending towards the northwest and descending towards the southeast, while flanked by mountains on three sides, thereby attributing to mountainous terrain constituting 62 percent of the total area. The climatic classification places it within the warm-temperate semi-humid zone, characterized by an average annual precipitation around 600 mm.

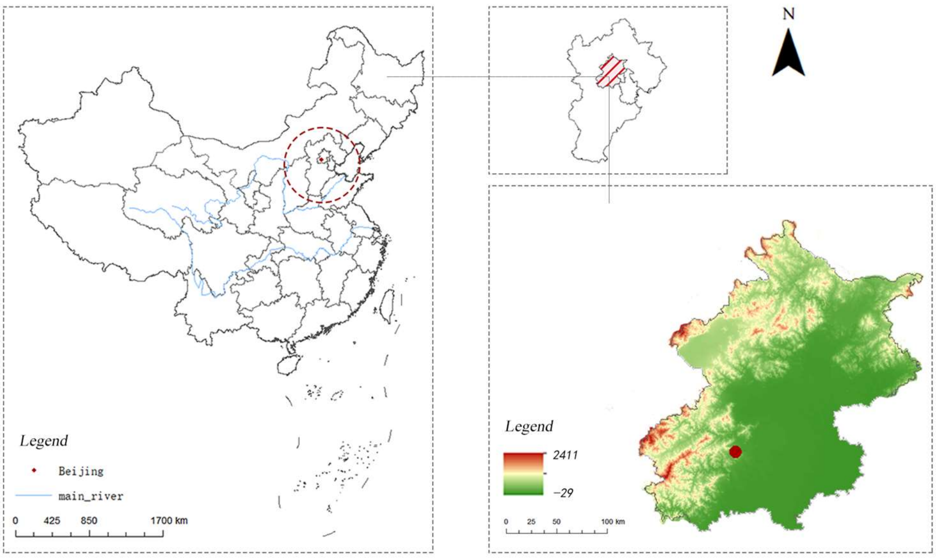


Figure 1. Overview map of the study area.

Following the establishment of the People's Republic of China, Beijing has evolved into a global metropolis endowed with multifaceted roles encompassing politics, culture, economy, science, and education. Propelled by population migration and urbanization, the city has undergone unparalleled demographic expansion [21]. By the year 2022, Beijing's resident population had reached 21.843 million, representing a remarkable increase of 944.47% from the base year of 1949. While the population has surged, the city has managed to sustain a commendable pace of economic growth. Over the past three decades, Beijing's GDP has exhibited an average annual growth rate of 14.53%. By the year 2022, the city's GDP reached an impressive 4161.09 billion yuan, yielding a notably elevated per capita GDP of 190,000 yuan, thereby securing the foremost position among Chinese cities. Concomitant with the trajectory of urbanization, economic expansion, and social transformation, the landscape of land use in Beijing has experienced profound metamorphosis, highlighted by an intensity of land development that has escalated to an extent of 48 percent. The pronounced concentration of both population and economic activity, coupled with the incongruous configuration of land-use functions, has given rise to issues ranging from water scarcity to environmental degradation and ecological disturbances within Beijing [5].

In 2017, Beijing embarked on a comprehensive initiative labeled the "Dismantling, Rectifying, and Promoting Enhancement" campaign. This effort sought to dismantle non-essential functions from the capital, alongside addressing the challenges posed by "Big City Disease"—a complex set of urban challenges including congestion, pollution, and resource strain. Navigating the harmonization of the urban spatial arrangement and functional allocation stands pivotal in realizing a trajectory of land development and socio-economic growth that is both intensive and efficient. This pursuit represents the foremost quandary confronting the contemporary urban development of Beijing.

2.2. Data Sources

The data essential for this study encompass three primary categories. Firstly, they encompass foundational geographic information data encompassing the administrative boundaries of Beijing, spatial coordinates and nomenclature of communities, as well as digital elevation data (SRTM) and the traffic network. These data sources have been procured from the National Geomatics Centre of China (https://www.webmap.cn/, accessed on 15 November 2021). Secondly, the study relies on several gridded datasets, such as UN-adjusted population from the worldPop dataset [22], GDP from RESDC (http://www.resdc.cn/DOI, accessed on 28 April 2023), and CAS [23]. Lastly, the study incorporates imagery data from the Landsat series, accessed through the GEE platform. These imagery data comprise various types, such as TM/ETM+/OLI.

To efficiently conduct this study, we decided to select the long time-series land-use dataset to characterize the evolution of development intensity. Therefore, the GEE platform was leveraged to sift through the Landsat imagery data covering the 30-year period spanning from 1990 to 2020 in Beijing and to produce the final land-use dataset. The criteria used for this screening process are as follows: firstly, data were collected during two distinct periods—June to October (characterized by flourishing vegetation) and November to March (marked by a more subdued, yellowish vegetation appearance); secondly, the data selected exhibited cloud coverage of less than 15%. Through this meticulous screening process, a comprehensive dataset was assembled, encompassing region-wide imagery data with minimal cloud interference, achieved through pixel-mosaic-based image acquisition methods. Combining RF classifier and sample points collected by visual interpretation, we obtained a 30-year land-use dataset of Beijing. To further improve the accuracy of our classification dataset, we conducted a bi-directional detection correction, which has been proved efficient in the existing research [24].

3. Methods

This study proposed an integrated framework to investigate the nexus and relationship between population, GDP, land development, and ecological protection in the community scale of Beijing. The framework contains three major stages (Figure 2). Firstly, performing land-use classification based on random forest (RF) on GEE; second, using a time-series clustering technique to explore the evolution pattern of land change at the grid scale and community scale; third, conducting population–economy–land linkage analysis to uncover the interactions between the components.

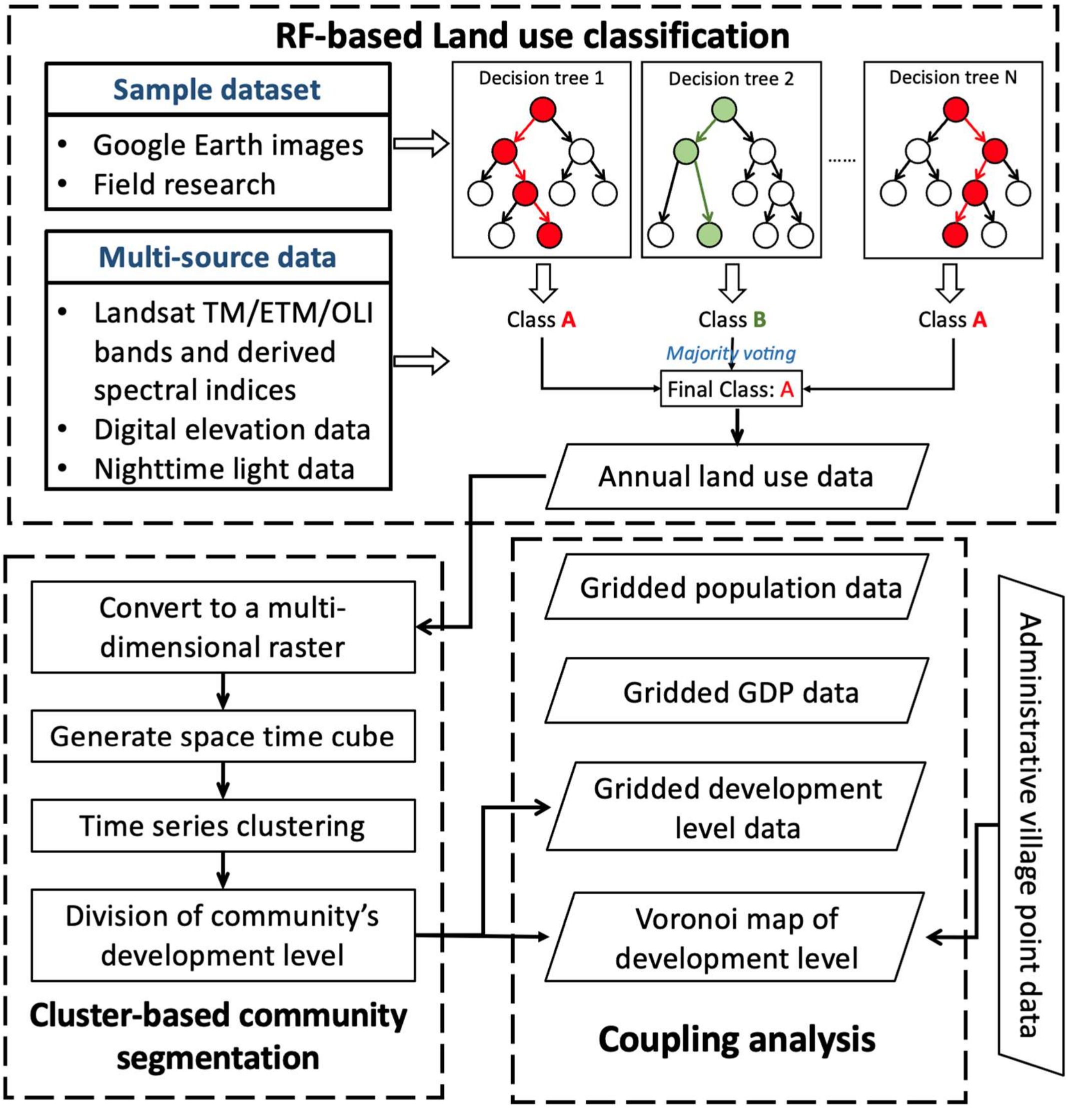


Figure 2. An overview of the technical framework, red and green circles mean the classification results of A and B in a single Decision Tree.

3.1. Land-Use Classification

We drew on previous research to create a functional land-use classification system with seven types: construction land, arable land, forests, shrubs, grasslands, water bodies, and bare land [25]. Following that, we selected samples manually and conducted three field trips over a 2-year period to gain an intuitive understanding of each type within the study area and select high-quality sample data. We implemented a pixel-by-pixel backward modification approach using high-resolution images from Google Earth and obtained 30 years of sample data. Eighty percent of the samples were set aside for training, and the remaining 20% for validation. Next, we computed feature variables, including the normalized difference vegetation index (NDVI), normalized difference building index (NDBI), and normalized difference water index (NDWI). These variables were combined with VIIRS night-time lighting data and digital elevation data (SRTM) to create different candidate feature variables. We compared the accuracy results of different combinations to identify feature vectors with higher importance. Subsequently, we randomly divided sample points from each image into training and validation sets proportionally. The RF classifier was trained year by year to classify the remote sensing images. The classification results were optimized by adjusting sample point distribution, feature variable combination, and window size [26].

3.2. Time-Series Clustering and Community-Scale Segmentation

We used a time-series clustering method to analyze the evolution pattern of land development intensity within each community in Beijing after collecting the abovementioned land-use classification data. A 1 km × 1 km spatial grid was determined to divide the raster dataset, and the areal fraction of construction land was computed grid by grid over a year. The areal fraction results were temporally and spatially merged to a multi-dimensional raster. The FCM clustering algorithm was employed to investigate the spatial and temporal evolution of construction land at the grid scale [27]. Considering that direct clustering may generalize detailed features, we used a two-step clustering approach to reveal finer dynamics of land change. The cluster corresponding to the lowest values in the first clustering process was extracted and clustered again. We derived the ultimate clustering curve by assigning weights based on the quantity of elements within each cluster.

The generated clusters represent a collection of data entities, where objects within the same cluster exhibit similar development trends, differing from those in other clusters. In other words, within a given cluster, the grid cells follow analogous land evolution patterns. As the administrative boundary data at the community-scale in Beijing are not publicly available, we used Thiessen polygons of village points as an alternative. The Thiessen polygons were created using point of interest (POI) data of administrative villages. Each polygon delineates a region of influence around its central point, ensuring that any location within the polygon is closer to that point than any other points. This implies the assumption that the jurisdiction of each administrative village is correlated within its distance from the central point.

3.3. Population–Economy–Land-Use Linkages Analysis

The GDP raster data and population data were uniformly aggregated to 1 km × 1 km spatial cells, and the total GDP and population within each grid cell were computed. Reflecting the evolution characteristics of GDP and population, the grid underwent hierarchical division node by node. Subsequently, grid cells were subjected to cold hotspot spatio-temporal clustering to identify hotspots and rapidly developing regions within the Beijing socio-economic system. To extract the spatio-temporal evolutionary features, we adopted the Time-Series-Clustering algorithm, which could classify grids into several categories based on value characteristic [28]. The value characteristic is calculated by:

$$D_{i,j} = \sqrt{\sum (X_{i,y} - X_{j,y})^2}$$

where $X_{i,y}$, $X_{j,y}$ means value of long time-series data i, j in the time node y.

Building upon the clustering results of GDP and population, we overlaid the classification outcomes and reclassified them based on the coupling characteristics of GDP and population evolution. This approach, viewing spatial coordination between population agglomerations and the economic core, generated GDP–population evolution clustering results. This preliminary investigation aimed to identify grid cells in Beijing's socio-economic system where the evolution of population and GDP is not coordinated, uncovering potential risk areas. From the perspective of the spatial structure of socio-economic development and land resources development and protection, the GDP–population evolution clustering results were overlaid with the construction land–natural land evolution clustering results for coupling analysis. This exploration aimed to reveal potential decoupling between the socio-economic system and the land system. Based on the degree of coupling and decoupling elements in the overlaid clustering results, outcomes were classified into three zones: comprehensive coordination zone, local coordination zone, and problematic zone. The full coordination zone denoted grid cells where the characteristics of GDP, population, construction land, and ecological land categories coincided. The partial coordination zone represented grid cells where high and low characteristics were the same in the superposition results, with no significant lag in the evolution trend. Problematic zones characterized grid units with a significant lag in the development of one or more elements or an unstable system evolution. These problematic zones were further subdivided into zones of lagging population concentration, areas of excessive population concentration, zones of lagging economic development, zones of excessive land development, and zones of unstable ecosystems based on the problematic elements.

Drawing on the results of Beijing's community administrative boundary demarcation, the area share of problematic units and the number of coupled problems in each community were calculated. This allowed for an analysis of potential risks in each community in terms of scale and abundance, facilitating the identification of communities requiring urgent governance. These findings provided valuable support for community-scale policy governance and the development of targeted early warning tools.

4. Results

4.1. Land-Use Classification

The classification results reveal that land-use changes in Beijing from 1990 to 2020 primarily involve three categories: construction land, forest land, and arable land. Notably, construction land has exhibited consistent growth at an average annual rate of 6.66% over the past three decades, expanding from 946.24 km^2 (5.77%) in 1990 to 2836.13 km^2 (17.30%) in 2020 (Figure 3). Spatially, new construction land is concentrated in Yanqing District and the plains in the east-central part of the country. It radiates in all directions, with the central urban areas of Xicheng, Dongcheng, Haidian, Chaoyang, and Fengtai serving as the core. Similarly, forest land shows a clear growth trend, increasing from 8021.98 km^2 (48.94%) in 1990 to 9338.90 km^2 (56.97%) in 2020. The growth is notably concentrated between 2009 and 2015, where new forest land accounts for 66.79% of the total increase. Beijing's forest land is primarily located in the mountains in the west and north, with new additions concentrated in those areas. However, from 2010 to 2020, some new forest land also appeared in the central and eastern plains, likely due to increased emphasis on the human environment in urban planning during this period, leading to the addition of green spaces and parks to enhance the ecological quality of urban spaces.

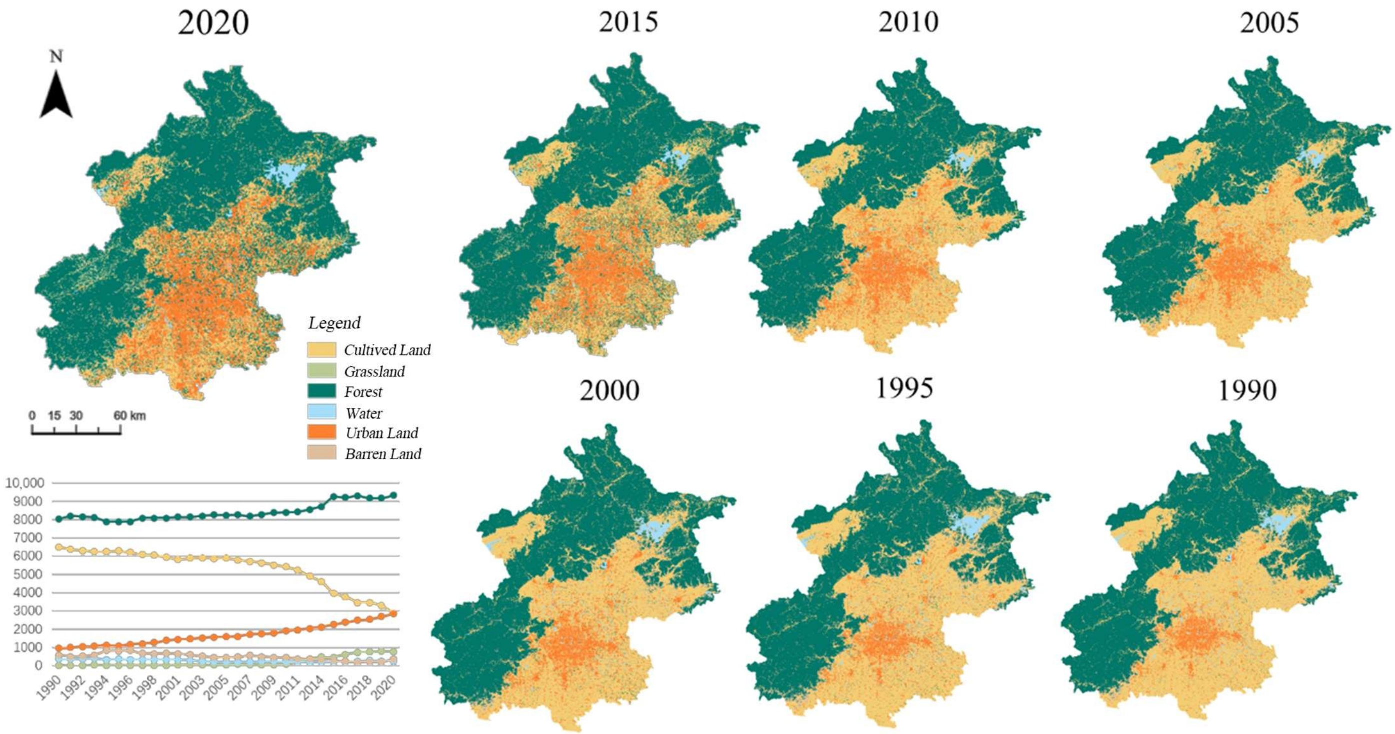


Figure 3. Results of long-term time-series land-use classification.

In contrast, arable land has significantly decreased over the past three decades, with its proportion dropping from 39.68% in 1990 to 17.44%, resulting in a total area decrease of 3644.83 km^2. The turning point for arable land occurred in 2005. From 1990 to 2005, arable land decreased at a relatively moderate rate, averaging 41.2 km^2 per year. However, from 2006 onwards, there was a sharp decline, amounting to a decrease of 3026.9 km^2 over the next 15 years. Arable land is predominantly found in the plains, including Yanqing District and the central and eastern urban areas. As the population grows and urbanization progresses in Beijing, arable land in the plains has been gradually overtaken by the expansion of construction sites. This phenomenon underscores the impact of population growth and urbanization on the reduction of arable land in the plains.

4.2. Community-Scale Classification

We conducted a classification based on the evolution patterns of built-up land (Figure 4). Class I is characterized by constant low values, Class II represents slow growth at low values, and Class III reflects fast growth at low values. Notably, the development intensity of Class III was initially lower than that of Class II until 2014. However, it subsequently surpassed Class II with a faster growth rate, indicating the accelerated urbanization and outward radiation of towns and cities in the suburbs in recent years. Classes IV, V, and VI correspond to different trajectories of the development of Beijing's main urban areas, representing the suburban area, dense and semi-dense urban cluster, and urban center, respectively. Class II tends to spread out around downtown Beijing in a "concentric circle-like" shape. Additionally, typical agglomerations occur in areas farther away from the urban center, such as Yanqing periphery, northeastern Miyun, and northern Huairou. On the other hand, Class III is more closely linked to the existing urban areas and is dotted among Class IV. This suggests a more interconnected relationship with the developed urban areas compared to Class II.

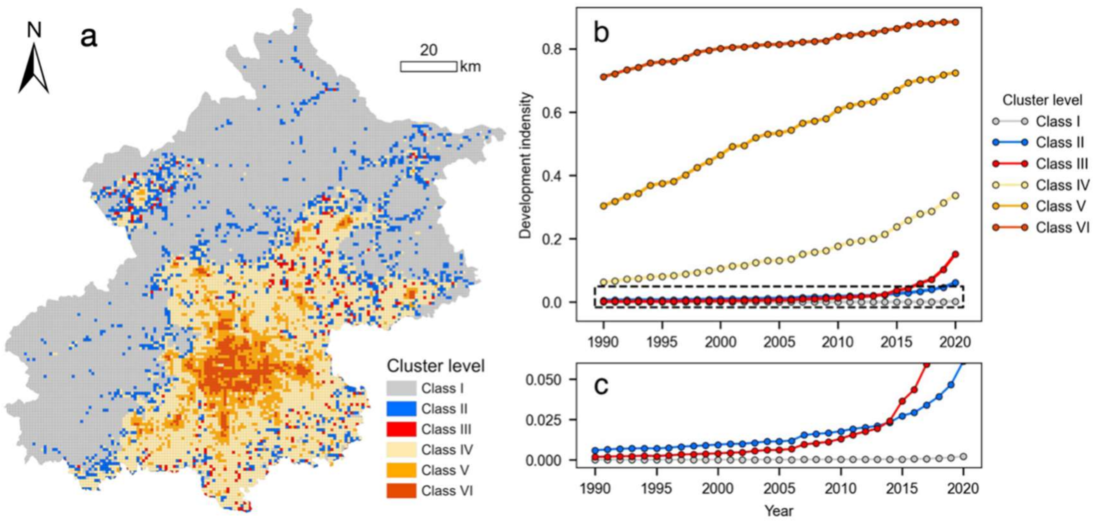


Figure 4. Spatial evolution patterns of built-up land (**a**) and corresponding cluster level curves (**b**). The dashed black box is presented is panel (**c**).

Based on the classification of the time-series evolution characteristics of Beijing's built-up land and ecological land, a coupling classification is conducted, taking into account the magnitude of change in ecological land and the development speed of built-up land and their relative degrees (Figure 5). The urban area exhibits significant feature of core-periphery structure, which could be shown by the urban core surrounded by developing urban area and urban-expansion-dominated area. Areas with high values of ecological land, which mainly consists of forest and grassland, are predominantly situated in the western and northern parts of Beijing. Simultaneously, a few clusters with low values for both construction land and ecological land are identified, primarily in Yanqing District in the northwest and Pinggu District in the east. The unstable ecological area is mainly observed in Miyun District in the northeast. This classification sheds light on the varying dynamics between built-up land and ecological land, providing insights into the overall development patterns in different regions of Beijing.

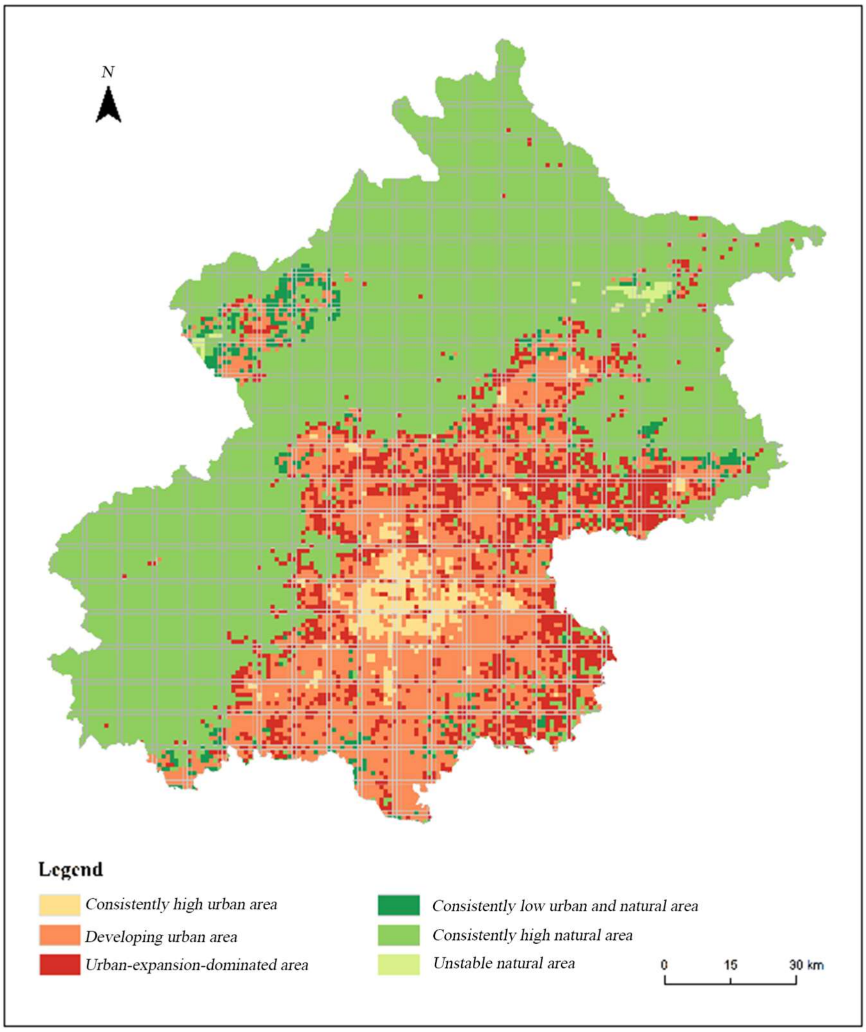
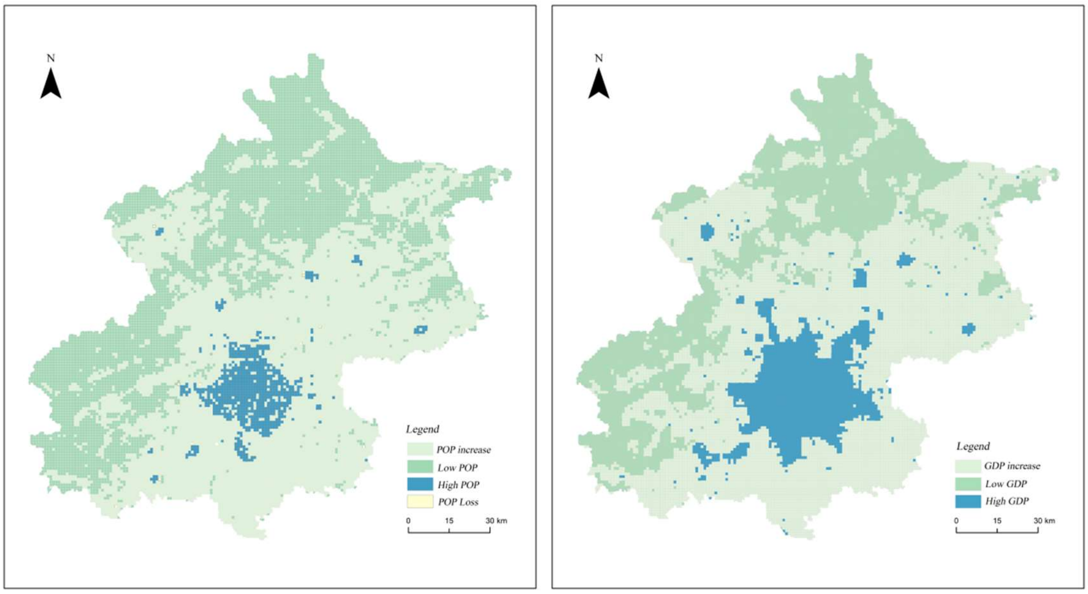


Figure 5. Spatial evolution patterns of coupling classification of built-up land and natural land.

4.3. Population–Economy–Land-Use Linkages

Upon grading and aggregating the historical evolution of Beijing's population and GDP (Figure 6), the coupled population–GDP clustering results exhibit a distinct core-edge structure (Figure 7). High population and high GDP clusters are predominantly concentrated in the core urban areas. As one moves from the central urban zones towards the peripheral suburbs, these clusters gradually transition into low population and high GDP clusters, where population development lags behind GDP growth. Ultimately, the clusters evolve into low population and low GDP clusters, primarily concentrated in the western and northern suburbs of Beijing. This delineates the polarizing effect of the core urban area and the spillover impact on the spatial neighborhoods of Beijing's socio-economic development.



(a) (b)

Figure 6. The development of population (**a**) and GDP (**b**).

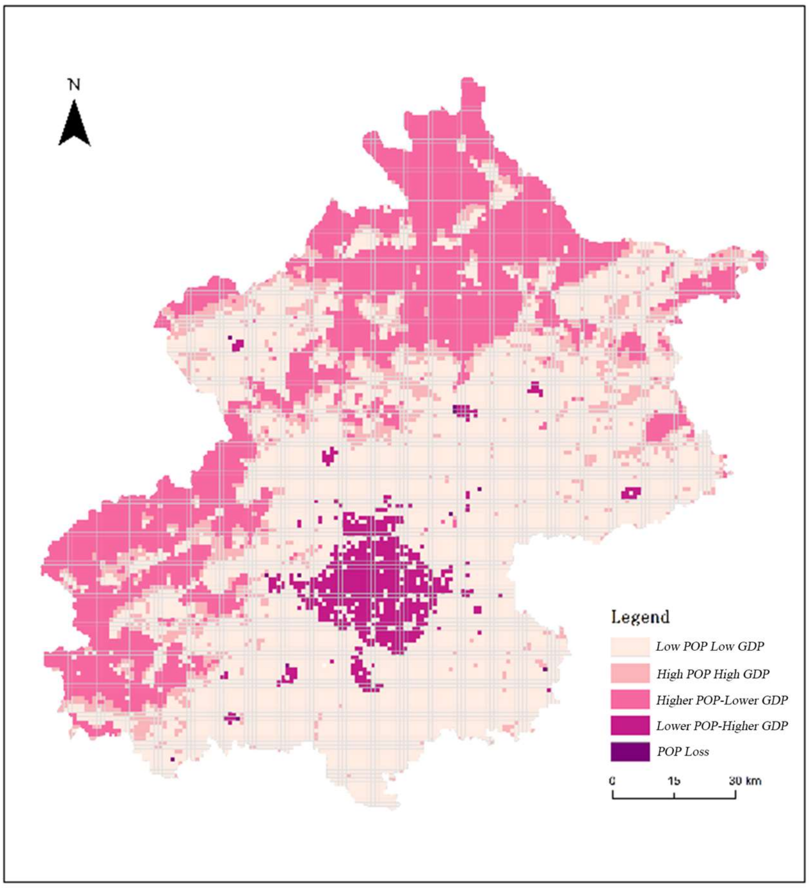


Figure 7. The coupled population–GDP clustering of grid scale.

Simultaneously, suburban areas such as Changping and Pinggu emerge as regional hotspots for socio-economic development, displaying limited-scale polarization and economic spillovers (Figure 8). Within the low-population low-GDP clusters, there exist some high-population low-GDP clusters, indicating that the rate of small-scale population agglomeration is significantly faster than GDP growth. These clusters are mainly distributed in fringe suburbs like Huairou and Pinggu, accounting for 72.49% of the total number of such clusters, and there is a high probability that these areas are commuter towns, which mainly provide resting places for industrial personnel. This nuanced analysis provides valuable insights into the dynamics of socio-economic development, urban polarization, and population clusters across different zones within and around Beijing.

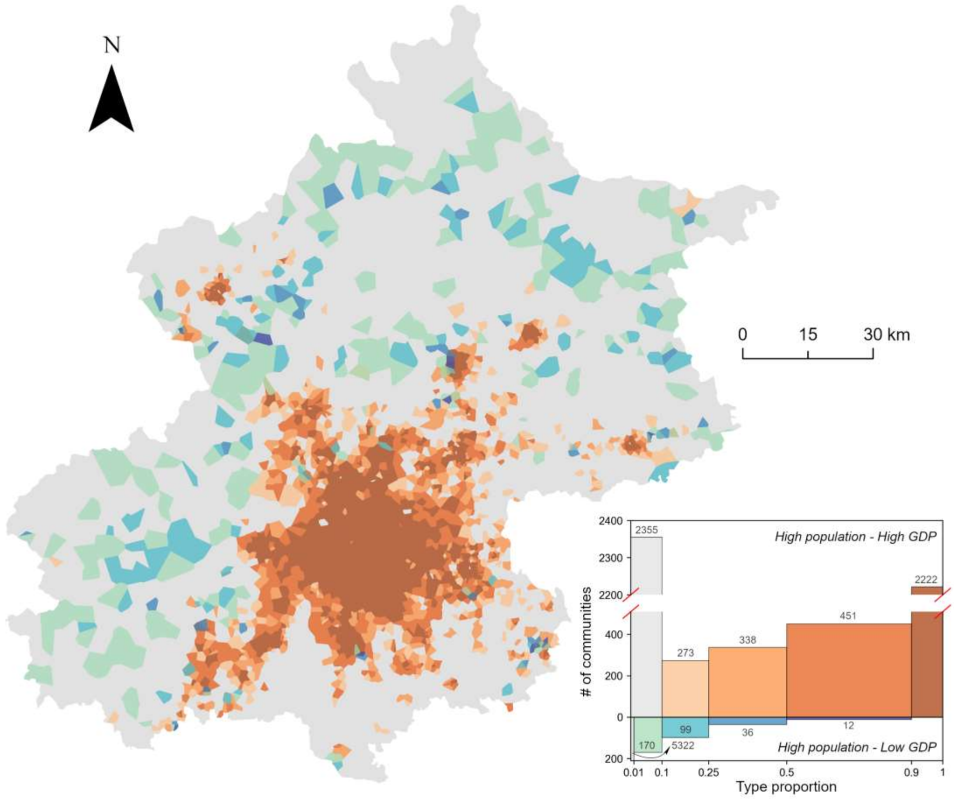


Figure 8. The coupled population–GDP clustering in the community scale. The y-axis in the panel represents the number of communities for two clusters, and the x-axis represents the proportion of grids included in the community.

The coupling of socio-economic results with land-use clustering in Beijing reveals a relatively good integration of population–economy–development–ecology, with partially coordinated districts dominating the kilometer grid, accounting for 78.60% of the total number of grid cells (Figure 9). Spatially, the overall structure follows a circular evolution from the urban center coordination zone outward to the urban fringe problem areas and then to the partial coordination zones in the fringe areas. Major urban areas predominantly fall into partial coordination zones and full coordination zones, with shares of 19.03% and 76.61%, respectively. The central urban area, characterized by high population–GDP built-up land coupling, primarily constitutes a partially coordinated zone with a slightly lower proportion of ecological land. In contrast, the fringe area benefits from the growth of ecological land, such as urban green space, and is predominantly a fully coordinated zone.

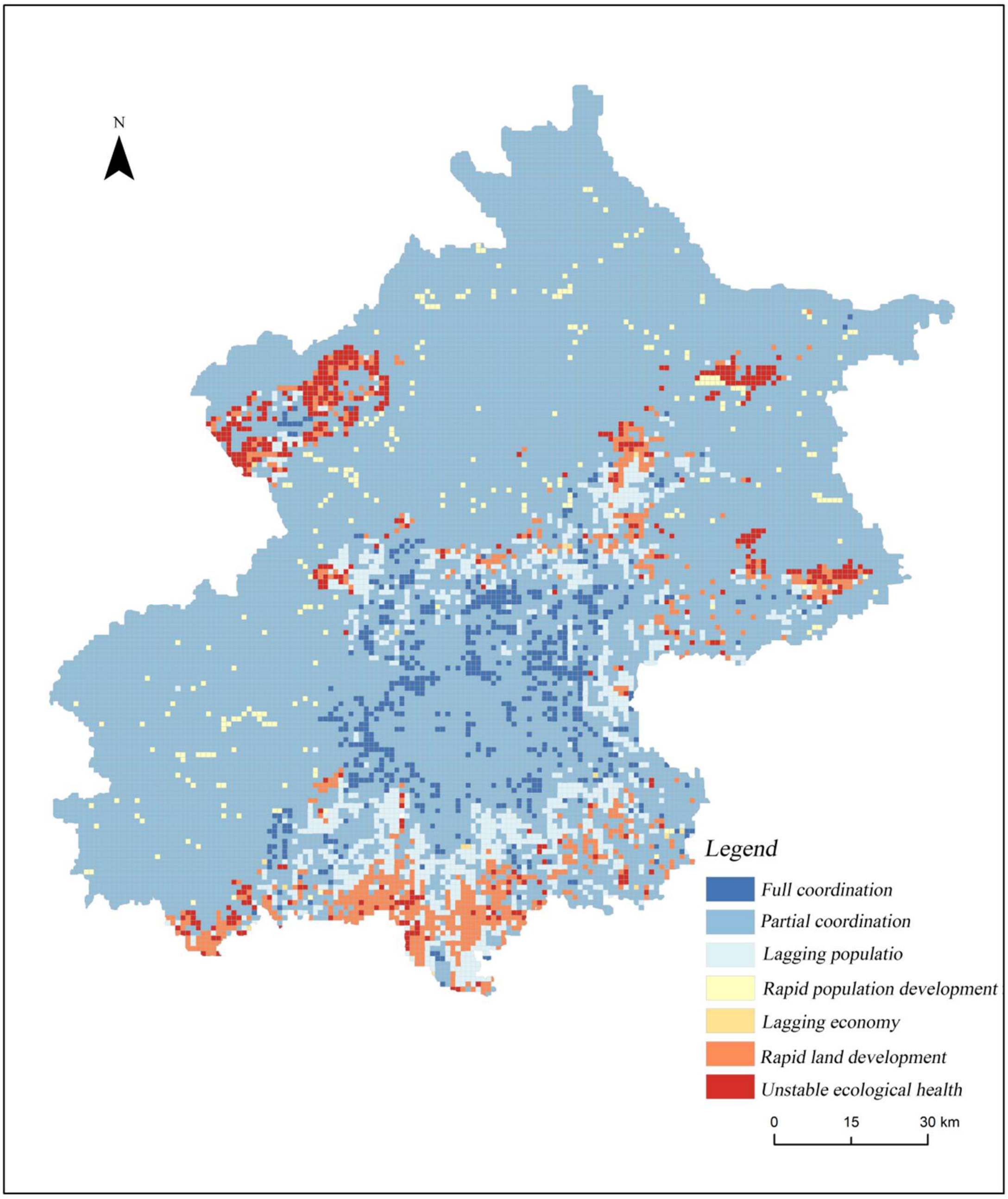


Figure 9. The coupling of socio-economic results with land-use clustering in Beijing.

Problematic areas are concentrated around the urban areas in the southern and northern suburbs of Beijing. The main issues include lagging population, rapid land development, and unstable ecological health, accounting for 45.13%, 27.05%, and 17.63% of the problematic units, respectively. The zones with lagging population concentration are located at the edges of Beijing's major urban areas, developing along the planned development axes of Fangshan–Changping–Yanqing and Tongzhou–Huairou. These areas are characterized by significant population concentration lagging behind the growth of GDP and the expansion of construction land. The zone of over-rapid land development is primarily found in the south of Beijing, where the issue is that the expansion of construction land has significantly exceeded the needs of population accommodation and socio-economic development. The zone of unstable ecological health mainly comprises areas with serious ecosystem fluctuations, spatially concentrated in the three districts of

Yanqing in the northwest and Huairou and Pinggu in the northeast, accounting for 27.15%, 21.76%, and 14.93% of the total area.

Results at the kilometer grid level were aggregated to the community scale to analyze the proportion of problem areas and the number of dimensions of problem types in each community unit (Figure 10). The majority of communities in Beijing demonstrate well-coupled dimensions of population–economy–construction and development–ecological protection, with 70.33% of community units having no uncoupled problem areas. Only 0.87% of communities, totaling 49, exhibit more serious risks in terms of the proportion of area and the types of problems. These communities, primarily located in the southern part of Beijing and the edges of suburban urban areas, face challenges such as population lagging and fast land development, indicating a risk of over-expansion of construction land in non-core areas. The transition zone between Fangshan District and Tongzhou District stands out as an area with frequent community uncoupling risks, where 48 communities experience such risks, occupying 10.40% of the total number of communities at risk in Beijing. In addition to the large, uncoupled areas in the south, the marginal jurisdictions of Machikou Town in Changping, Sunjiaying Town in Yanqing, Nandule Town in Pinggu, and BuLaoTun Town and Xitiange Town in Miyun also experience a small percentage of over-representation of uncoupled areas. Moreover, there is a strong concurrent correlation between some of the risks. Within the 1034 community units with over-expansion of land, 63.25% of communities exhibit concurrent problems of lagging population agglomeration, and 45.55% have issues related to unstable ecological health. This overlapping of uncoupled risks underscores the need for urgent risk management strategies.

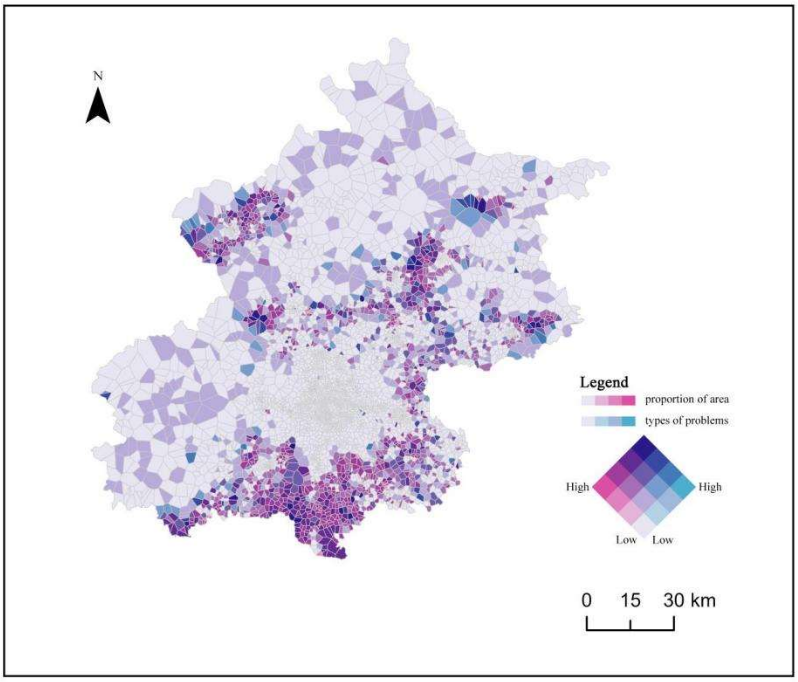


Figure 10. The proportion of problem areas and the number of dimensions of problem types in each community unit.

5. Discussion

The coherence of population concentration, economic agglomeration, land development, and ecological protection serves as a crucial indicator of successful urban governance [29,30]. Assessing the spatial and temporal synergy of these elements at the community scale and using it as a basis for categorizing governance is vital [31]. Beijing has undergone significant changes in population concentration, economic agglomeration, land development, and ecosystems over the past 30 years [32–34]. Beijing's resident population surged from 10.86 million in 1990 to 19.612 million in 2010 and gradually reached 21.893 million in 2020. Similarly, GDP per capita increased from US$104.70 in 1990 to US$10,910 in 2010 and to US$23,800 in 2020. The intensity of land development rose from 5.77% in 1990 to 11.48% in 2010, slowing to 17.30% in 2020. The dynamic changes in population, GDP, and land development make Beijing a typical case for studying these issues. Our study reveals significant differences not only at the city level but also in the time evolution process and spatial differentiation of resident population, GDP, land development, and ecosystems. In the time dimension, a clear phase is evident, highly correlated with the change in GDP per capita. Spatially, focusing characteristics emerge, especially in the urban fringe and the southern region with strong resource and environmental constraints. Identifying differences in the temporal and spatial evolution of these elements at the community scale and pinpointing communities needing focused attention and potential issues are major features of this paper.

To aim at this issue, we employ a problem-oriented approach to assess the synchronization of population, economy, land development, and ecological conservation in this study. Our hypothesis revolves around the temporal and spatial alignment of these elements to achieve desired social, economic, and ecological effects in line with sustainability goals. Any potential asynchrony or spatial incoherence may pose social risks. Discrepancies between population and economy impact the sustainability of economic benefits [35,36]. Similarly, incongruities between land development and population/economy not only affect economic sustainability but also pose threats to social equity and social sustainability, as supported by existing research [37,38]. Localized spatial agglomerations of population and economy result in significant differences in land prices, leading landowners to be under-motivated and uncooperative in choosing industrial forms or supporting public infrastructure services within the bounds of the plan. The intensity of land development and the type of industry, in turn, influence the health of the surrounding ecosystem, constraining the realization of ecosystem sustainability [39]. The ability of ecosystems to provide healthy and stable services is crucial for the overall resilient development and security of the city. Therefore, problems at the community scale may affect the sustainability of the city as a whole, either through spatial effects or near-remote coupling. It is imperative for overall urban governance to study the relationship between population, economy, land development, and ecological protection starting from the smallest community scale of the city.

The population and GDP data in this paper are derived from publicly published 1 km grid cell data, rather than actual statistics. Meanwhile, the land development and ecosystem data come from the team's Google Engine-based land cover classification data. Acknowledging the uncontrollable errors inherent in any data source, we utilize the characteristics of time series stability. Employing the method of time series clustering of kilometer grid cells, we categorize the cells typologically, reducing the impact of data accuracy. During the aggregation from grid cells to the community scale, we set specific thresholds to categorize the community grid cells. Simultaneously, in the continuous integration of population, GDP, land development intensity, and ecosystem protection, we monitor the uncertainty of grading thresholds, selecting the most stable ones to classify community types. We selected 2 communities from each of the 16 districts in Beijing to conduct research and interviews and asked community workers and older villagers to recognize the results of the study. After evaluation, we found that more than 80% of the community identification results met expectations, which, to some extent, indicates the reliability of this study.

The method presented in this paper exhibits good scalability. As community governance involves multiple dimensions such as economy, population, industry, science and technology, culture, and governance capacity, future data can be superimposed to comprehensively evaluate shortcomings and sustainability combinations of community units. Spatio-temporal clustering at the kilometer and community scales in this paper precisely identifies existing problems in urban governance. This study not only delineates spatio-temporal dynamic processes of population, economy, land development, and ecosystem protection but also identifies different combination types and existing problems through clustering and integration. This study holds significant revelation value for urban governance, providing decision support for planners and policymakers.

As Beijing, a mega-city under China's robust policy management, strives for sustainable development, it has prioritized enhancing spatial governance. Responding to challenges stemming from exponential population growth from the 1990s to the early 21st century, Beijing pioneered the orderly decentralization of its non-capital functions in 2015, becoming China's first mega-city to curtail its expansion. Subsequently, in 2017, Beijing introduced the Beijing Urban Master Plan (2016–2035), delineating the city's future development goals and setting forth a novel urban development blueprint characterized by "one core, one major urban area, two axes, multiple points, and one district." These initiatives have bolstered Beijing's overall coordinated development, with our research indicating higher levels of population–economy–development–ecology synergy, particularly in major urban areas where over 76% of the city's regions exhibit full coordination. However, challenges persist in certain urban peripheral areas, marked by lagging population growth, rapid land development, and absence of coordinated development strategies. These issues necessitate tailored interventions targeting specific regions and problems. Recognizing the community as the fundamental unit of urban spatial governance, we advocate for precision and efficacy in urban governance enhancement.

Drawing from our findings, we propose the following recommendations for Beijing's future spatial governance: Firstly, expedite comprehensive enhancements and optimizations in problematic communities. This entails bolstering transportation infrastructure, education, healthcare, and other public services in areas with lagging population growth to augment community appeal and capacity for urban residents. Additionally, facilitate the transition of rapidly developing communities through stringent control of new land development, coupled with strategic community function positioning, aimed at revitalizing inefficient development spaces. Secondly, prioritize a holistic and interconnected approach to problematic community governance. Our research underscores the interrelation between various risk factors in troubled communities. For instance, among 1034 community units experiencing excessive land expansion, 63.25% exhibit lagging population concentration, while 45.55% suffer from unstable ecological health. Thus, in addressing community governance, alongside tackling primary issues, attention must be directed towards interlinkages among pertinent elements to elevate overall community development coordination through comprehensive planning and systematic execution. Thirdly, incrementally refine urban physical assessments and urban master plan implementation evaluations at the community level to bolster planning implementation precision and spatial governance refinement. Leveraging the existing city–district–street (township) urban management framework, explore avenues for refining the urban management system down to the community level. Strengthen community-level big data platforms and talent pools, fostering intelligence and specialization in community spatial governance.

6. Conclusions

Analyzing the spatial and temporal changes and the matching relationship between socio-economic and land-use structures in large cities on a long time-series and micro scale is crucial for supporting fine-grained spatial governance. Utilizing multi-source remote sensing data and a big data platform, this paper explores a method of multi-factor integration at different spatial scales. It analyzes the global and local characteristics of the evolution of population, GDP, and land use in Beijing over the past 30 years. It identifies and clusters areas with lagging or excessive population concentration, economic lag, excessive land development, and unstable ecosystems based on the expectation of the balance of population, economic, and land change using a problem-oriented approach.

The study reveals several key findings: (1) Beijing's population, GDP, and land use have undergone significant changes, with a notable 11.53% increase in the intensity of land development. Population and the economy have generally clustered simultaneously but with significant variations in different phases and spatial localities. (2) Temporal and spatial mismatches between population and GDP, population and land development, and GDP and land development account for 18.07%, 27.62%, and 20.89% of Beijing's area, respectively. Areas of rapid or lagging population agglomeration, lagging economic agglomeration, rapid land development, and unstable ecosystems account for 4.74%, 10.48%, 11.21%, and 0.36% of Beijing's area, respectively. (3) The mismatch between population and economic agglomeration, land development, and ecosystem stability poses potential governance risks. Types of communities with medium or higher risks account for 18.08% of the number of community units in Beijing, with the weights of high-risk types also accounting for 4.27%.

This research expands the risk analysis method by integrating and analyzing multi-dimensional and multi-factors at the micro-analysis unit level. It incorporates natural, economic, scientific and technological, cultural, and governance elements into a common analysis framework. This systematic analysis of comprehensive governance problems in big cities will provide decision-making support for the fine-grained governance of these cities. This study delineates potential risks associated with community-scale spatial governance by examining the interplay between population dynamics, economic trends, allocation of construction, and ecological lands. These potential risk categories serve as preemptive indicators, aligning with principles of risk mitigation, regional equilibrium, development land efficiency, and ecological preservation. To address areas of concern such as lagging population concentration and economic development, we advocate for optimizing spatial infrastructure and public service allocation, thereby fostering balanced development and synchronized growth of population and economy within defined parameters. In regions experiencing rapid expansion of construction land but sluggish population concentration and economic productivity, we recommend enhancing land utilization efficiency through incentivized mechanisms and stringent monitoring protocols. Areas witnessing pronounced and unstable ecological decline necessitate robust ecological management strategies and essential restoration efforts. Moreover, we advocate for bolstering town development functionalities, urban agriculture initiatives, and leveraging ecological tourism to unlock the land's multifunctional potential.

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